EFRC Report

Inventory to the Emissions of Reciprocating Compressor Systems

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Foreword

The EFRC is the European Forum for Reciprocating Compressors has been founded in 1999 by Neuman & Esser, Leobersdorfer Maschinenfabrik, Hoerbiger Ventilwerke, TNO, TU Dresden, Thomassen Compression Systems, Wärtsila Compression Systems and Burckhardt Compression. The target of the EFRC is to serve as a platform to facilitate exchange of information between vendors, operators and scientists working in the field of reciprocating compressors.
This is achieved by knowledge transfer (conferences, internet, student workshops, training and seminars), standardization work (e.g. EFRC Guidelines, API 618, ISO 20816-8), and by joint pre-competitive research projects, aiming at improving the performance and the image of the reciprocating compressor.
In the R&D projects the forces are combined of all interested parties to solve or investigate problems which are beyond the scope of a single player. The basic research and pre-competitive research projects are carried out at research institutes or universities. In this way the R&D group of the EFRC will serve as the scientific arm of the reciprocating compressor community.

The research and standardisation working group are open to all EFRC members and the annual budget is funded by participating members. The results are owned by the EFRC and the research results are disclosed to EFRC research group members only.

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List of important abbreviations

(E)-PRTR	(European) Pollutant Release and Transfer Register
40 CFR	Title 40, Code of Federal Regulations
APIS	Air Pollutant Information System
AR	Assessment report
bbl	Barrel
CAA	Clean Air Act
CCAC	Climate and clean air coalition
CH_4	Methane
CMR	Center for Methane Research
CO_2	Carbon dioxide
CONCAWE	Conservation of Clean Air and Water in Europe
COP21	2015 United Nations Climate Change Conference held in Paris
ECS	Equilibrium Climate Sensitivity
EF	Emission factor
EPA	Environmental Protection Agency
eq.	Equivalent
GHG	Greenhouse Gas
GHGI	Greenhouse Gas Inventory
GMI	Global Methane Initiative
Gt	Giga tonnes
GTI	Gas Research Institute
GTP	Global Temperature change Potential
GWP	Global Warming Potential
H_2O	Water
IEA	International Energy Agency
IED	Industrial Emission Directive
INDC	Intended Nationally Determined Contribution
IPCC	Intergovernmental Panel for Climate Change
IPIECA	International Petroleum Industry Conservation Association
IPPC	Integrated Pollution Prevention Control
MACT	Maximum achievable control technology
MRR	Mandatory Reporting Rule
NEC	National Emission Ceiling
NEC	National Emission Ceiling
NERC	National Emissions Reduction Commitments
Nm^3	Normal cubic meter
NMVOC	Non-methane Volatile Organic Compound
NSPS	New Source Performance Standards
O&G	Oil and gas
PEMEX	Petróleos Mexicanos
PPA	Pollution Prevention Act
ppbv	Parts-per-billion volume
ppmv	Parts-per-million volume
PM	Particulate Matter
RF	Radiative Forcing in W/m^2
SOCMI	Synthetic Organic Chemical Industry
T&S	Transmission and storage

TOC	Total Organic Compound
UNFCCC	United Nations Framework Convention on Climate Change
VOC	Volatile Organic Compound
W/m^2	Watts per square meter
WMGHG	Well-mixed greenhouse gas

List of important organisations and programs

The US Environmental Protection Agency (EPA, https://www.epa.gov/)
Is the regulatory authority on most US national environmental topics. When the congress writes an environmental law, the EPA implements it by writing regulations. The regulations of the EPA are gathered under Title 40, Code of Federal Regulations (40 CFR). Of particular importance to compressors is the New Source Performance Standards (NSPS), which is based upon the Clean Air Act, both we will discuss in depth below. The compressor relevant standards are found in the natural gas context, gathered under the New Source Performance Standard (NSPS) Subpart OOOOa.

Global Methane Initiative (GMI)
Without any exclusive ties to any government, the Global Methane Initiative is an organisation which provides a program to reduce methane emissions:

The Global Methane Initiative (GMI) promotes cost-effective, near-term methane recovery through partnerships between developed and developing countries, with participation from the private sector, development banks, and nongovernmental organizations.

Launched in 2004, the GMI is the only international effort to specifically target methane abatement, recovery, and use by focusing on biogas (which includes agriculture, municipal solid waste, and wastewater), coal mines, and oil and gas systems. Working in collaboration with other international organizations, the initiative has formed key alliances with partners such as the United Nations Economic Commission for Europe (UNECE) and the Climate and Clean Air Coalition (CCAC) to reduce global methane emissions. Focusing collective efforts on methane emission sources is a cost-effective approach to reduce greenhouse gas (GHG) emissions and increase energy security, enhance economic growth, improve air quality and improve worker safety (GMI, n.d.)

Oil & Gas Methane Partnership (OGMP) of the CCAC
The CCAC's voluntary program for methane reductions is called the Oil & Gas Methane Partnership. This partnership makes its appearance with their technical guidance documents, including reduction methods for all major emission sources and quantification guidance.
The Climate and Clean Air Coalition created a voluntary initiative to help companies reduce methane emissions in the oil and gas sector. The Oil & Gas Methane Partnership was launched at the UN Secretary General's Climate Summit in New York in September 2014. The initiative currently has the following partner companies: BP, Eni, Neptune Energy International SA, Pemex, PTT, Repsol, Shell, Statoil, and Total. Currently, companies representing about 12.5% of global oil and gas production are members.

The Environmental Partnership from the American Petroleum Institute (API,https://www.api.org/news-policy-and-issues/environment/the-environmental-partnership-website)
In the area of private enterprises, we find the Environmental Partnership, a platform *for* and *by* US operators looking to address VOC and methane emissions. Relevant to compressor emissions is their leak detection, monitoring and repair program.

The Environmental Partnership is comprised of companies in the U.S. natural gas and oil industry committed to continuously improving the industry's environmental performance. It includes companies of all sizes, including many of the country's major natural gas and oil producers.
It takes action on the environmental performance; building upon their knowledge; fostering collaboration among stakeholders

IPIECA http://www.ipieca.org/our-work/sustainability-reporting)
Another example of an environmental effort initiated by the oil and gas industry itself, is the IPIECA. The IPIECA is a not for profit association that provides a forum for encouraging continuous improvement in industry performance. IPIECA is the only global association involving both the upstream and downstream oil and gas industry. It is also the industry's principal channel of communication with the United Nations.

IPIECA develops, shares and promotes good practice and knowledge to help the industry and improve its environmental and social performance. We do this with the understanding that the issues that dominate the sustainable development agenda – climate and energy, environmental and social issues – are too big for individual companies to tackle alone. The industry must work together to achieve improvements that have real impact. IPIECA helps to achieve this goal. (IPIECA, 2018)

The US Clean Air Act (CAA, https://www.epa.gov/laws-regulations/summary-clean-air-act)
Is the extensive federal law that regulates air emissions from stationary and mobile sources. This law authorizes the EPA to establish National Ambient Air Quality Standards (NAAQS) to protect public health and public welfare and to regulate emissions of hazardous air pollutants (EPA, 2017, August 24th).

The Natural Gas STAR Program (https://www.epa.gov/natural-gas-star-program) of the Environmental Protection Agency (EPA)
The NG STAR Program offers guidance on best practices in reducing methane emissions. Working collaboratively with the U.S. oil and natural gas industry since 1993, Natural Gas STAR provides a framework for partner companies to implement methane reducing technologies and practices and document their voluntary emission reduction activities. Through this work, the oil and natural gas industry has pioneered some of the most widely-used, innovative technologies and practices that reduce methane emissions.

The US Greenhouse Gas Reporting Program (GHGRP)
Provided here, is a short summary of the program including important regulatory aspects such as definition issues. Officially titled 40 CFR part 98, the GHGRP is a mandatory Greenhouse Gas (GHG) reporting program established in 2010. The program is compelled for US facilities emitting more than 25,000 tonnes of CO_2 equivalent per year, or suppliers selling product with the same combustion potential.

The European Industrial Emissions Directive (IED, https://ec.europa.eu/environment/industry/stationary/ied/legislation.htm)
In the European Union there are several legal instruments targeting industrial emissions. As the multitude of laws were rather dense yet scattered, they were brought under a single clear legislative instrument: the Industrial Emission Directive (IED). In the IED, there is one program of special importance for compressor systems: the IPPC (Integrated Pollution Prevention and Control), a *license* directive based on the usage of Best Available Technology (BAT).
This permit shall contain conditions set in accordance with the principles and provisions of the IED (European Commission, 2016). The BAT permit regulation is most relevant IED component for compressor systems. These permit regulations are gathered under the IPPC (Integrated Pollution Prevention Control) program. Implementation of the IED and its IPPC permits, is the individual responsibility of each EU member state. The member states will implement the IED through *operating licenses*, where are company's operations are approved by the government, the provinces, states, or municipality.

In the IED, there is one program of special importance to reciprocating compressor systems: the IPPC (Integrated Pollution Prevention and Control), a *license* directive based on the usage of Best Available Technology (BAT). The IPPC Directive requires industrial and agricultural activities with a high pollution potential to have a permit. This permit can only be issued if certain environmental conditions are met, so that the companies themselves bear responsibility for preventing and reducing any pollution they may cause.

1 Introduction

The industry faces increasing pressure to reduce emissions from flaring and venting. Governments focus on reduction of greenhouse gas emissions (including methane), especially as natural gas positions itself as a transition fuel for the coming decades. Process gas leakage costs operator's revenue and is most 'visible' when process gas is a sales product. The figure below shows an overview of the natural gas supply chain, from production to consumer and leaks can occur in every step of the supply chain.

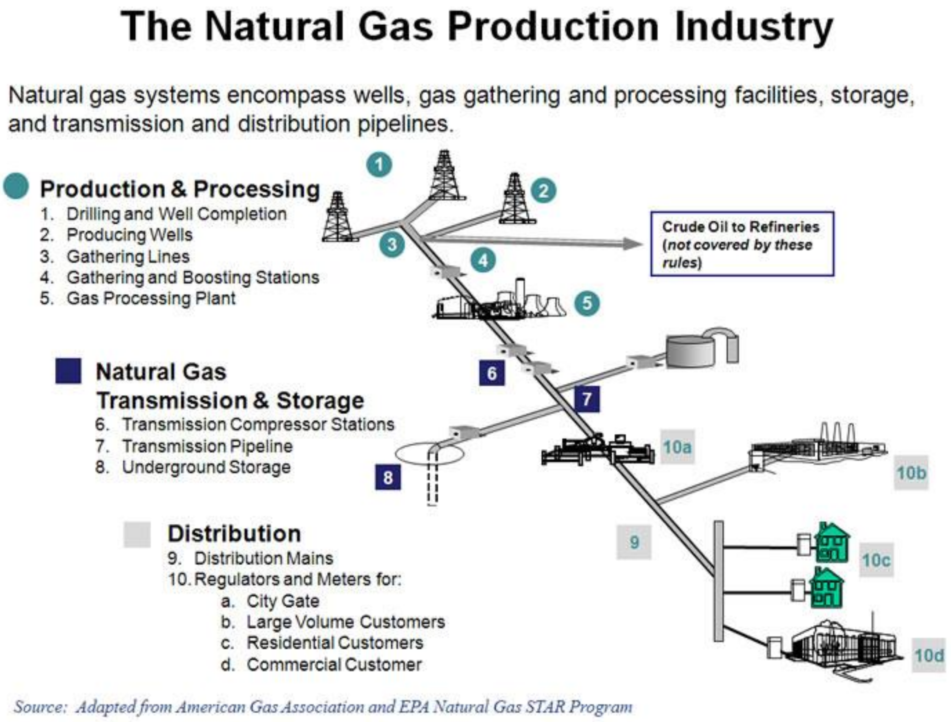

Figure 1 Natural gas flow from the well to consumer (EPA NG STAR Program)

The trends & outlook which are recognised are as follows:

- It is well known that most of the leak gas of a reciprocating compressor occurs via the piston rod packing. There are already ongoing research projects to improve the quality of the piston rod packing with a final target of zero emissions.
- There is an increased focus on the reduction of greenhouse gas emissions, including methane.
- There is an increased focus on the reduction of flaring leak gas by:
  - 'Zero routine flaring' for oil fields.
  - Emissions rules for refineries as laid down by the Environmental Protection Agency (EPA) from the USA.
  - Global Gas Flaring Reduction partnership.

Reciprocating compressors will always play a significant role in the industry and will become more important in the "new energy" market and for that reason other gases such as H2, CO2 and CH4 will become more important.
Due to the increased focus on the reduction of greenhouse gas emissions, including methane and the reduction of flaring leak gas, the research group of the EFRC is

focussing more on projects how emissions of reciprocating compressors can be reduced. To get more data and information on the emissions of reciprocating compressors an inventory study was carried in 2018 on emissions of reciprocating compressor systems. This study was focussing on the following aspects:

- What is known on emissions of reciprocating compressor systems>
- Measurement methods.
- Emission factors currently being used.
- How are emissions monitored and documented by operators?
- Emissions of reciprocating compressors in comparison with other equipment (e.g. turbo compressors, process equipment, valves, etc.).
- How can emissions of reciprocating compressor systems be reduced?
- Which standards are available on emissions.
- Differences with respect to legislation, practice, monitoring etc. between different countries.
- Which measures are already implemented by operators and components suppliers to reduce emissions.
- What can be learned from other countries, e.g. USA (studies, reports, emissions reduction methods applied in the field, etc.).

The information has been collected from literature (conference proceedings, internet, industrial standards, etc). In addition, to gauge the view of the industry, an interview with several operators was held.

The results have been summarised in an internal EFRC report. However, the EFRC has the opinion that more information on emissions of reciprocating compressors shall become available for all interested companies who are working with reciprocating compressor systems such as compressors OEM's, parts suppliers and end-users. For that reason it was decided by the members of the EFRC to make a publicly available report with a summary of the internal EFRC report. This summary report starts with some general background information which is helpful in understanding emissions in general and why it is important to reduce emissions.
It is followed by how emissions can be quantified, measured and monitored. The last and important part is on how emissions of reciprocating compressor system can be reduced. This is made concrete in the following chapters:

Chapter 2 "Emissions of the reciprocating compressor industry"
This chapter starts with some basics: what are emissions, and how are they relevant to reciprocating compressors?
While economics and health & safety are unambiguous perspectives, the climate perspective exists on a spectrum of which the catastrophic narrative is currently most influential. The climate aspect to gas emissions is one of the foremost reasons for the EFRC report's existence. However, the climate perspective has proved to be much more nuanced and broader than initially expected. This subject has been approached as a spectrum of varying methods, opinions and predictions, named "Bigger Picture". Due to the fact that not all readers of this report might be interested in this complex subject, it is placed in Appendix A.

Chapter 3, "Emissions in the natural gas industry"
This chapter is a case study of *the* industry in which compressor emissions are most thoroughly studied and understood.

Chapter 4, "Methane emissions of reciprocating compressors"
Actual data and measurements on reciprocating compressor emissions are discussed and put into context.

Chapter 5, "Measurement, Monitoring and Estimation"
This chapter contains the discussion on how emissions are *quantified*. Both measurement techniques, as well as estimation methods are discussed in their technical aspects and theoretical limitations.

Chapter 6, "Emission reduction methods"
This is one of the most important chapters if one is interested how emissions of reciprocating compressor can be reduced It gives a summary of most effective reduction methods known in practice and literature. Both *techniques* as well as *technologies* prove to be effective reduction methods.

Regardless the operators view on emissions, operators are forced by legislation to monitor, report and reduce emissions. For that reason, the most important parts of this report are those chapters on the emissions of reciprocating compressor systems (chapter 4), how to estimate, measure and monitor emissions (chapter 5) and how to reduce emissions of reciprocating compressor systems (chapter 6). The reader, who is not interested in the backgrounds and details, may want to skip the other chapters.

Formatting styles
This report will contain the following formatting styles:
Using the APA reference style, the author's last name and year of publication are added when their works are explained or paraphrased, as such: (Mr XXX & Mr. YYYl, 2018). When text is directly quoted, "the page number is added too" (XXX & YYY, 2018, p.9).

> When a large portion of text is cited, the quotation marks are left out and instead the text is marked in *blue*, with an increased indent (XXX & YYY, 2018, p.9, *italics* in original).

Occasionally, emphasis in *italics* or **bold**, are in the original text or added by this report's author. Similarly, the author of this report will paraphrase *within* a quotation to clarify certain issues. The paraphrased text is indicated with [brackets surrounding the text]. The (…) symbol indicates pieces of text that are intentionally left out by this report's author.

The references of each chapter are compiled in the reference list at the end of each chapter. Sources are displayed more elaborately, including a website link when possible, in the following fashion:

XXX, A., & YYY, J. (2018). EFRC Project: Inventory of the emissions of reciprocating compressor systems. Retrieved from https://www.recip.org

More general information on the APA style is found at (URL: www.apastyle.org/)

2 Emissions of the reciprocating compressor industry

2.1 Introduction

In this chapter it is explained what emissions are and why do they matter for the reciprocating compressors industry.
This question lays the foundation for this report, creating clarity on the boundaries and the importance of the matter. Often, throughout the report, there will be returned to this question and the answer, simply to keep the reader on the right track.

‘To emit’ is to send outward substance, light, vibration or heat. Compressor emissions fit many of these categories, yet the pre-defined focal point of this report is the emission of substances or particles. Why, do these emissions matter?

The phenomenon of “Emissions” often triggers immediate associations with climate change and greenhouse gasses. Even though this perspective is relevant to this study, it does not constitute the entirety of the interest in reciprocating compressor (recip) emissions. Most broadly, the emissions from recips are of interest from three perspectives:

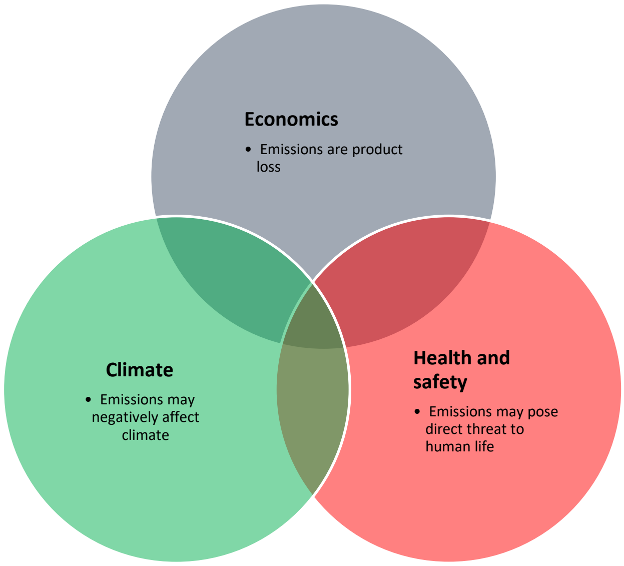

Figure 2 Three perspectives/reasons for interest in recip emissions

As Figure 2 above shows, these areas can be taken separate but may also overlap with each other. Seemingly, when a recip emission falls under all the three reasons of interest, the incentive to *do something* about it and achieve *results*, is greatest. Yet, the incentive can be equally great from a single perspective, for example the need to reduce toxic H_2S emissions is most important for its health aspect, while the associated climate or bottom-line aspects are auxiliary.

Although it is alluring to turn instantly to the aspects of *reduction opportunities* and *reduction results*, these *are* a large part of this report which will be discussed in chapter 6.

The economic perspective is rather straightforward. Compressor emissions are saleable as the handled gas is seldomly worthless. This perspective on the bottom-line hinges greatly on a cost benefit analysis: if the reduction costs are lower than the payback of reduced product loss, the economic perspective is relevant. If the cost efficiency is too low, the payback period may become unrealistically long or non-existent, thereby making the emission at hand irrelevant for the bottom-line. However, the environmental costs should also be included in the economic consideration. As an example, the environmental costs are quantified as the penalty for CO2 emissions caused by the power industry in Europe.
Whether this is the case, depends on the *reduction measures* available (discussed in chapter 6).

The other two perspectives, health & safety and climate, are more complicated and take more than one paragraph to understand. Instead, these topics are associated with complex science issues, elaborate terminology and dense regulations. The climate perspective, for example, will prove to be a spectrum of different stances.

The least complicated and controversial perspective, health and safety, is discussed in the next section 2.2

The climate aspect to gas emissions is one of the foremost reasons for this report's existence. However, the climate perspective has proved to be much more nuanced and broader than initially expected. In fact, the need will be find to distinguish the prevailing, more catastrophic climate predictions, as one mode of the climate perspective. Although this mode has gained large momentum, occupying the mainstream story, the exploration of the climate perspective will not begin with one or the other mode. Instead, this subject will be approached as a spectrum of varying methods, opinions and predictions, named "Bigger Picture". Due to the fact that not all readers of this report might be interested in this complex subject, it is placed in Appendix A.

2.2 Emissions as direct health and safety threats

Compressor emissions *may* pose direct threats to health and safety when the substance emitted are *toxic, asphyxiant, flammable or explosive*. Incentives to tackle these emissions originate from the protection of human life and loss of product and equipment, e.g. fire and explosions. The reduction efforts yield immediate results.

A well-known safety concern is the combustion danger of gas leakage into the compressor crankcase. Often, operators are well aware of the flammability of the process gas, although they may not be aware of the danger of gas leakage into the crankcase. Additionally, there is the more subtle concern of negative health impacts through inhalation of emissions. An important matter for this aspect is the *volatility* of the handled gas. For this reason, this report will often use the category Volatile Organic Compound (VOC), which are "*organic chemical compounds whose composition makes it possible for them to evaporate under normal indoor atmospheric conditions of temperature and pressure."* (EPA, 2017, April 12th)

> VOCs emissions are of significant environmental concern because some have the potential for Photochemical Ozone Creation Potential (POCP), Ozone Depletion Potential (ODP), Global Warming Potential (GWP), toxicity, carcinogenicity and local nuisance from odour (IPPC & EU, 2003, p. 71).

The story about VOC emissions gives the impression that VOCs are unnatural, chemical and caused only by humans. However, this is misguided as anthropogenic (human activity) VOC emissions are total 142 tera grams of carbon per year, whilst biological sources, mainly plants, emit 1150 tera grams of VOC carbon per year (Goldstein & Galbally, 2007). Forests and mountains known under such names as “Smokey-” or “Blue-” Mountains, owe their name to the plenty of VOC emissions coming from trees (Watts, 2014). The pleasant forest smells are nothing more than plant VOC emissions (Watts, 2014). Especially tree VOC emissions are known to create ground level (tropospheric) ozone (Watts, 2014). Additionally, even the human *breath* contains a few thousand volatile organic compounds (Buzsewski, Kesy, Ligor & Amann, 2007). However, due to the sheer *breadth* of the VOC category, the health impacts are hard to generalize. Therefore, whether or not a particular gas classifies as a VOC, will not help, say, a recip operator, to understand the potential health impacts of his leaking gas. Instead, to determine health impacts, the emitted gas is best studied on its individual characteristics.

In regulating VOC emissions, the US Environmental Protection Agency (EPA) excludes any non-harmful VOCs from their definition of VOC. The EPA-VOCs classify as either outdoor and indoor pollutants, where indoor impacts concern direct health detriments due to inhalation. Outdoor VOC pollutants are those substances with a photochemical *reactive* ability to create smog, ozone or fine particles. Some common volatile organic compounds do not have direct toxic effects, nor a reactive ability, and are excluded from the EPA-VOC definition; excluded are such gases as carbon mono- and dioxide, methane, ethane and many fluorocarbons (PRCI & GMRC, 2011). Not only the EPA has a custom VOC definition, for example methane is sometimes included as a VOC, and excluded in the term Non-Methane Volatile Organic Compounds (NMVOCS) (AQT, n.d.).

Due to the breadth of the VOC category, there are also VOCs with a potential climate impact. This aspect is discussed in Appendix A.

Methane, regardless of its characterisation as a VOC, is especially relevant to compressor systems involved in the natural gas industry, where methane is the main component of handled gas stream. The industry uses compressors when the gas needs to be transported or processed. Methane’s high volatility makes for a great potential for emissions through leakage. However, as far as health impact goes, the detrimental effects of methane exposure at *high* concentrations come primarily from methane’s ability to act as a simple *asphyxiant*, displacing oxygen supply causing suffocation, with such signs as dizziness and vomiting (NIH, 2014). At lower concentrations, however, its *toxicity* and reactive ability is not well-understood, and the lack of reliable information leaves this topic open for interpretation and misrepresentation (CMR & GTI, 2018). For instance, one recent study over-estimated methane emissions’ ability to form ground level (tropospheric) ozone, which causes such health detriments as increased asthma risk (CMR & GTI, 2018). The press picked up this story and over sensationalized it, leaving aside the many uncertainties concerning methane and copying the oversimplification of the study (CMR & GTI, 2018).

Methane is a volatile organic compound, but, as noted before, not all VOCs are health threatening and at the same time VOCs don't encompass all health endangering emissions. It is important to be aware of substances other than VOCs, especially since recips handle a wide variety of substances. For example, recips may handle sour-gas which contains the *non-organic* hydrogen sulphide, which is both *volatile* and *toxic*. For many health endangering emissions, the legal standards serve as guidance, notably the EPA's classifications of six “criteria air pollutants” and 187 hazardous air pollutants (HAPs), which are subject to increasing research and regulatory standards (EPA, 2017, March 16th; EPA, 2018, March 8th). Some important EPA listings are tropospheric ozone, particulate matter, carbon monoxide, lead, sulphur dioxide and nitrogen dioxide. These emissions may also contribute to the infamous smog phenomenon which is caused by both particulate matter and ozone formation, a photochemical reaction of nitrogen oxides, carbon monoxide and several VOCs (EPA, 2017, December 7th).

A major source for knowledge on health endangering substances is the Hazardous Substances Data Bank (HSDB), which contains professional overviews of many substances, available at: (https://toxnet.nlm.nih.gov/newtoxnet/hsdb.htm).

2.3 References

(AQT) Advanced quality technologies. (n.d.). Volatile Organic Compound. Retrieved March 19, 2018, from http://aqt-vru.com/emissions/volatile-organic-compound/

(CMR) Center for Methane Research, & (GTI) Gas Technology Institute. (2018). *An introduction to methane and the center for methane research*.

http://www.gastechnology.org/CMR/Documents/Intro_to_Methane_021318.pdf

(EPA) Environmental protection agency. (2017, April 12). Technical Overview of Volatile Organic Compounds. Retrieved March 19, 2018, from https://www.epa.gov/indoor-air-quality-iaq/technical-overview-volatile-organic-compounds

(IPCC) Intergovernmental panel on climate change. (2013). *Climate change 2013: The physical science basis. Working Group I contribution to the IPCC Fifth Assessment Report*. Retrieved from http://www.ipcc.ch/report/ar5/wg1/

Buzsewski, B., Kesy, M., Ligor, T., & Amann, A. (2007). *Human exhaled air analytics: biomarkers of diseases*. (https://onlinelibrary.wiley.com/doi/abs/10.1002/bmc.835)

Goldstein, A., & Galbally, I. (2007). *Known and Unexplored Organic Constituents in the Earth's Atmosphere* (https://pubs.acs.org/doi/abs/10.1021/es072476p)

NIH. (2014, June 30). National Institutes of Health (NIH) Hazardous Substance Data Bank: Methane. Retrieved March 15, 2018, from https://toxnet.nlm.nih.gov/cgi-bin/sis/search2/f?/temp/~L9y6LD:1

(PRCI) Pipeline research council international, & (GMRC) Gas machinery research council. (2011). *Standardized nomenclature for natural gas transmission and storage greenhouse gas emissions*. Retrieved from Classified

Watts, A. (2014, February 26). A case of the vapours: source of 'climate-active' organic aerosol particles pinned down. Retrieved July 2, 2018, from https://wattsupwiththat.com/2014/02/26/a-case-of-the-vapours-source-of-climate-active-organic-aerosol-particles-pinned-down/

3 Emissions in the natural gas industry

3.1 Introduction

The three fundamental aspects to emissions (economics, health & safety and climate) are relevant for recip emissions as explained in the former chapter and in Appendix A. From the many different possible gas emissions coming from recips, methane emissions in the natural gas industry has been explored. Why specifically methane and the natural gas industry? Because the available data and literature on recip emissions is *limited* to natural gas emissions. The natural gas industry will function as a *thorough case study* where *one* type of recip emissions is explored: methane. However, it shall be kept keep in mind that recip systems can handle a wide variety of gases like nitrogen, hydrogen, helium, carbon dioxide, oxygen, air, ethylene, ammonia, nitric acid, urea and a wide variety of hydrocarbons. These other emissions have their own unique blend of the three relevant perspectives of economics, health & safety and climate. By focussing on methane emissions, one such combination is studied in detail and it is shown how the weight of each perspective is determined. *As such, lessons learned from recip emissions in the natural gas industry, it is assumed that it can also be applied to other types of gases in other parts of the industry e.g. refineries and chemical plants*

This chapter introduces the topic of emissions of the natural gas industry.

3.2 Supply chain and sectors

To understand (reciprocating) compressor's role in the natural gas industry, the natural gas supply chain is divided into sectors and Figure 3 shows a schematic of the different natural gas sectors. Throughout the chain, the gas is transported by means of compression, for example from the wellhead to the processing plant, or from an underground storage system to a distribution centre. Often, the gas is moved across immense distances, for example 5000 kilometres from West-Siberia to Mid-Europe which requires compressor stations at approximately every 80 kilometres.

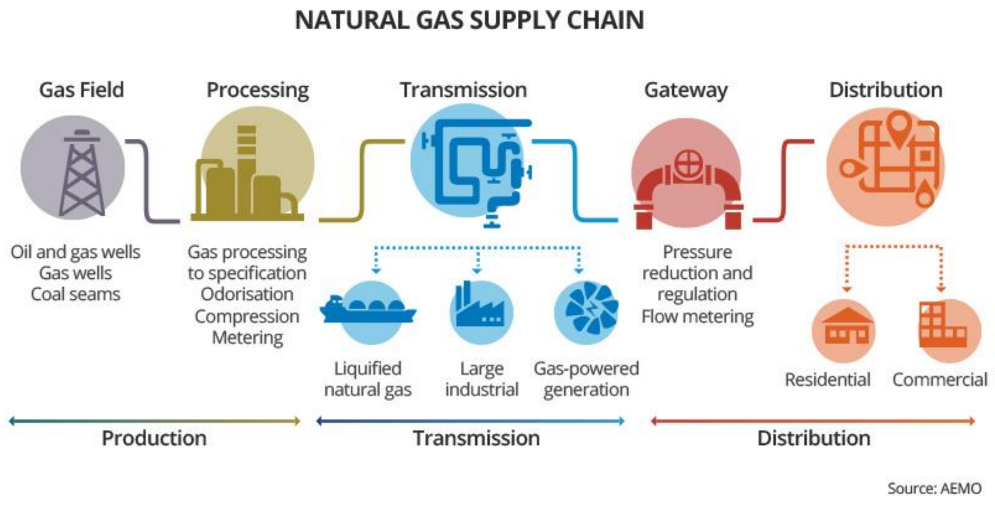

Figure 3 A schematic display of the segments in the oil and natural gas industry (AMO, n.d.)

The transmission sector is often grouped with the activity of natural gas storage, creating the abbreviation T&S (transmission & storage). Saleable gas is often stored rather than immediately sold because natural gas demand is very variable throughout the seasons. The storage spaces include such areas like underground natural caverns, which are injected by compressors with high pressure natural gas.

Compressors are most often used in the *processing, transmission and storage sectors*. Each sector is associated with different activities, pressures and natural gas compositions, and therefore different emissions. This can also vary considerably for different countries. Russia for example operates many more kilometres of pipelines than the Netherlands, resulting in higher emissions from the transmission sector.

Despite that fact that natural gas has many advantages, methane emissions contribute to a challenge faced by the global natural gas industry also due to the fact that the demand of natural gas is increasing worldwide as explained in section 3.3.

There are many benefits to natural gas: its use produces the least emissions compared to all other fossil fuels, its use is more efficient than other fossil fuels, and generally its prices are low and continue to decline. However, natural gas contributes to the Green House Gas (GHG) emissions.

3.3 Natural gas industry emissions as part of global emissions

Just like most fossil fuel industries, the natural gas industry has been on a steady growth as both supply and demand keep rising. The application of natural gas as a transition fuel (mainly in Europe), towards renewable energy sources will lead to a further growth of the natural gas industry in the coming decennia. Helpful technological developments like shale gas exploitation further help to meet the demand in several countries, especially in the US. Figure 4 below shows worldwide natural gas *production* from 1991 to 2016, with a clear strong increasing trend, except for the dip during the economic crisis in 2008.

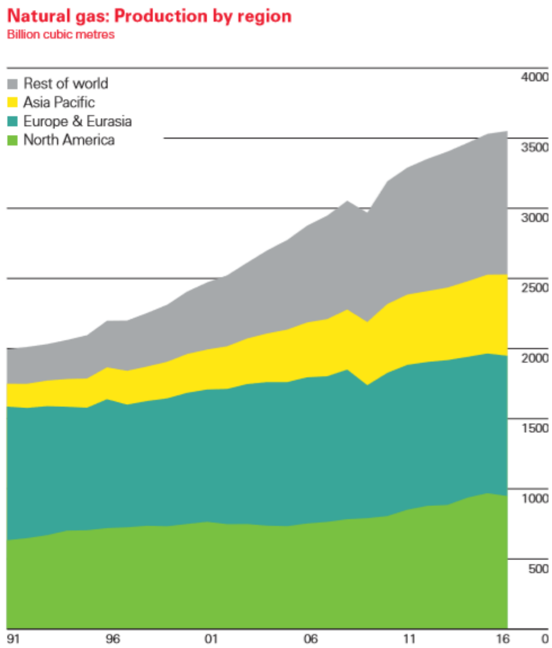

Figure 4 - Worldwide natural gas production, sorted by region. Timescale: 1991 to 2016. NG quantity in billion cubic metres (BP, 2017, p. 32)

The methane emissions associated with the natural gas supply chain are classified as either fugitive or vented emissions. As Balcombe et al. indicate: “the definition of ‘fugitive’ is not uniform across the literature and may cause confusion” (Balcombe et al., 2015, p. 13). This report will use fugitive emissions as unintentional leakage, contrasted with vented emissions which are ‘intentional’. These emissions are self-reported by governments and combined at a global scale, creating such overviews as Figure 5 below, where yearly methane emission from the oil and gas (O&G) industry are compared to total global emissions (including natural sources).
The O&G industry methane emissions in the US have a high 32% share of total methane emissions, yet worldwide the O&G share is 11% and in Europe 8%. This data is in agreement with the global methane cycle as depicted in Appendix A.

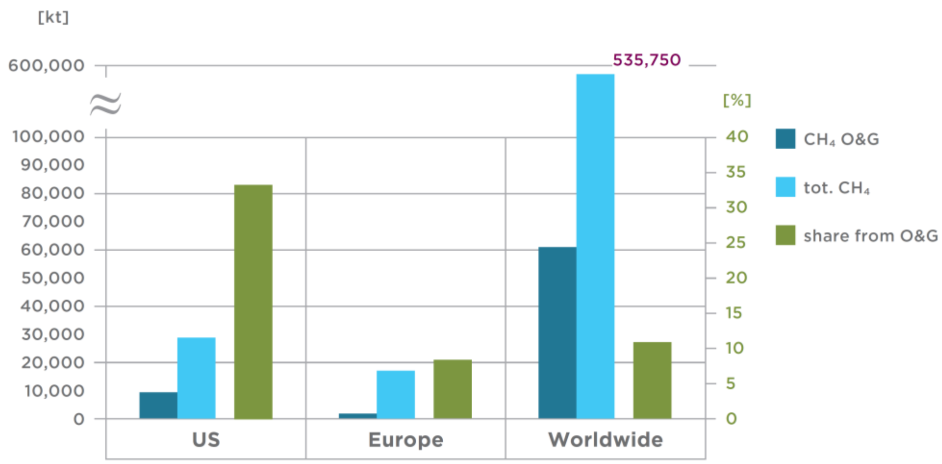

Figure 5 Total yearly methane emissions and share from the O&G sector in different regions. In green, the share in [%] is reported on the right axis. Note the break line for total worldwide methane emissions. (Cremonese & Gusev, 2016, p. 17)

However, a separation of natural gas from the oil industry is of special importance to reciprocating compressor systems. Figure 6 displays such a separation, using methane inventories gathered by the UNFCCC. The black and grey coloured bars represent the oil industry, while the other colours account for the natural gas methane emissions. As one can see, the natural gas industry's methane emission share ranges from several percent to substantial 50 to 99 percent.

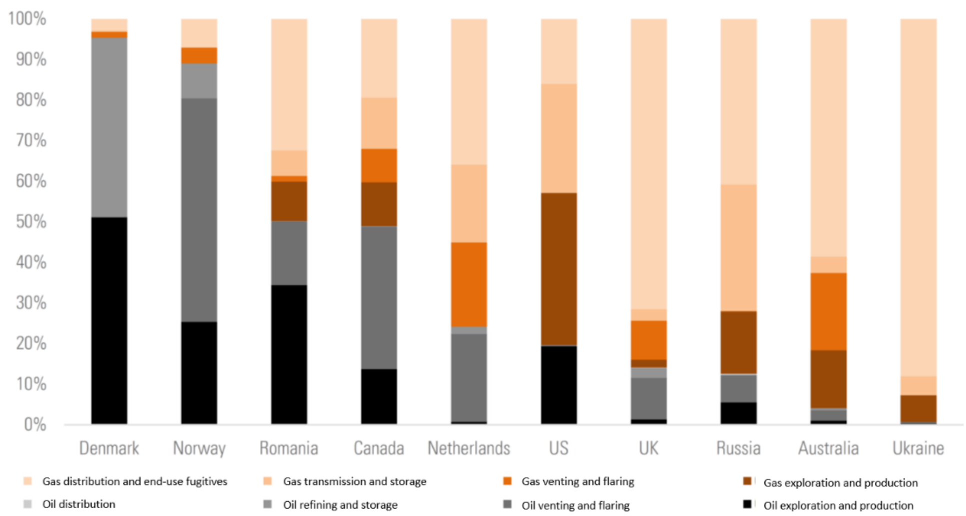

Figure 6 - Distribution of methane emissions from oil and gas system. Share of total in 2012, top 10 developed country oil and gas producers. (Larsen, Delgado, & Marsters, 2015, p. 7)

Yet, to create a proper context, methane emissions (from the natural gas industry) should also be compared to the total (human) GHG emissions. One white paper does exactly this, by comparing the radiative forcing of the US natural gas industry's methane emissions to the global radiative forcing. The findings, shown in Figure 7 below, show a 0.2% contribution of the US natural gas industry to *global* radiative forcing. It must be noted that this low share is in relation to the *total* GHG emissions, including non-human sources.

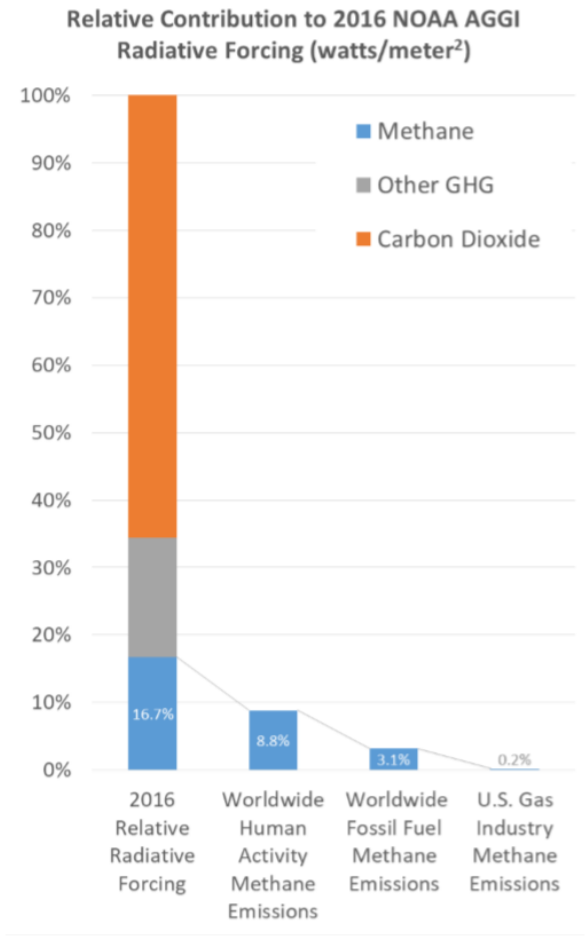

Figure 7 - *Relative* contribution of methane emissions to *global* radiative forcing (CMR & GTI, 2017, p. 1)

3.4 References

(AEMO) Australian Energy Market Operator. (n.d.). [Infographics] [Illustration]. Retrieved April 6, 2018, from https://www.aemo.com.au/About-AEMO/About-the-industry

(BP) British Petroleum. (2017). *BP Statistical review of world energy*. Retrieved from https://www.bp.com/content/dam/bp/en/corporate/pdf/energy-economics/statistical-review-2017/bp-statistical-review-of-world-energy-2017-natural-gas.pdf

(Balcombe et al. (2015) *Methane and CO2 emissions from the natural gas supply chain*

(CMR) Center for Methane Research, & (GTI) Gas Technology Institute. (2018). *An introduction to methane and the center for methane research*. Retrieved from http://www.gastechnology.org/CMR/Documents/Intro_to_Methane_021318.pdf

Cremonese, L., & Gusev, A. (2016). *The uncertain climate cost of natural gas*. Retrieved from www.iass-potsdam.de/sites/default/files/files/wp_dec_2016_en_uncertain_climate_cost_of_natural_gas.pdf

(EPA) Environmental protection agency. (2018 April 12th). *Inventory of US greenhouse gas emissions and sinks: 1990-2016*. Retrieved from https://www.epa.gov/sites/production/files/2018-01/documents/2018_complete_report.pdf

Larsen, K., Delgado, M., & Marsters, P. (2015). *Untapped potential: Reducing global methane emissions from oil and natural gas systems*. Retrieved from https://rhg.com/research/untapped-potential-reducing-global-methane-emissions-from-oil-and-natural-gas-systems/

4 Methane emissions of reciprocating compressors

4.1 Introduction: The ‘why’ and ‘how’ of compressor emissions

The previous chapters (and Appendix A) introduced the three perspectives from which emissions are relevant: health and safety, climate, and economics. To make these perspectives more concrete, the focus in this chapter is on emissions of recips.

At the end of this chapter, the reader will have more detailed information on recip emissions: how emissions are *quantified*; what the *share* of recip methane emissions is, in both *relative* and *absolute* terms; and how the emissions of recips compare to other equipment types in the natural gas industry.

First, to make the phenomenon of leakage and gas venting more *concrete*, one can look at infrared video’s which provide visualisation of emissions. Below, Figure 8 shows a static image from such video material, specifically from the vent stacks of a centrifugal wet seal compressor. The video of a centrifigal compressor with a wet seal is available at:
https://www.youtube.com/watch?v=3thAGMf20QQ). Another video of various emission sources, both leaks and vents from reciprocating compressors, available at: (https://www.youtube.com/watch?v=C5HJ_clrVFA

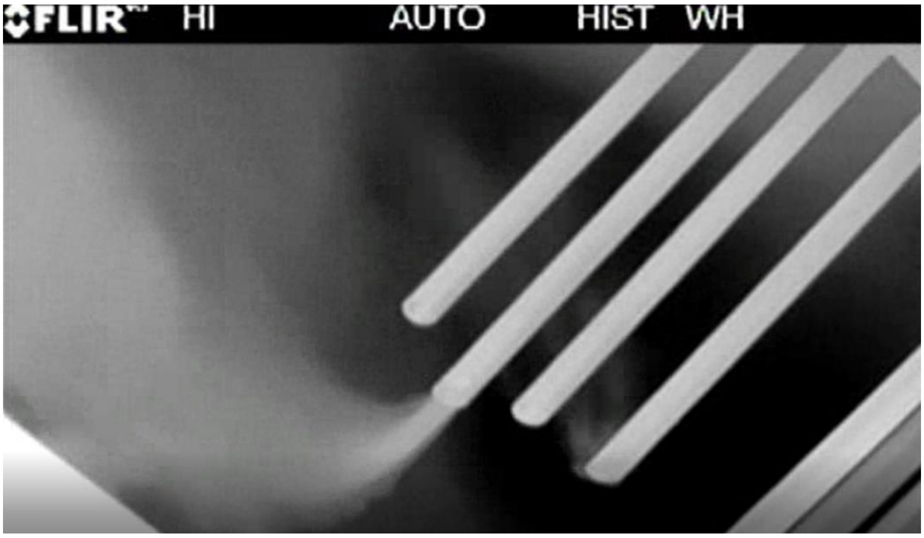

Figure 8 – Gas emitted from a vented stack from a centrifugal wet seal compressor

4.2 Compressors in the natural gas industry

GHG inventories give more information on recip emissions Only those inventories are useful, which track emissions per component (e.g. piston rod packing) source, on the level of machinery such as reciprocating compressors. One of the more specific GHG inventories is the US EPA’s Greenhouse Gas Inventory (GHGI). The GHGI’s emission estimates provide an useful overview of emissions per industry, sector or component and how these change over time. Subsequently, the GHGI inventory’s data is used by other studies to make such graphs as Figure 9 below.

Despite a possible lack of accuracy, the graph indicates that compressor stations cause a significant part of the emissions in the *processing and transmission & storage* sectors. It must be noted that compressor stations consist of more than only the compressors. Other components also contribute significantly to the emissions of a station, especially in the production, gathering and boosting, and in the distribution as can be seen from Figure 9.

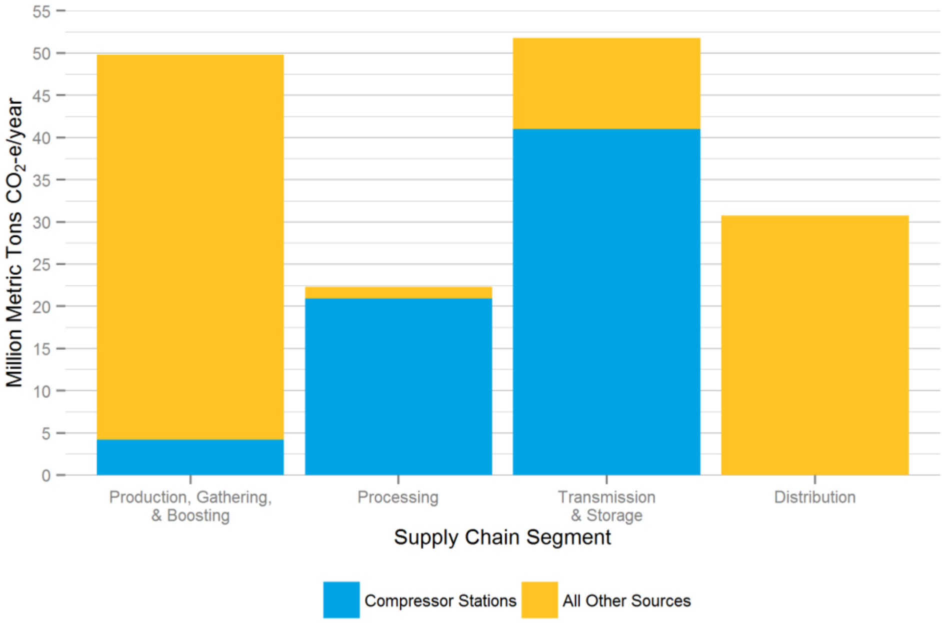

Figure 9 - US GHGI estimates of methane emissions from natural gas compressors within each supply chain segment in 2012. Source: EPA 2014a (Heath et al.)

This finding can be used to know where to look for compressor emissions. But, to be more specific than the broad category of compressor station emissions, Balcombe et al., (2015) who used the GHGI of 2012 concluded that compressors (recips and centrifs) specifically, were responsible for 20% of all methane emissions of the US natural gas industry.

Case study of US natural gas emissions (GHGRP)

However, these facts and also the data from Figure 9, are limited to *absolute* data, or only *relative* to the smaller context of specifically methane emissions. Such knowledge is especially useful from the economic and health perspectives, as *absolute quantities* of *product loss* and *hazardous substances* become apparent. However, from the climate perspective, the context shall be broadened again, to include *all GHG* emissions, so that the recip emissions as part of the total emission picture can be retrieved.

Another data set from the US, called the US Greenhouse Gas Reporting Program (GHGRP) is available from which the recip emission can be retrieved.
The GHGRP is a *mandatory* reporting program for all US companies (not exclusive to the O&G) that emit more than 25,000 tons of CO_2 eq. yearly, and requires them to submit both emission *measurements* and *estimates* using Emissions Factors (EFs, see explanation in section 4.4) and engineering data on throughput,

machinery downtime etc. The data of the GHGRP consists of emission amounts per industry and equipment type. Although the GHGRP data set is *smaller* than the GHGI, it yields more *accurate* data than the US GHGI. Further discussion on the GHGRP is also provided in section .

The most recent GHGRP 2016 data, provides more detailed information which can be used to compare reciprocating compressor emissions with all other US GHG emissions, for example CO_2 emissions from combustion in the natural gas industry. To begin with an overview of the entire natural gas industry, Figure 10 below shows emissions sorted by sub-sectors. The units are in CO_2 equivalents, meaning that the N_2O and CH_4 emissions have been multiplied with their respective Global Warming Potentials (GWPs), as discussed in Appendix A, Assuming the GWPs are *realistic,* and as far as the greenhouse effect is concerned, one kg of CO_2 versus one kg of CO_2 *equivalent* through CH_4 are *equally* impactful. We can therefore safely compare the various GHGs and the advantage of using the GWPs in such a way, is that different emission *types* can be easily compared to their climate impact.

Below in Figure 10, some sectors are clearly much larger emitters than others, sometimes with a factor 20. Additionally, in some sectors the methane emissions are relatively very small compared to those of CO_2, while emissions from those like the distribution sector are predominantly methane.

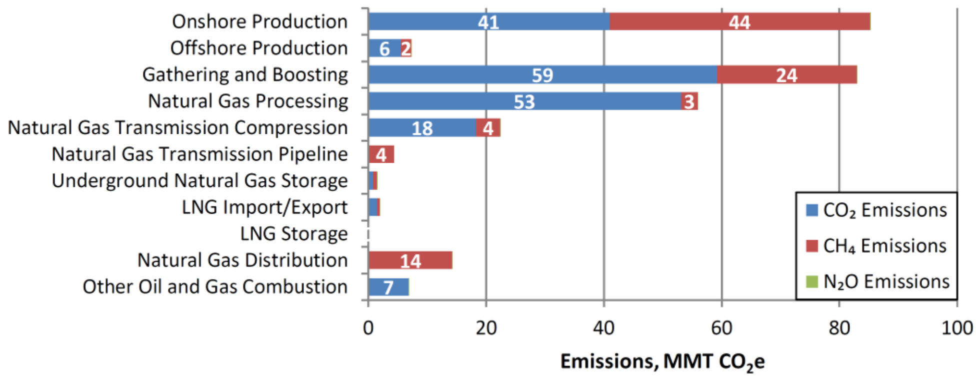

Figure 10 - Total reported US emissions to GHGRP 2016. Sorted by sub-sectors. (EPA, 2017, December 18, p. 5)

A more detailed look at the *relevant* sectors for our discussions on (reciprocating) compressors will give more information on emission of recips. These three sectors are, as we previously found in Figure 9, the transmission compression, processing and underground storage sectors. For each sector, the GHGRP data provides detailed data on sub-sources, so that we can see what the emissions sources of each sector are.

Transmission sector
Starting with the transmission compression sector, shown below in Figure 11. In this sector, reciprocating compressors are the largest *methane* emission source, although its share of *total* GHG emissions in that sector is approximately 8%.

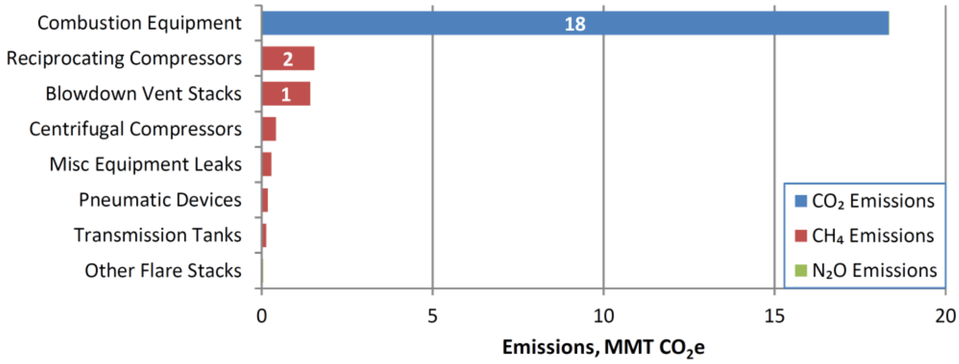

Figure 11 – US NG transmission compression: Top reported emission sources GHGRP 2016. Sorted by CO2, CH4 and N2O emissions, converted to MMT CO2 eq. (EPA, 2017, December 18, p. 10)

Underground storage sector

Figure 12 shows the data of the underground storage sector, also associated with high recip emission. Recip emission shares are most significant *methane* source in this sector, being four times larger than the second highest methane emitter, pneumatic devices. Compared to the combustion CO_2 emissions, recips are approximately 70%. Yet, the relative CH4 emission of recips from the underground storage sector is very small compared to the *total combined* emissions of all sectors as shown in the overview of Figure 10.

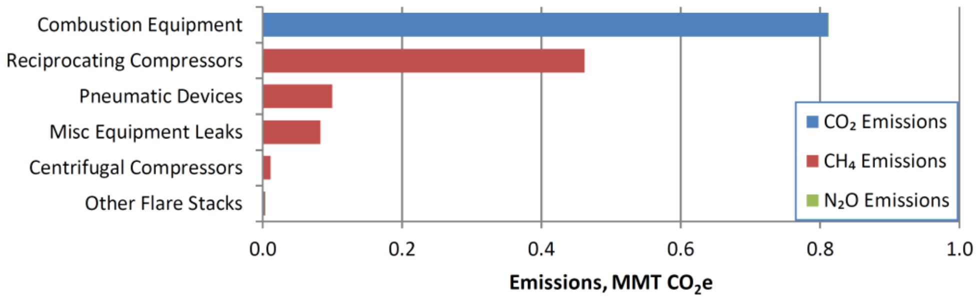

Figure 12 – US Underground natural gas storage: Top reported emission sources GHGRP 2016. Sorted by CO_2, CH_4 and N_2O emissions, converted to MMT CO_2 eq. (EPA, 2017, December 18, p. 11)

Processing plants sector

The third sector where recips are commonly used is in natural gas processing plants. Figure 13, below, shows that recip emissions make up almost half of all *methane* emissions. Yet, taking in *all* GHG emissions of the sector, they make up only 2%.

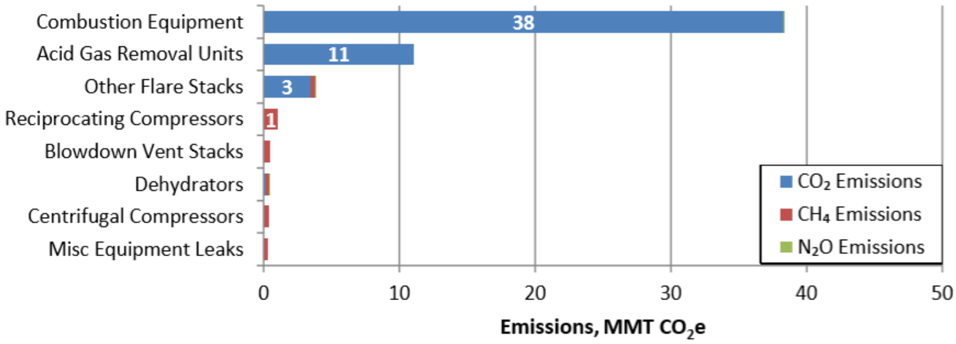

Figure 13 – US NG Processing: Top reported emission sources GHGRP 2016. Sorted by CO2, CH4 and N2O emissions, converted to MMT CO2 eq. (EPA, 2017, December 18, p. 10)

An important conclusion is that the graphs above show the importance of keeping the *larger* context in mind. When facts and figures are presented *without* context, they could easily be misunderstood in getting an idea of the relative methane emissions caused by recips. The broader context shows that the share of recip *methane* emissions in the US natural gas industry is relatively small to the *total* US *methane* emissions. If contextualized even further by incorporating the data from Figure 7, it is reminded that the *entire* US methane emissions constitute 0.2% of *total* greenhouse effect radiative forcing.

Note that the GHGRP data comes with its weaknesses, as indicated by Subramanian et al. (2015). They observe, for example, that the emissions for standby recip rod packings are *not* included in the program. The inclusion of these would *increase* recips emission share. However, another flaw is the exclusion of methane emissions from combustion equipment. These so called *methane slips*, often contribute significantly to total emissions, *lowering* the relative share of all other methane sources like recips. More on the issue of engine emissions is found at the end of this chapter. Additionally, it shall be kept in mind that the Emission Factors (EFs) as used by the GHGRP, are not always accurate which will be explained more into detail in section 4.5.

Yet, putting recip methane emissions in perspective raises the question of the *significance* of recip emissions from the *climate* perspective.
Very important in the discussion on emissions is the *distribution* of emissions: *where* are *what* amounts of emissions occurring? However, the topic of emission distribution is also very important for the *economic* and *health/safety* perspectives, simply because *reduction efforts* are most effective when the *largest* emitters are tackled. It is concluded that the overall emission distribution is not mainly caused by recips (in the natural gas industry).

4.3 Super emitters and distribution

The *distribution* of emissions is important for reduction efforts for all purposes: economic, safety and climate perspective. Yet, there is one phenomenon left unaddressed which can highly influence the distribution of emissions, namely the phenomenon of ‘super-emitters’ which are defined as follows:

> Specific points on the system that are responsible for disproportionately large volumes of gas leakage, [which] may be a consequence of system design – for example large volumes of gas being vented as a safety measure. More usually, however, they occur following a catastrophic failure, malfunction or operational error (Le Fevre, 2017, p. 16).

Super-emitters are often overlooked due to the limitation of so-called bottom-up estimations as explained in section 5.3. The issue of super-emitters has been addressed thoroughly in the natural gas emission literature and it is known to contribute to a *Pareto distribution*, also known as the *80-20 rule*, which in our case implies: Approximately 80 percent of emissions are caused by 20 percent of the sources. For the most effective reduction efforts it seems straightforward to simply target the 20%. However, effectively reducing this special group of emitters is less straightforward because *any* component with an unforeseen malfunction can *become* a super-emitter, making it difficult to prevent super-emitters *before* they occur.

In order to understand super-emitters and how to deal with them effectively, the first step is to get its *concept* straight. However, the definition of super-emitter leaves room for interpretation: *what* exactly is a ‘*point* on the system’? Balcombe et al. defined that point as a *facility* along the natural gas supply chain (2015). However, that point on the system can *also* be defined as an *individual component*, like a flange or recip rod-packing. In essence, both degrees of specificity are correct as the phenomenon of super-emitters appears on a *spectrum* of sources, varying from entire facilities to individual units.

This spectrum becomes more concrete when studying the various *occurrences* and *evidences* of super-emitters below in Table 4.1.

Table 4.1 - Evidence of super-emitters across the supply chain, sorted by supply chain stage. (Balcombe et al., 2015, p. 53)

Reference	Stage	Region	Description
ERG 2011 [162]	Extraction	US	10% of gas wells emitted 70% of fugitive methane emissions.
Allen 2015 [51]	Liquids unloading	US	20% of wells with plunger lifts that vent account for 70% of plunger venting emissions.
Shires 2012 [25]	Liquids unloading	US	10% of total well population account for over 50% of liquids unloading emissions.
Shires 2012 [25]	Liquids unloading	US	3% of wells without plunger lifts account for over 90% of no-plunger unloading emissions.
GHGRP 2015 [150]	Liquids unloading	US	10% of well population in 2013 account for 65% of total unloading emissions.
Mitchell 2015 [89]	Gathering	US	30% of gathering sites accounted for 80% of fugitive methane emissions.
Mitchell 2015 [89]	Gathering	US	Fugitive emissions were over 5% of production for six out of 108 gathering sites, but less than 1% for 85 and less than 0.1% for 19.
NGML 2006 [92]	Extraction/ Gathering/ Processing	US	Top 10 leaks from each facility studied (12 well sites, seven gathering compressor stations, five processing facilities) contribute 58% of total leak emissions.
Clearstone 2002 [91]	Processing	US	The top 10 equipment leaks from each facility studied (four processing plants) contributed 54% of leak emissions.
Lechtenboehmer 2007 [99]	Transmission	Russia	0.5% of compressor and valve components account for 90% of leaks in the transmission network.
Harrison 2011 [159]	Compressor stations	US	One leak out of 2,800 sampled valves and flanges contributed 29% of the leaked emissions measured.
Subramanian 2015 [103]	Compressor stations	US	10% of compressor stations account for 50% of compressor venting emissions.
Venugopal 2013 [106]	Compressor stations	Canada	Compressor venting emissions were four times higher than those estimated in Lechtenbohmer et al. [99] due to the inclusion of older plant equipment.
Allen 2015 [155]	Pneumatics	US	20% of pneumatic devices account for 96% of pneumatic venting emissions.
Lamb et al. 2015 [104]	Distribution	US	Three individual pipeline leaks (of 230) account for 50% of total emissions.

Knowing *what* a super-emitter *can* be, their *causes* can be understood and therefore also their *solutions*. Balcombe et al. provides a helpful summary of both causes and solutions:

> The causes of such high emissions are likely to be due to the use of inefficient equipment that is either not the best available technique for the duty, is too old, or has failed due to insufficient operation, maintenance and monitoring procedures. It is the authors' opinion that if appropriate operational control and maintenance procedures were carried out, these high emissions could be largely eliminated. However there is clearly potential in targeting super emitters for *cost-effective* supply chain emissions reduction (Balcombe et al., 2015, p. 54, italics added).

Therefore, the question is what does the phenomenon of super-emitters means for reciprocating compressor emissions? Primarily, it means a compressor station, a recip compressor or a compressor component, are *potential* super-emitters. This creates the clear motif to *prevent* recip super-emissions, simply because they are large emission sources that provide *cost-effective* reduction opportunities, good for safety, health, climate and economics.
These reduction opportunities, however, are much like *regular* reduction efforts. Prevention of super-emitters, like Balcombe et al. note, involves *appropriate operational control and maintenance procedures, and the usage of appropriate techniques and technologies*. For recips then, prevention of super-emitters requires maintaining a good condition of say rod packings, which is also a way to minimize regular emissions. Therefore, to minimize the 80% of the emissions caused by 20% of sources, attention is required to 100% of sources.

4.4 Quantification: Estimation and Emission Factors (EFs)

Before going in detail on the emissions of recips, it shall be understood *how* emissions are quantified. Although the topic of quantification is more deeply discussed in chapter 5, a start can be made on the investigation of some basics. Quantification is performed by either a top-down or a bottom-up method, both consisting of varying degrees of *measurement* and *estimation*. Top-down approaches *measure atmospheric,* or *ambient concentrations*, either at a surface level or higher altitudes, and can use that data to *estimate* emissions. In the same way, bottom-up approaches *measure* individual emissions sources and may use that to *estimate* emissions from similar sources (T Allen, 2014).More information on these approaches is given in section 5.2 and in 5.3.

Important in the next chapter is the bottom-up estimation, which relies on the creation of application of E*mission Factors* (EFs). Emission factors are generalised emission properties of a certain source, coming in such forms as e.g. the amount of gas for a compressor per day. By creating one's own EFs, the quantification relies more on measurement than when one uses standard EFs, thereby increasing accuracy. For example, an operator may measure emissions from one type of compressor to create a custom EF and multiply this factor with all other similar compressors. In theory, the bottom-up approach may also rely entirely on measurement, not using standard EFs, increasing accuracy greatly but at large economic expense.

Emission factors and their calculation are described by the EPA as follows:

> An emission factor is a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant.
>
> These factors are usually expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant (e.g., kilograms of particulate emitted per megagram of coal burned).
> Such factors facilitate estimation of emissions from various sources of air pollution. In most cases, these factors are simply averages of all available data of acceptable quality, and are generally assumed to be representative of long-term averages for all facilities in the source category (i.e., a population average).
>
> The equation for the estimation of emissions before emission reduction measures are applied is: $E = AxEF$
>
> The equation for the estimation of emissions after emission reduction measures are applied is: $E = AxEF(1 - ER/100)$
>
> Where:
> E = emissions, in units of pollutant per unit of time
> A = activity rate, in units of weight, volume, distance, or duration per time
> EF = emission factor, in units of pollutant per unit of weight, distance, etc.
> ER = overall emission reduction efficiency, %
>
> ER is further defined as the product of the control device destruction or removal efficiency and the capture efficiency of the control system (EPA, 2016 September 27th).

The EPA has heavily invested in emission factors and inventories, making them a valuable source for standard EFs. The EPA's Emission Factor and Inventory Group (EFIG) documents its EFs in the AP-42 series (EPA, 2018 March 22nd). It contains information for more than 200 air pollution source categories. For methane emissions in the natural gas industry, the EFs largely originate from a measurement study by EPA and GRI (Gas Research Institute; currently Gas Technology Institute (GTI)) performed in 1996.

An EF is multiplied with its appropriate activity rate, e.g. the number of similar compressors, but activity data can also be the total length of pipeline, the power of an engine, etc. As exhibited above, the more a bottom-up approach relies on *estimations* rather than *measurements*, the cheaper and quicker but also the less accurate the quantification. However, the accuracy of estimations depends also on the *specificity* of the EFs and activity data. For example, one could estimate emissions based EFs for fuel consumed, but also based on exact number of rod packings, flanges, etc.

Additionally, accuracy of estimation depends on the *quality* of the data behind the emission factors. EFs should resemble the *reality* of the sources they represent; an EF determined from a worn and aged set of compressors will likely overestimate the emissions from a new and well-maintained compressor.

4.5 Emission Factors for recips and comparison with other equipment

To get a sense of absolute and relative emissions the US natural gas transmission sector in 2012 provides a breakdown of sources as shown in Table 4.2. Particularly useful for comparison, is the display of the *activity data* and the *EFs* that constitutes the emission estimates. The table shows that reciprocating compressors are the largest contributors to total emissions. However, from the EFs and the activity data, it is also known that emissions of an *individual recip* are in general lower than an *individual centrif*, while total recip emissions are merely amplified by their great numbers in the NG industry in the US. Note that pneumatic devices and engines are also large contributors and are often part of *compressor stations*. This explains the high emission share of compressor stations in Figure 9 in section 4.2.

Table 4.2 - Methane emissions in 2012 for the US natural gas transmission sector, using data from the US GHGI (Balcombe et al., 2015, p. 30)

	Activity Data		Emission Factor		Mg CH_4/year
Pipelines					
Leaks	489,900	km	0.027	m³/ day/ km	3,310
Compressor Stations					
Station	1,807	Stations	248	m³/ day/ station	111,200
Reciprocating Compressor	7,265	Compressors	430	m³/ day/ compressor	774,800
Centrifugal Compressor (wet seals)	672	Compressors	1,422	m³/ day/ compressor	236,700
Centrifugal Compressor (dry seals)	57	Compressors	912	m³/ day/ compressor	12,880
Compressor Exhausts					
Engines	3.59E+13	MWhr	5.066	m³/ MWhr	222,200
Turbines	8.57E+12	MWhr	0.211	m³/ MWhr	2,209
Venting					
Pneumatic Devices	114,500	km	4,591	m³/ year/ device	221,700
Pipeline Venting	489,900	km	895,880	m³/ year/ mile	185,200
Station Venting	1,807	Stations	1.E+08	m³/ year/ station	151,400
Total					**1,922,000**

Remark: the comma (,) in the table indicates thousands and the dot (.) indicates a decimal

The EFs of Table 4.2 are particularly useful to make a comparison between recips and other equipment types, specifically centrifs. A comparison of recip versus centrif emissions is valuable because the compressor with lowest EF will have an advantage on the issues of climate impact, health and safety threats, and product loss. Furthermore, knowing how emissions are distributed is essential for all reduction efforts.

EFs can be represented by several parameters, for example the *power* of the compressor or its *pressure* or *capacity*. Inclusion of such parameters would create *normalized EFs* along the lines of [m^3 gas/day/Watt]. Without such normalization it is difficult to make *solid* comparative conclusions. For example, wrong conclusions can be drawn when e.g. the recip EF of Table 4.2 is based on low power compressors, while the centrif EF is based on e.g. much higher capacity. compressors. However, even if the data is normalized for power, it shall be kept in mind that there will always be a wide spread in EFs. This becomes clear when a more detailed investigation is done to their *specific emitting components*. Table 4.3 below displays three different EFs for each component. These EFs originate from three different studies who performed their own independent measurements. The great variance of these EFs shows the *inherent limitation* of generalisations in industrial supply chains, where each process condition is uniquely customized. In the same way, no one rod packing is the same as the other.

Table 4.3 - Comparison of compressor emission factors from Subramanian et al., Harrison et al. and the EPA/GRI. m^3 as normal cubic meters (Balcombe et al., 2016, p. 51)

<table>
<tr><th>Emission Source</th><th>Subramanian et al. 2015 (m³/min)</th><th>Harrison et al. 2011 (m³/min)</th><th>EPA/GRI 1996 (m³/min)</th></tr>
<tr><td colspan="4">Centrifugal compressors</td></tr>
<tr><td>Blowdown vent operating</td><td>0.153</td><td>0.004</td><td rowspan="2">0.504</td></tr>
<tr><td>Blowdown vent operating + idle</td><td>–</td><td>0.085</td></tr>
<tr><td>Wet seal (operating)</td><td>0.747</td><td>0.438</td><td>0.009</td></tr>
<tr><td colspan="4">Reciprocating compressors</td></tr>
<tr><td>Blowdown vent (pressurised + idle)</td><td>0.008</td><td>0.105</td><td rowspan="3">0.198</td></tr>
<tr><td>Blowdown vent + Pressure relief valve (operating)</td><td>0.192</td><td>0.458</td></tr>
<tr><td>Blowdown vent + Pressure relief valve (idle and depressurised)</td><td>–</td><td>0.850</td></tr>
<tr><td>Rod packing (pressurised + idle)</td><td>0.088</td><td>0.659</td><td rowspan="2">0.021</td></tr>
<tr><td>Rod packing (operating)</td><td>0.125</td><td>1.594</td></tr>
</table>

Additionally to rod packing emissions, Table 4.3 above, shows other major recip emission sources: blowdown vent and pressure relief valve emissions. These sources are bound by the operational mode of the compressor. The recip can either be operating; pressurized and idle; or depressurised and idle. Each mode is associated with different emissions, making it a reduction opportunity to switch to the lowest emitting mode. This reduction measure is more thoroughly discussed in chapter 6: Emissions reduction methods.

For those looking to quantify their emissions and find reduction targets, the EPA/GRI 1996 EFs show that the blowdown vents emits roughly ten times more than a piston rod packings. However, this is negated by Harrison's study in Table 4.3 above, which shows that an operating rod packing will leak much more than blowdown vents. Such variance is greatly confusing for those wanting to quantify and reduce their emissions using EFs. Likely the quality of the EFs varies greatly due the difference in measuring methods and equipment state. For example, one study could have measured highly worn out rod packings, while the other measured freshly replaced rod packings.

Emission factors remain averages for components that in reality operate under strongly varying conditions. However, it is possible to account for varying conditions by applying more specific EFs.

As already explained, the accuracy of EFs is crucial to the accuracy of all estimates of emissions, be it for GHG inventories or for individual companies wanting to quantify their emissions.

Because EFs remain estimates, they can vary greatly as the data where EFs are based on can vary largely. Standard EFs, based on measurements made by other companies, are often updated when studies show large discrepancies in measured versus estimated emissions.

Based on their measurements, Subramanian et al. concluded that, although the programme provides valuable information:

> Before using the GHGRP for inventory calculations, one must account for all the biases and uncertainties in the emissions data (…) The value of the GHGRP data for emissions inventory development would be improved by requiring more direct measurements of emissions (as opposed to using counts and emission factors), avoiding the use of acoustic devices, eliminating exclusions such as rod-packing vents on standby pressurized reciprocating compressors, and using more appropriate emission factors for exhaust methane from reciprocating engines (Subramanian et al. 2015, p. 3260).

The EPA also made a statement on the uncertainty involved in estimation, inventories and emission factors:

> Uncertainty is dependent on the kind of emissions released, the number of tests used to determine the emissions factor, the appropriate decision level (or percentile) within the distribution range, and the number of similar emissions units within a specific area. (…) [Our] intent is to educate sources and regulators about the accuracy of emission factors and to improve such accuracy through the incorporation of the results of direct emissions testing into the estimation of future emission factors (EPA, 2016, September 27th).

Additionally, bottom-up approaches which rely entirely upon estimation are unable to capture the phenomenon of super-emitters, as discussed in chapter 4.3. These extraordinarily large emission sources occur accidentally, and to be quantified require *measurement* either through bottom-up or top-down approach.
Even when a bottom-up approach relies only partly on estimation, by creating custom EFs, the presence of super-emitters is still likely to be missed.

These findings, and the conclusions of the EPA and Subramanian et al. are aligned with the studies cited in chapter 4.5 and the numerous uncited literature behind this report. They all come down to a view on EFs along the following lines: Emission factors are generalizations of complex situations, therefore one shall realise that the published EFs can strongly deviate from those of the system of interest. However, the concept of EFs is promising, and its ability to accurately estimate emissions increases as they are custom made and adapted to the unique situation of each site. In short, more direct measurements are necessary, both for companies to have a grip on their emissions, and to increase accuracy of (inter-)national inventories.

4.6 References

Balcombe, P., Anderson, K., Speirs, J., Brandon, N., & Hawkes, A. (2015). *Methane and CO2 emissions from the natural gas supply chain: An evidence assessment*. Retrieved from https://www.sustainablegasinstitute.org/wp-content/uploads/2015/09/SGI_White_Paper_methane-and-CO2-emissions_WEB-FINAL.pdf?noredirect=1

(EPA) Environmental protection agency. (2014, April). *Comments: Oil and Natural Gas Sector Pneumatic Devices Report for Oil and NATURAL Gas Sector Pneumatic Devices, Review Panel 2014"*, Prepared by U.S. EPA Office of Air Quality Planning and Standards (OAQPS).

(EPA) Environmental protection agency. (2016 September). *Basic Information of Air Emissions Factors and Quantification*. Retrieved from https://www.epa.gov/air-emissions-factors-and-quantification/basic-information-air-emissions-factors-and-quantification

(EPA) Environmental protection agency. (2017, December 18). *GHGRP Petroleum and Natural Gas Systems Sector Industrial Profile*. Retrieved from https://www.epa.gov/ghgreporting/ghgrp-petroleum-and-natural-gas-systems-sector-industrial-profile

(EPA) Environmental protection agency. (2018, March 22nd). *AP-42: Compilation of air emissions factors*. Retrieved from https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emissions-factors

Le Fevre, C. (2017). *Methane emissions: From blind spot to spotlight*. Retrieved from https://www.oxfordenergy.org/publications/methane-emissions-blind-spot-spotlight/

Subramanian, R., Williams, L., Vaughn, T., Zimmerle, D., Roscioli, J., Herndin, S., . . . Robinson, A. (2015). *Methane emissions from natural gas compressor stations in the transmission and storage sector: measurements and comparisons with the EPA greenhouse gas reporting program protocol*. Retrieved from https://pubs.acs.org/doi/abs/10.1021/es5060258

T Allen, D. (2014). *Methane emissions from natural gas production and use: reconciling bottom-up and top-down measurements*. Retrieved from http://dx.doi.org/10.1016/j.coche.2014.05.004

5 Measurement, Monitoring and Estimation

5.1 Introduction

Quantification of emissions knows two approaches, the top-down and the bottom-up. Both use a combination of *measurement* and *estimation.* Top-down approaches *measure atmospheric,* or *ambient concentrations*, either at a surface level or higher altitudes, and can use that data to *estimate* emissions. These measurements are in general used to measure the emissions of larger parts of an area, e.g. a complete refinery.

In the same way, bottom-up approaches *measure* individual emissions sources e.g. compressor system or parts of a compressors system and may use that to *estimate* emissions from similar sources (T. Allen, 2014). In the coming sections, we will discuss both approaches with their respective limitations and strengths. Additionally, we will exhibit several practical measurement techniques as well as guiding documents and software for emission quantification and documentation.

Many companies can benefit from guidance on the topic of quantification. Having a rough understanding of top-down, bottom-up, measurement and estimation is one thing, actually quantifying emissions is a second. Especially when regulation and mandatory reporting are associated with the quantification, it is important to confirm to the required reporting standards. For this exact purpose, those in the natural gas and oil industry can turn towards to several tools and programs such as the API 2009 Compendium, a guidance document on emission quantification, covering all associated topics like reporting, detection, and estimation, for many different sectors. These tools and programs are summarised in Appendix B.

5.2 Top-down

The top-down approach is based on *measurements* and *estimation.* Measurements of atmospheric concentrations of methane can be *either* at the surface using mobile and road vehicles, fixed ground monitors, *or* at higher altitudes by aircraft or satellite. When the top-down approach aims to measure not just ambient *concentrations* for a specific part of a plant, but quantify *emissions* of the complete plant, it also involves some *estimation.* For example, the *measurement* of particle concentration on the down-wind side of a plant, may be extrapolated to *estimate* the plant’s total emissions.

An example of a measurements in the top-down approach with an aircraft is shown below in Figure 14. Measurements of atmospheric concentrations of methane from ground, aircraft and satellite platforms can be used to derive total methane emissions in a region. For example, for aircraft measurements, the difference between average concentrations of methane upwind and downwind of a natural gas production region can be multiplied by the advection rate (transport of substance by bulk motion) of the air over the basin (mixing height multiplied by the average wind velocity and the horizontal dimension of the basin), to arrive at a basin total for emissions.

If the emissions of methane from all sources other than the natural gas supply chain can be *estimated*, and are subtracted from the total methane emissions in the area, emissions from natural gas operations can be *estimated*. Assuming this can be done, there can be additional challenges in applying a top-down approach, for example, separating emissions from natural (e.g. geological seepage) and legacy emission sources (e.g. abandoned wells) from current natural gas operations.

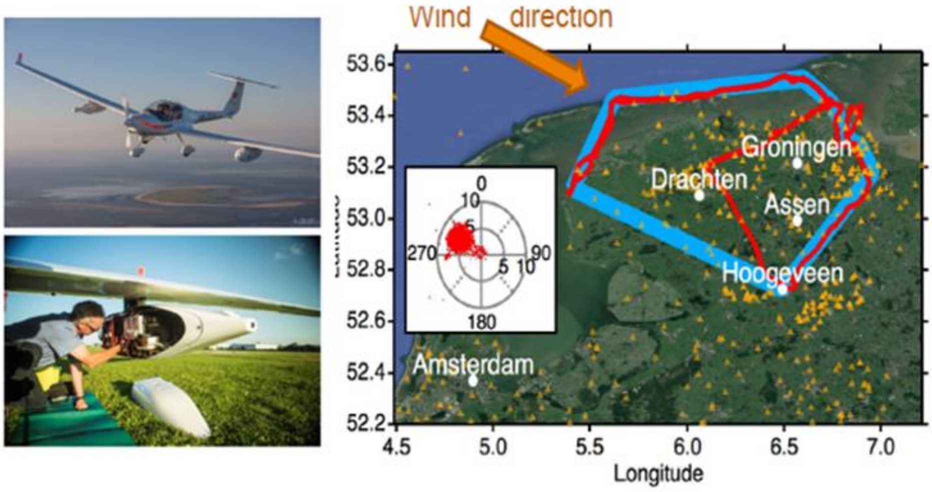

Figure 14 Example of the METAIR-DIMO aircraft which measures CH4, CO2, CO, NO2, NOx & meteorological data (source: TNO)

Although the top-down approach has several benefits, especially compared to the bottom-up (see section5.3), it also has some weaknesses:

> **Extrapolating from point measurements to derive a figure for a larger region:** Bruhwiler et al (2017) explain factors such as atmospheric variability, sampling biases, and choice of upwind background can make these estimates *unreliable.*
>
> **Attributing global methane measurements to specific sources of emission**: Estimates of emissions from the oil and gas sector have been achieved by various methods including determining the level of emissions from other sources and then subtracting these from the total, the use of "finger printing" techniques by measuring the presence of other gases such as ethane that are present in natural gas streams (Balcombe et al, 2015), or the use of carbon isotopes (Le Fevre, 2017, p. 11, bold added).

Or, as Balcombe et al. put it:

> Top-down approaches often highlight emissions that may be from the gas sector and are not accounted for in bottom-up approaches [37, 105, 182], but they are not able to determine the cause of these (Balcombe et al., 2015, p. 58).

However, a large upside to the top-down method is highlighted by Miller et al. (2013) and Brandt et al. (2014) who have concluded that ambient (top-down) measurements of NG emissions, point out missing emission sources in bottom-up inventories. These missing sources were estimated by Brandt et al. to be 2.6% of total US natural gas production. Therefore, the strength of the approach is that it provides an aggregate of all emissions, which can be compared to total bottom-up measurements. The comparison has generally revealed that sources are missing from current bottom-up inventories. The weakness of the top-down approach is that, unless tracers (fingerprint compounds) for specific sources can be identified and measured, the top-down approach does not reveal which of the many potential sources in the natural gas supply chain might be incorrectly estimated in emission inventories.

A very good example of an impressive recent improvement of a top-down measurements system is the ESA (European Space Agency) Sentinel-5 Precursor (S-5P) which is a mission focusing on global observations of the atmospheric composition for air quality and climate.

The **TROPO**spheric **M**onitoring **I**nstrument (TROPOMI) is the payload of the S-5P mission and is jointly developed by The Netherlands and ESA (scientific partner : SRON, TNO, VU; User Committee : EDF, ADSN, Shell, TNO). With TROPOMI, the worldwide detection and quantification of localized CH4 emissions, with a focus on CH4 leaks from the energy sector (oil, gas, coal) is improved considerably.

TROPOMI is a revolutionary technology that uses freeform optics to produce razor-sharp images and the most accurate information to date. TROPOMI has four detectors, together capable of detecting wavelengths in the infrared, visible and ultraviolet light spectrums. By comparing sunlight it has measured in space with light reflected back from Earth (see left picture of Figure 15) it is possible to calculate how certain concentrations of gases, such as O3 (Ozone), NO2 (Nitrogen Dioxide), SO2 (Sulfur Dioxide), HCHO (Formaldehyde), CO (Carbon monoxide), CH4 (Methane) and Aerosol layer height. An example of a TROPOMI measurement is shown in the right picture of Figure 15. From a global perspective on CH4 emissions: TROPOMI is a huge step forward and can scan the complete earth surface in one day with a resolution of 7x7 km.

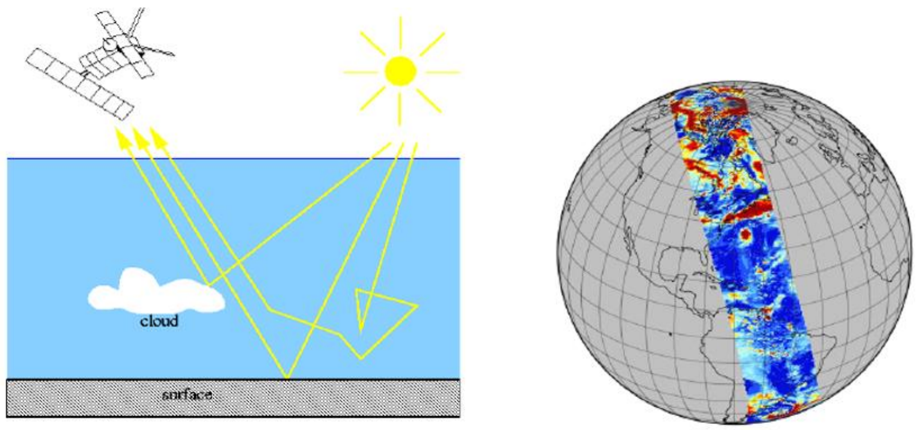

Figure 15 Measuring principle (left) and an example of a measurement with TROPOMI (right) (source: SRON (left picture and KNMI (right picture)

5.3 Bottom-up

5.3.1 Introduction

The bottom-up approach (or, the direct method) too is built from the elements of *estimation* and *measurement*. The bottom-up approach measures flow and mass of gas coming from individual emission sources. The bottom-up estimation relies on the *creation* and *application* of *emission factors* (EFs) as explained into detail in section 4.5.

Bottom-up estimations and EFs play an essential role in the creation of national or international GHG inventories. Although the inventories can be rather *rough*, using *unspecific* (broad) or *inaccurate* EFs, they do provide an idea of where and how much is emitted by which sources (be it an industry sector or component type). Although the GHG emission inventories have been primarily created from climate perspective, it is assumed in this report that they can also be used to get an estimate (both in absolute and relative sense) of the emissions of recips, for all three perspectives: health, economics and climate.

Various measurement techniques will be discussed shortly how to measure the EFs. Figure 16 shows an example of such measurement, using a so-called high volume sampler.

Figure 16 Example of leak measurement using a high volume sampler (EPA, 2003 a, p. 3)

An EF is multiplied with its appropriate activity rate, in the example above the number of similar compressors, but activity data can also be the total length of pipeline, the power of an engine, etc. As exhibited above, the more a bottom-up approach relies on *estimations* rather than *measurements*, the cheaper and quicker but also the less accurate the quantification. However, the accuracy of estimations hinges also on the *specificity* of the EFs and activity data. For example, one could estimate emissions based EFs for fuel consumed, but also based on exact number of rod packings, flanges, etc.

Bottom-up EFs allow for easy quantification of emissions and are also at the core of national and international GHG inventories, where efficient and cost-effectiveness are a priority and two of them are discussed in the next section.

5.3.2 GHG Inventories.

Companies of those countries participating in the United Nations Framework Convention on Climate Change (UNFCCC), submit their emissions data for the creation of (inter-) national greenhouse gas inventories. For the creation of the national GHG inventories, the IPCC developed inventory methodologies with the most recent guideline from 2006 available at (URL: https://www.ipcc-nggip.iges.or.jp/public/2006gl/). Currently a new edition is being created, set to be released in 2019. The guidelines are supplemented with software for inventory calculations; available at URL: https://www.ipcc-nggip.iges.or.jp/software

The finished national inventories are gathered and compiled into the UNFCCC's inventory, available online at (URL: http://di.unfccc.int/time_series). The inventory provides tools to compare (URL: countries, gases, categories, years) as well as individual excel sheets for detailed emission data.

The IPCC classifies *three tiers* of methodological approaches to bottom-up quantification. The higher the tier, the more measurement is involved, making the quantification more complex and time and resource consuming, but also more accurate (GEO, 2013).

In tier 1, the activity data consists of fuel produced or combusted, multiplied with *default* EFs provided by the IPCC, in such general forms as [x kg CO_2eq./Joule of gasoline consumed] (Foundation Foot Print, n.d.).

Tier 2 is fit to approximate emissions from a particular source. It uses slightly more specific activity data, such as engineering estimates of energy usage and recovery system effectiveness. This data is multiplied with *country specific* EFs, which are "developed by taking into account country-specific data, such as carbon content of the fuels used, carbon oxidation factors, fuel quality and (for non-CO2 gases in particular) the state of technological development" (Foundation Foot Print, n.d.).

Tier 3 is the most specific tier because it uses activity data based on actual measurements on energy use, methane recovery, gas throughput. The emission factors reflect more accurately the reality of the plant, taking into consideration the equipment age, control technology, operating conditions and the quality of maintenance (Foundation Foot Print, n.d.). The EFs come close to such specificity as seen in section 4.5, in the form of [x kg CO_2eq./compressor/minute].

However, countries that report to the UNFCCC, are free to divert from the IPCC guidelines for estimations. As a result there is large variety in different approaches and methods. In Europe, among the 11 countries most involved in the natural gas industry, there are 8 different methods used. In an attempt to bring unity to these methods, the European technical natural gas association, Marcogaz, currently collaborates with the European Gas Research Group (GERG) to create a European estimation standard. Under the name of Methane Emissions Estimation Methods (MEEM), the project should provide more consistent and transparent estimation in Europe, especially in the distribution and transmission sectors (DBI & GERG, 2016).

The inventory that is most often used in emission literature, is the US Greenhouse Gas Inventory (GHGI). This inventory provides detailed and relatively high-quality data from a country with one of the largest natural gas industries worldwide (EPA, 2018 February). The specificity of AP-42 EFs approach the IPCC's tier 3 (EPA, 2018 March 22nd). Note, that these EFs are still standardized, making them less accurate than custom created EFs, based on individual measurement. This customization of EFs is applied in the US GHGRP.

5.3.3 Detection and screening techniques

Thus far undiscussed, but quite important is the topic of detection. Before emissions can be *quantified*, the emission sources need to be *identified*. It is obvious that a vent stack will have emissions, yet this is not as straightforward for fugitives at flanges, seals and meters. For this reason, operators first need to *detect* the emissions sources through *screening*. What follows are screening/detection techniques recommended by the Direct Inspection & Maintenance (DI&M) program often applied by companies and regulators, see also section 6.9. This program is focussed on *detection*, measurement and repair, in that order. This chapter is adapted from the two DI&M guidance documents (EPA, 2003 a, October 18th) and (EPA, 2003 b, October 18th):

Soap bubble screening
This is a fast, easy, and very low-cost leak screening technique. Soap bubble screening involves spraying a soap solution on small, accessible components such as threaded connections. Soaping is effective for locating loose fittings and connections, which can be tightened on the spot to fix the leak, and for quickly checking the tightness of a repair. Operators can screen about 100 components per hour by soaping.

Electronic screening
Small hand-held gas detectors or "sniffing" devices provides another fast and convenient way to detect accessible leaks. Electronic gas detectors are equipped with catalytic oxidation and thermal conductivity sensors designed to detect the presence of specific gases. Electronic gas detectors can be used on larger openings that cannot be screened by soaping. Electronic screening is not as fast as soap screening (averaging 50 components per hour), and pinpointing leaks can be difficult in areas with high ambient concentrations of hydrocarbon gases.

Figure 17 Example of a electronic sniffer screening

Organic Vapor analysers (OVA's) and Toxic Vapor Analysers (TVA's)
These are portable hydrocarbon *detectors* that can also be used to identify leaks. An OVA is a flame ionization detector (FID), which measures the concentration of organic vapours over a range of 9 to 10,000 parts per million (ppm). One benefit to using a FID rather than a photo ionization detector (PID) is that a FID can be used as a methane gas *detector* (PID's do not detect methane). The TVA, see also section 5.3.4, combines both an FID and a photo ionization detector (PID) and can measure organic vapours at concentrations exceeding 10,000 ppm. TVA's and OVA's measure the concentration of methane in the area around a leak.

Infrared cameras
Video material of infrared cameras was presented in section 4.1, and provides a good impression of their practical use. The cameras work according to the principle that hydrocarbon emissions absorb infrared light in a certain wavelength. Infrared (IR) cameras use this characteristic to detect the presence of gas emissions from equipment by converting the scanned area into a moving image in real time such that the gas plumes are visible due their absorption of the IR light. Because of this, an IR camera is able to screen hundreds of components per hour. An additional advantage is the ability to screen inaccessible equipment: components in confined spaces or in elevated locations can be screened remotely from an accessible location within viewing distance. In addition, IR cameras can be hand-held for walking surveys of individual components, mounted on trucks and other vehicles for close-range inspection over moderate distances, or mounted on aircraft for aerial inspection to locate major leaks and vents over long distances. While it may not be able to pinpoint individual leaking components with low leak rates, aerial inspection is useful to screen many km's of transmissions pipelines or dispersed equipment to detect plumes from large emissions sources.

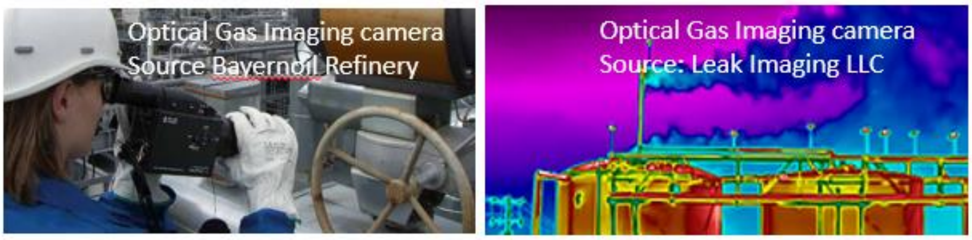

Figure 18 Examples of optical gas imaging camera's

Acoustic leak detection
These instruments use portable acoustic screening devices designed to detect the acoustic signal that results when pressurized gas escapes through an orifice. As gas moves from a high-pressure to a low-pressure environment across a leak opening, turbulent flow produces an acoustic signal, which is detected by a hand-held sensor or probe, and read as intensity increments on a meter. Although acoustic detectors do not measure leak rates, they provide a relative indication of leak size, a high intensity or "loud" signal corresponds to a greater leak rate. Acoustic screening devices are designed to detect either high frequency or low frequency signals.

Figure 19 Example of an acoustic leak detection (EPA, 2003 a, p. 2)

High frequency acoustic detection is best applied in noisy environments where the leaking components are accessible to a handheld sensor. An acoustic sensor is placed directly on the equipment location to detect the signal.

Alternatively, ultrasound leak detection is an acoustic screening method that detects airborne ultrasonic signals in the frequency range of 20 kHz to 100 kHz. Ultrasound detectors are equipped with a handheld acoustic probe or scanner that is aimed at a potential leak source from a distance up to 30 meter. Leaks are pinpointed by listening for an increase in sound intensity through headphones. Ultrasound detectors can be sensitive to background noise, although most detectors typically provide frequency tuning capabilities so that the probe can be tuned to a specific leak in a noisy environment.

5.3.4 Measurements techniques (concentration, flow and mass)

After *identifying* the emission sources, the bottom-up approach may continue with the *measurement* of flow, concentration and mass. What follows are recommended measurement techniques for the Direct Inspection & Maintenance (DI&M) program often applied by companies and regulators. This program is focussed on *detection*, measurement and repair, in that order. Measurement is important as it provides awareness of the highest emitters, so that resources can be effectively put to reduction efforts. DI&M is further discussed in section 6.9. This chapter is adapted from the two DI&M guidance documents (EPA, 2003 a, October 18th) and (EPA, 2003 b, October 18th):

Toxic Vapor Analysers (TVA's)
These instruments can be used to estimate mass leak rate. The TVA-measured *concentration* in ppm is converted to a mass emissions rate by using a correlation equation. A major drawback to TVAs for methane leak measurement is that the correlation equations are typically not site-specific. The mass leak rates predicted by general TVA correlation equations have been shown to deviate from actual leak rates by as much as three or four orders of magnitude. Similarly, a study conducted jointly by Natural Gas STAR partners, EPA, the Gas Research Institute (GRI– currently GTI (Gas Technology Institute)), and the American Gas Association (AGA) found that TVA concentration thresholds, or "cut-off" values, such as 10,000 ppm or 100,000 ppm, are ineffective for determining which methane leaks at

compressor stations are cost-effective to fix. Because the use of general TVA correlation equations can increase measurement inaccuracy, the development and use offsite-specific correlations will be more effective in determining actual leak rates.

Calibrated bagging techniques
Are commonly used to measure mass emissions from equipment leaks. The leaking component or leak opening is enclosed in a "bag" or tent. An inert carrier gas such as nitrogen is conveyed through the bag at a known flow rate. Once the carrier gas attains equilibrium, a gas sample is collected from the bag and the methane concentration of the sample is measured. The mass emissions rate is calculated from the measured methane concentration of the bag sample and the flow rate of the carrier gas. Leak rate measurement using bagging techniques is a fairly accurate (within ± 10 to 15%), but slow, process (only two or three samples per hour). Although bagging techniques are useful for direct measurement of larger leaks, bagging may not be possible for equipment components that are very large, inaccessible, and unusually shaped. Figure 20 shows the two used principles

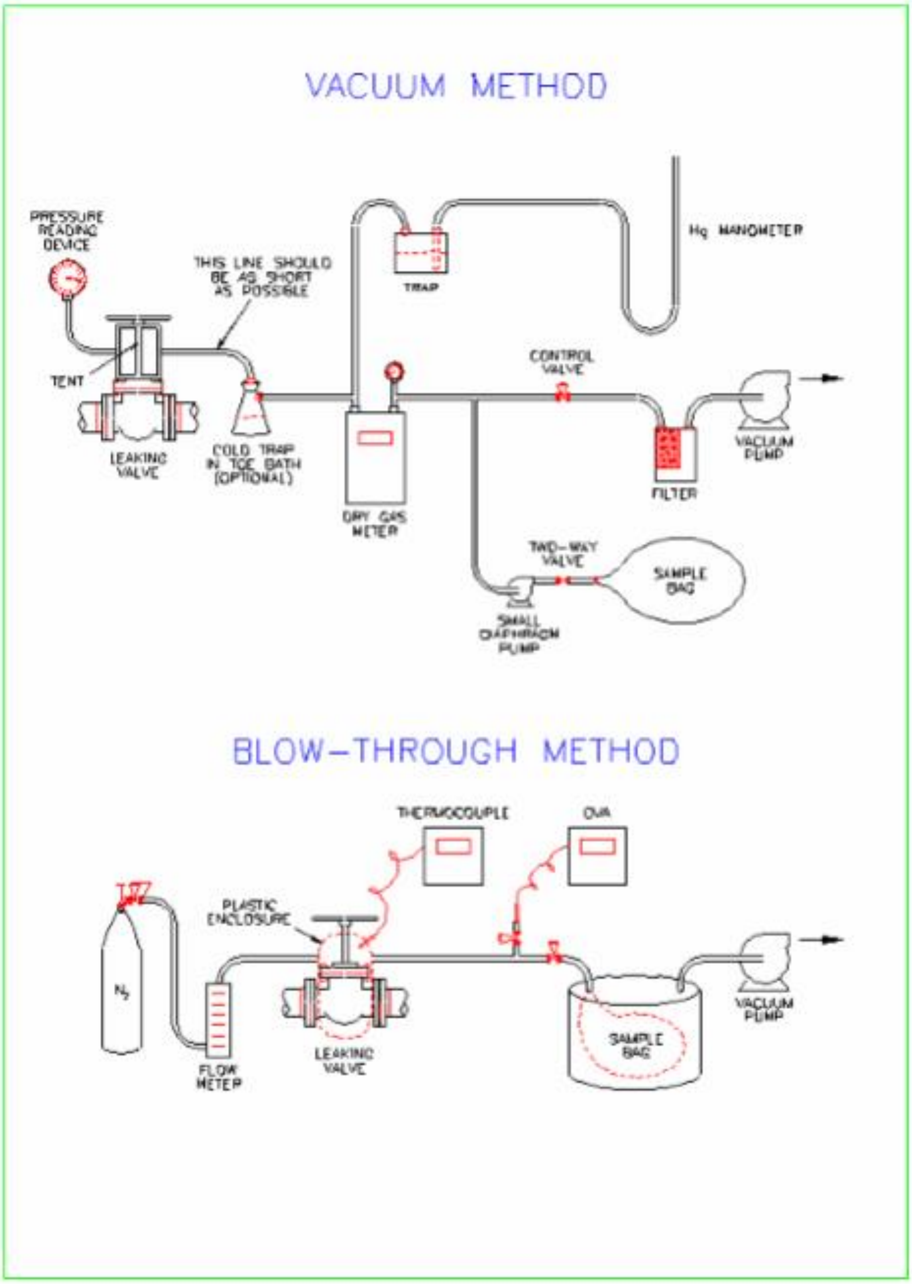

Figure 20 Principle of bagging techniques (source: Clearstone Engineering)

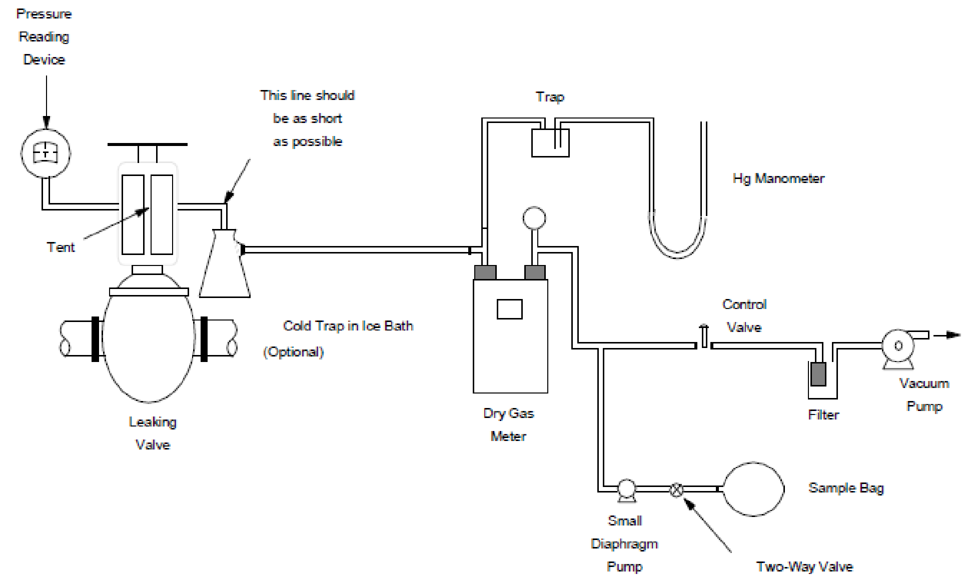

Figure 21 Sampling train for bagging a source using the vacuum method (EPA, 1995, p. 4-5)

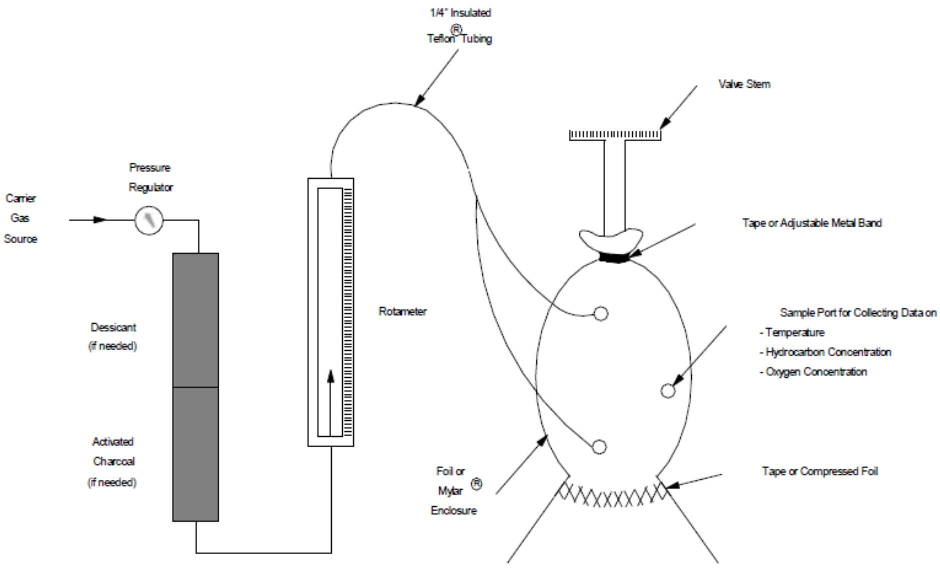

Figure 22 Sampling train for bagging a source using the blow-through method (EPA ,1995, p. 4-10)

High volume samplers

These instruments capture all of the emissions from a leaking component to accurately quantify leak emissions rates. Figure 23 below shows a leak measurement using a high volume sampler. Leak emissions, plus a large volume sample of the air around the leaking component, are pulled into the instrument through a vacuum sampling hose. High volume samplers are equipped with dual hydrocarbon detectors that measure the concentration of hydrocarbon gas in the captured sample, as well as the ambient hydrocarbon gas concentration. Sample measurements are corrected for the ambient hydrocarbon concentration, and a mass leak rate is calculated by multiplying the flow rate of the measured sample by the difference between the ambient gas concentration and the gas concentration in the measured sample. Methane emissions are obtained by calibrating the hydrocarbon detectors to a range of concentrations of methane-in-air.

High volume samplers are equipped with special attachments designed to ensure complete emissions capture and to prevent interference from other nearby emissions sources. High volume samplers measure leak rates up to 0.22 m^3/min, a rate equivalent to 816 m^3/day. Leak rates greater than 0.22 m^3/min must be measured using bagging techniques or flow meters. Two operators can measure thirty components per hour using a high volume sampler, compared with two to three measurements per hour using bagging techniques.

Figure 23 Example of leak measurement using a high volume sampler (EPA, 2003 a, p. 3)

Rotameters
Rotameters and other flow meters are used to measure extremely large leaks that would overwhelm other instruments. Flow meters typically channel gas flow from a leak source through a calibrated tube. The flow lifts a "float bob" within the tube, indicating the leak rate. Because rotameters are bulky, these instruments work best for open-ended lines and similar components, where the entire flow can be channelled through the meter. Rotameters and other flow metering devices can supplement measurements made using bagging or high volume samplers.

The *costs* for several of the detection and measurement techniques described in the last two chapters, is approximated below in Figure 24, with additional summaries of their application and effectiveness.

Instrument/Technique	Application and Usage	Effectiveness	Approximate Capital Cost
Soap Solution	Small point sources, such as connectors.	Screening only.	Under $100
Electronic Gas Detectors	Flanges, vents, large gaps, and open-ended lines.	Screening only.	Under $1,000
Acoustic Detectors/ Ultrasound Detectors	All components. Larger leaks, pressurized gas, and inaccessible components.	Screening only.	$1,000 to $20,000 (depends on instrument sensitivity, size, associated equipment)
TVA (flame ionization detector)	All components.	Best for screening only. Measurement requires site-specific leak size correlation.	Under $10,000 (depends on instrument sensitivity/size)
Bagging	Most accessible components.	Measurement only; time-consuming.	Under $10,000 (depends on sample analysis cost)
High Volume Sampler	Most accessible components (leak rate <11.5 Mcfd)	Screening and measurement.	> $10,000
Rotameter	Very large leaks.	Measurement only.	Under $1,000

Figure 24 Summary of screening and measurement techniques (EPA, 2003 a, p. 4)

5.4 Top-down versus bottom-up

This section discusses the weaknesses and strengths of the top-down and bottom-up method.

Most literature that weigh top-down against bottom-up approaches, are situated in the methane and natural gas context. In this context, it is important to accurately quantify methane emissions, as their perceived climate impact could lessen the ‘green-appeal’ of NG.

Both top-down and bottom-up approach have their own weaknesses and strengths. For example, bottom-up approaches tend to miss super-emissions, which heavily influence total emissions and distribution. Top-down in comparison is often able to capture super-emitters, but doesn’t specify as to which sources are leaking how much. When total methane emissions (non-human and human sources) are quantified, the bottom-up approaches tend to provide larger amounts of emissions, see Table 5.1 below.

Table 5.1 - Estimated methane emissions by source and method (million tonnes of CH_4 / yr) (Le Fevre, 2017, p. 12)

Source	Top-down		Bottom-up	
	Mid-point	range	Mid-point	range
Wetlands	167	127-202	185	153-227
Agriculture & waste	188	115-243	195	178-206
Biomass burning	34	15-53	30	25-35
Fossil Fuel prodn & use	105	77-133	121	114-133
Of which: Coal	n/a	n/a	41	26-50
Oil + NG	n/a	n/a	79	69-88
Other natural	64	21-132	199	104-297
Total	558	54-568	736	596-884

However, when the methane emissions of the NG industry are quantified, the top-down approach tends to give larger quantification than the bottom-up method (A Alvarez et al., 2018). Therefore, to make quantification as accurate as possible, the two approaches need to be reconciled, combining their strengths. In an article on reconciling bottom-up with top-down measurements of the natural gas industry, David T. Allen suggested the following:

> Moving forward, what is the best way to combine the best features of top-down and bottom-up approaches? (…) The concept of intelligently monitoring a group of process variables, or the composition of ambient air at a potential source site, and signalling for further analysis and testing when bounds are exceeded, has merit for identifying high emitters. Such smart sensing devices could be built into well pads, compression stations, distribution systems and other possible methane emission sources. Mobile methane sensors (e.g. infrared cameras deployed on aircraft or sensitive methane monitors on ground vehicles) could be deployed to identify leaks. Strategically sited ground measurements, or possibly aircraft or satellite measurements, could monitor progress in reducing regional emissions. Collectively, such multi-scale combinations of bottom-up and top-down approaches could, on an on-going basis, dramatically improve our understanding of methane emission sources. Once the sources are known, an emerging body of work suggests that technologies are available to reduce emissions (T. Allen, 2014, p. 81)

To successfully combine bottom-up with top-down approaches, as Allen suggests, it is beneficial to implement continuously measurement, where permanently placed sensors will provide reliable emission data.

5.5 References

(DBI) Deutschen Brennstoffinstituts Freiberg, & (GERG) European Gas Research Group. (2016). *Management summary GERG project phase I "Analysing the methods for determination of methane emissions of the gas distribution grid"*. Retrieved from http://www.dbi-gut.de/emissions.html

(EPA). November 1995. Protocol for Equipment Leak Emission Estimates. EPA-453/R-95-017; U.S. Environmental Protection Agency, Office of Air and Radiation, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolin

(EPA) Environmental protection agency. (2003 a, October 18th). *Direct inspection and maintenance at gas processing plants and booster stations*. Retrieved from https://www.epa.gov/sites/production/files/2016-06/documents/ll_dimgasproc.pdf

(EPA) Environmental protection agency. (2003 b, October 18th). *Direct inspection and maintenance at compressor stations*. Retrieved from https://www.epa.gov/sites/production/files/2016-06/documents/ll_dimcompstat.pdf

(EPA) Environmental protection agency. (2018 February). *Inventory of US greenhouse gas emissions and sinks: 1990-2016*. Retrieved from https://www.epa.gov/sites/production/files/2018-01/documents/2018_complete_report.pdf

(EPA) Environmental protection agency. (2018, March 22nd). *AP-42: Compilation of air emissions factors*. Retrieved from https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emissions-factors

(GEO) Group on Earth Observations. (2013). *Integrating remote-sensing and ground-based observations for estimation of emissions and removals of greenhouse gases in forests: Methods and Guidance from the Global Forest Observations Initiative*. Retrieved from https://www.reddcompass.org/mgd-content-v1/dita-webhelp/en/Box1.html#Box1

A Alvarez et al., R. (2018). *Assessment of methane emissions from the U.S. oil and gas supply chain*.http://science.sciencemag.org/content/early/2018/06/20/science.aar7204.full

Le Fevre, C. (2017). *Methane emissions: From blindspot to spotlight*. Retrieved from https://www.oxfordenergy.org/publications/methane-emissions-blind-spot-spotlight/

M Miller et al., S. (2013). *Anthropogenic emissions of methane in the United States*. Retrieved from http://www.pnas.org/content/pnas/110/50/20018.full.pdf

R Brandt et al., A. (2014). *Methane leaks from North American natural gas systems*. Retrieved from https://nature.berkeley.edu/er100/readings/Brandt_2014.pdf

T Allen, D. (2014). *Methane emissions from natural gas production and use: reconciling bottom-up and top-down measurements*. Retrieved from https://www.sciencedirect.com/science/article/pii/S2211339814000525

6 Emissions reduction methods

6.1 Introduction

The global attention to methane emissions has created the trend in many industries to develop methods and technologies to abate emissions. The compressor industry has been swept up in this reduction trend, especially for those compressors that are part of the oil and gas industry. Many abatement developments have taken place and new ones are continuously investigated and developed. These reduction methods, however, are not only useful from the climate perspective, but also from the health & safety and economic perspectives as discussed in chapter 2 and Appendix A. The economic perspective in fact hinges primarily on the costs and benefits of these abatement methods.

This chapter will exhibit several of the reduction methods available to reciprocating compressor systems, including peripheral equipment like pneumatic devices. The reduction methods are sometimes actual *technologies*, but also include maintenance *techniques,* like the DI&M (Direct Inspection & Maintenance), LDAR (Leak Detection & Repair) or recip *operation possibilities* like keeping recips pressurised when taken offline.

The methods (sometimes called *controls*, *measures* or *reduction opportunities*) discussed here originate from a small set of sources, simply because most methods are rather straightforward and are easily and comprehensively collected by agencies or organisations.

The three leading sources in this chapter are a collection of EPA's white papers, the "Lessons learned" by EPA's natural gas star program and "Technical guidance documents" from the Climate and Clean Air Coalition (CCAC). Although there are other sources available on the vast worldwide web, they are often derived from the EPA or CCAC.

Additionally, the reduction methods available for recips are often within the context of the natural gas industry. However, it is assumed that these reduction methods are also effective for other industries like the chemical and petrochemical.

In April 2014 the EPA released five white papers which focus on emissions from the oil and gas sector. Based on the finding that these emissions could be significantly reduced, the five white papers present *emission reduction opportunities* for VOC (including methane) in the following areas:

- Oil and Natural Gas Sector *Compressors.*
- Oil and Natural Gas Sector *Hydraulically Fractured Oil Well Completions.* and *Associated Gas during Ongoing Production*.
- Oil and Natural Gas Sector *Liquids Unloading Processes.*
- Oil and Natural Gas Sector *Pneumatic Devices.*
- Oil and Natural Gas Sector *Leaks.*

The papers focus on technical issues covering emissions and technologies and practices that target reductions in methane and VOCs. The EPA indicates that these papers and the comments they receive, will be used for future reduction guidance and regulation. The white papers support action by EPA directly regulating methane from this source category under Section 111b and 111d of the Clean Air Act, including both existing and new or modified sources. A commentary dating from the Obama administration, suggested that this approach is necessary to maximize methane reductions and meet the Obama administration's climate goals.

The white papers are complimentary to the NSPS (New Source Performance Standards) introduced in 2012 and are available at:

1. Oil and Natural Gas Sector Compressors: https://www.regulations.gov/document?D=EPA-HQ-OAR-2010-0505-5109

2. Oil and Natural Gas Sector Hydraulically Fractured Oil Well Completions and Associated Gas during Ongoing Production /April 2014 https://www.regulations.gov/document?D=EPA-HQ-OAR-2010-0505-5108

3. Oil and Natural Gas Sector Leaks/April 2014 https://www.regulations.gov/document?D=EPA-HQ-OAR-2010-0505-5110

4. Oil and Natural Gas Sector Liquids Unloading Processes/April 2014 https://www.regulations.gov/document?D=EPA-HQ-OAR-2010-0505-5032

5. Oil and Natural Gas Sector Pneumatic Devices/April 2014 https://www.regulations.gov/document?D=EPA-HQ-OAR-2010-0505-5030

A commentary by several environmentalist groups, stated that these papers demonstrate:

> Indeed, the urgent need for methane regulations was evident in information presented to the agency in 2011 and 2012, during its mandatory review of section 111 performance standards (PS) for the oil and gas industry that resulted in the 2012 NSPS (New Source Performance Standards) for VOC emissions.

The five white papers that EPA released in April 2014 and the studies summarized therein overwhelmingly affirm this conclusion. Specifically, these papers demonstrate that:

– Numerous sources of methane emissions in the oil and gas sector, including those for which the 2012 NSPS does not prescribe performance standards, are significant sources of methane emissions;
– Available control technologies can substantially reduce these methane emissions; and
– Costs for these control technologies are *reasonable* (EPA, 2014, June 16th, p. 3, *italics* added

Important is the claim that the costs for these control technologies are *reasonable*. Based on the above points, the environmentalist groups concluded that the EPA can and must take action now to control methane emissions from oil and gas industry sources directly. They further state *that "As the IPCC has repeatedly admonished, acting now will be more effective and cheaper than acting later" (EPA, 2014 June 16th, p. 3).*

The statement *"acting now will be more effective and cheaper than acting later"* can also be interpreted as accurate equipment-maintenance knowledge: Preventive maintenance to reduce emissions is cheaper and more effective than dealing with equipment failure and super-emitters.

The costs of reduction methods, reasonable or not, can be retrieved from the second source: the EPA's natural gas-star program. This voluntary US program is designed for NG companies to reduce emissions, and report their experiences on costs, benefits and effectiveness. These are reported under their "Factsheets" and "Lessons learned" documents, and although capital costs can vary greatly, these company reports provide a sense of the economic aspect: what is the effect of these reduction measures on the bottom-line?

The second source, EPA's "Lessons learned", are publicly available at URL: https://www.epa.gov/natural-gas-star-program/recommended-technologies-reduce-methane-emissions

The website provides a reduction-method-matrix for different equipment in the NG system such as compressors & engines, dehydrators, pipelines, pneumatic controls, tanks, valves, wells, and other. An example of this matrix for "compressors" is shown in Table 6.1. Additionally, it provides guidance on the reduction *technique* DI&M (Direct Inspection & Maintenance) (further discussed in section 6.9). The table provides further for each reduction method the estimated capital costs, estimated payback time, and for which segment of the natural gas supply chain (production, gathering and processing, transmission and distribution) it applies.

Table 6.1 - Matrix with possible reduction method measures for “compressors” (EPA, 2017 May 4th)

⬍ Document Title	▾ Capital Cost	⬍ Estimated Payback	⬍ Production	⬍ Gathering and Processing	⬍ Transmission	⬍ Distribution
Replace Gas Starters with Air or Nitrogen, PRO Fact Sheet #101	< $1,000	0-1 year	Production	Gathering and Processing	Transmission	
Reduce Natural Gas Venting with Fewer Compressor Engine Startups and Improved Engine Ignition, PRO Fact Sheet #102	< $1,000	0-1 year	Production	Gathering and Processing	Transmission	Distribution
Reducing Methane Emissions from Compressor Rod Packing Systems, Lessons Learned	< $1,000	0-1 year	Production	Gathering and Processing	Transmission	
Test and Repair Pressure Safety Valves, PRO Fact Sheet #602	< $1,000	0-1 year	Production	Gathering and Processing	Transmission	Distribution
Install Automated Air/Fuel Ratio Controls, PRO Fact Sheet #104	> $50,000	0-1 year	Production	Gathering and Processing	Transmission	Distribution
Install Electric Compressors, PRO Fact Sheet #103	> $50,000	1-3 years	Production	Gathering and Processing	Transmission	
Replacing Wet Seals with Dry Seals in Centrifugal Compressors, Lessons Learned	> $50,000	1-3 years	Production		Transmission	
Reducing Emissions When Taking Compressors Off-Line, Lessons Learned	$1,000-$10,000	0-1 year	Production	Gathering and Processing	Transmission	Distribution
Eliminate Unnecessary Equipment and/or Systems, PRO Fact Sheet #504	$1,000-$10,000	0-1 year	Production	Gathering and Processing	Transmission	Distribution
Install Electric Motor Starters, PRO Fact Sheet #105	$1,000-$10,000	1-3 years	Production	Gathering and Processing	Transmission	
Inject Blowdown Gas into Low Pressure Mains or Fuel Gas System, PRO Fact Sheet #401	$1,000-$10,000	1-3 years			Transmission	Distribution
Replace Compressor Cylinder Unloaders, PRO Fact Sheet #106	$10,000-$50,000	1-3 years	Production	Gathering and Processing	Transmission	
Wet Seal Degassing Recovery System for Centrifugal Compressors, PRO Fact Sheet	$33,000 (one compressor); $90,000 (four compressors)	0-1 year	Production	Gathering and Processing	Transmission	Distribution

The third source, the CCAC, provides reduction methods for the Oil & natural gas industry (similar to the EPA) in their “Technical Guidance” documents, publicly available at: URL: http://ccacoalition.org/en/content/oil-and-gas-methane-partnership-technical-guidance-documents, the documents cover several compressor relevant topics:

– *Natural Gas-Driven Pneumatic Controllers and Pumps*: Technical Guidance Document Number 1.
– *Fugitive Component and Equipment Leaks*: Technical Guidance Document Number 2.
– *Centrifugal Compressors with “Wet” (Oil) Seals*: Technical Guidance Document Number 3.
– *Reciprocating Compressors Rod Seal/Packing Vents*: Technical Guidance Document Number 4.

Based on these three sources (the EPA White Papers, NG Star and the CCAC), and *several supporting studies*, the next chapter will cover the following reduction topics relevant for compressors systems:

- Compressor engine driver.
- Reciprocating compressor piston rod packing.
- Reciprocating compressor cylinder unloaders.
- Vent and Flare Systems.
- Taking compressors off-line for maintenance (UGS systems).
- Pneumatic control devices.
- Leak Detection And Repair (LDAR).
- Direct Inspection and Maintenance at Compressor Stations (DI&M).

6.2 Compressor engine driver

6.2.1 Fewer Compressor Engine Start-ups & Improved Engine Ignition and Replace Gas Starters with Air or Nitrogen Ignition (EPA NG-star: Factsheet 101 and 102) adapted from (EPA, 2016 August 31st a & b)

Compressors driven by internal combustion engines are often equipped with gas expansion starters. Pressurized gas is expanded across the starter turbine spinning the engine and initiating the start-up. The discharge header of the compressor is typically vented to the atmosphere so the compressor is unloaded before the engine is started. The gas used to turn the starter turbine is also vented.

A single start-up of a properly tuned engine may require approximately 0.02 N/m^3 per kW engine power (EPA 2016 August 31st b).

Starter gas may be either high-pressure natural gas stored in a volume tank, or pipeline gas diverted to the starter. In either case, the starter and header gas are usually vented to the atmosphere. Reducing the frequency of compressor start-ups avoids blowdowns and therefore reduces the volume of gas vented to the atmosphere with each start-up.

Poorly maintained ignition systems increase the incidence of failed engine starts and can stall the compressor once it is loaded. The compressor must then be unloaded and re-started. Each failed engine start wastes gas, produces unnecessary methane emissions, and reduces efficiency. Operational inefficiencies due to failed starts, shutdowns, and restarts are magnified in large multi-compressor installations operated by production and transmission companies. Operating and maintenance schedules dictate how frequently compressor engines are scheduled for shutdown and restart.

EPA's Natural Gas STAR partners in the transmission and distribution sectors report that coordinating the maintenance and operating schedules for compressors can significantly reduce the total number of start-ups. Operating requirements are closely monitored to eliminate unnecessary shutdown of the compressors. Set schedules for shutdowns and maintenance are established.

Natural Gas STAR Partners have replaced and upgraded old ignition systems with electronic ignition systems, eliminating emissions from failed starts and reducing operating costs. Some Partners further improve operating efficiency and reduce emissions by installing automatic control systems such as programmable logic controls (PLCs). PLC systems manage unit performance, unit load, power requirements and safety shutdowns, that together improve the efficiency and reliability of compressors. Many electronic ignition systems are equipped with PLC controls installed (or available as an option) to enhance operation of the system.

Operating Requirements to reduce the frequency of engine starts, compressors should have set operating and maintenance (O&M) schedules, allowing maintenance to be performed during a planned compressor shut-down. A facility should also have procedures in place to review compressor function regularly to improve operating efficiency.

For electronic ignition and automated control systems, a small electric power supply is required, which can be generated by solar power at remote sites.

It has been found further by the Natural Gas partners that replacing the natural gas with compressed air or nitrogen for engine starting can reduce methane and VOC emissions considerably. This practice simply fills the start-up volume tank with compressed air or nitrogen instead of gas. No facility changes are necessary except a high pressure air or nitrogen connection and a stationary or mobile air or Nitrogen compressor is required.

6.2.2 Electric motors instead of combustion engines for compressor power (EPA NG-star: Factsheet 103) adapted from (EPA, 2016 August 31st c) and (Armendariz, 2009)

When considering NOx, VOC, HAPs, and greenhouse gas emissions from compressor engines, it is important to understand that the work to move the gas in the pipe lines is performed by the compressors, which by themselves produce no direct combustion emissions. The emissions come from the exhaust of the internal combustion engines, which are fuelled with a small amount of the available natural gas. As an alternative, the compressors could be operated with electrically-driven motors (Armendariz, 2009).

The use of electric motors instead of internal combustion engines to drive natural gas compressors is not new to the natural gas industry, and already numerous compressors driven by electric motors are operational.

The use of an electric motor (which causes *indirect* emissions) instead of a gas-fired engine to drive gas compression completely eliminates combustion emissions from the wellhead or compressor station and the leakage of methane through the gas shutoff valve.

Electric motors do require electricity from the grid, and in so far as electricity produced by power plants that emits pollutants, the use of electric motors is not completely emissions free. However, electric motor use does have important environmental benefits compared to using gas-fired engines.

Modern gas-fired internal-combustion engines have mechanical efficiencies in the 30-35% range, values that have been relatively static for decades. It is doubtful that dramatic increases in efficiency (for example, to 80 or 90%) are possible anytime in the near future. This means that carbon dioxide emissions from natural gas-fired engines are not likely to drop substantially because of efficiency improvements. In addition, the scrubbing technology that is used in some large industrial applications to separate CO_2 from other gases also is unlikely to find rapid rollout to the thousands of comparatively-smaller exhaust stacks at natural gas wellheads and compressor stations. The two facts combined suggest that the greenhouse gas impacts from using internal combustion engines to drive compressors are likely to be a fixed function of compression demand, with little opportunity for large future improvements.

In contrast, the generators of grid electric power are under increasing pressure to lower greenhouse gas emissions. Wind energy production is increasing and solar projects are receiving renewed interest from investors and regulators. As the electricity in the grid is produced by sources with lower carbon dioxide emissions, the use of electric motors to drive natural gas pipelines also has lower GHG emissions.

Stated another way, carbon dioxide emissions from gas-fired engines are unlikely to undergo rapid decreases in coming years, whereas the electricity for operating electric motors is at a likely carbon maximum right now. Electric-powered compression has a long-term potential for decreased GHG emissions, as non-fossil fuel alternatives for grid electricity generation expand in the future.

6.2.3 Install electric starters (EPA NG-star: Factsheet 105) adapted from (EPA, 2016 August 31st d)

Operators have found that replacing the starter expansion turbine with an electric motor starter, similar to an automobile engine motor starter, can avoid methane emissions. Electric motor starters require a power supply. Power can be provided from electrical utility, portable and solar-recharged batteries, or generated onsite.

6.2.4 Controls for Compressor Engines (US Forest Service, 2011)

When an electric motor is not feasible to apply, improved emission controls can be used on new or existing engines using a combination of techniques such as the following:

- Closed loop engine control.
- Selective catalytic reduction.
- System-installed power supply (solar powered, battery powered).
- Ultra-low sulphur diesel.
- Diesel particulate filter.
- After burner, and/or
- Other new technologies.

The above measures will lead to a reduction of emissions of: NOx, SO2, CO and CO2 and some PM2.5 (particle matter). Additionally, the benefits are the moderate cost, depending upon application and options selected. The above mentioned reduction methods can be applied to:

- Projects involving natural gas compression.
- Include control package as an option on new engines.
- Retrofit on existing engines.

Limitations are the availability by engine type and the year of manufacture. It may require testing to confirm target emission rate is achieved.

Selective Catalytic Reduction (SCR)
This works by injecting Diesel Exhaust Fluid (DEF, a mixture of water and urea) into the exhaust to lower NO_x. The DEF works with the heat of the exhaust and a catalytic converter to convert the oxides of nitrogen into nitrogen and water vapor. Commonly, a diesel particulate filter is included in the emission control package with selective catalytic reduction.

The emissions which will be reduced are NOx, PM2.5 and PM2.5 and hydrocarbons (if diesel particulate filter is included).

The benefits are a proven capability to reduce emissions and retrofitting is easy to apply. This can be applied for exhaust streams, e.g., on large engines, particularly where loads are steady or predictable. This is very efficient where oxides of nitrogen emissions are of concern.

The limitations may be the high cost, the availability for a specific application and it may require testing to confirm target emission rate is achieved.

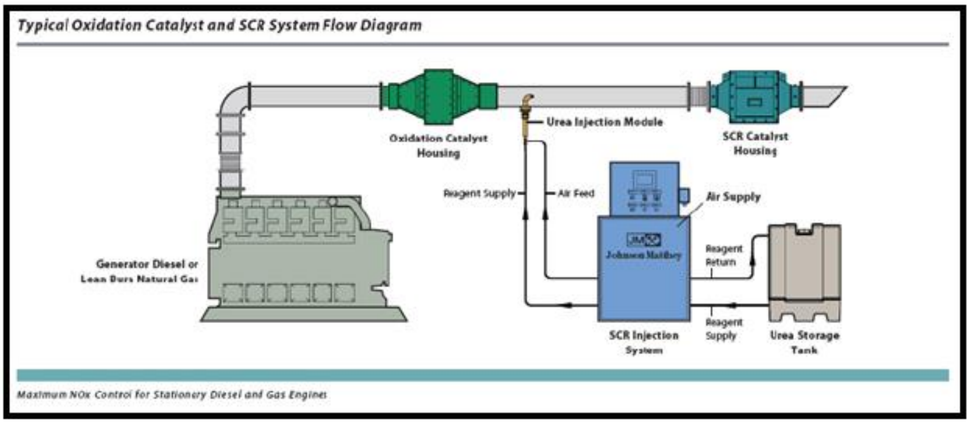

Figure 25 NOx control for diesel and gas engines (source: US Forest Service 2011, p. 34)

6.2.5 *Cap-Op: Alternative reduction measures for gas engines (Cap-Op, 2013)*

Cap-Op Energy Inc. has carried out an inventory study for PTAC Petroleum Technology Alliance Canada with support from Alberta Innovates – Energy and Environment Solutions. The report was published in September 2013, entitled "Opportunities to Reduce Greenhouse Gas Emissions at Existing Distributed Facilities".

In the Cap-Op report the following potential alternative greenhouse gas reduction measures are given for gas engines:

Engines Coupled with Waste Heat Recovery
Methane gas plants are an example of a facility that would be able to make use of low quality waste heat that can be captured at these facilities using waste heat recovery units, and diverted to one or more other processes.
Due to the large installation cost (waste heat projects require longer downtime to retrofit facilities with the equipment to capture waste heat) and variability of GHG savings from waste heat projects, a conservative estimate was made on the number of facilities where waste heat could be applicable, and so a large discrepancy between the total number of facilities and the eligible facility estimation of 1000 sites in Canada. This eligible count only includes largest gas facilities and larger compressor stations because large amounts of waste heat are required to make the type of waste heat recovery possible.
Waste heat recovery systems could result in GHG emissions reductions of up to 2000 tonnes CO2e per year per engine. This estimate comes from producer experience and projects for scheduled projects. These are larger energy efficiency projects and can result in greater CO2e savings. Across the 1000 eligible sites, 2000 million tonnes CO2e per year could be saved by employing waste heat recovery systems. Other facilities may be suitable for smaller waste heat recovery systems but will not be able to avoid the 2000 tCO2e estimated.

Engines coupled with Vent Gas Capture (VGC) systems
A Vent Gas Capture (VGC) system is another alternative for facilities with multiple pneumatic devices, or other equipment venting or bleeding small amounts of low-pressure methane. The diffuse sources of methane are captured and fed into an engine using a computer-controlled system.

The application of a VGC system may be an operationally-appropriate solution for gas plants and other large facilities, depending on site-specific conditions. VGC systems are not reliant upon electricity grids, as instrument gas to instrument air systems are. They allow for the collection of fuel gas from many sources, and thus the estimation of eligible vent gas capture sites is larger than the instrument gas to instrument air sites. VGC systems can be paired with rich burn or lean burn engines that have a digital air fuel ratio control system installed.
The eligible count targeted sites that had an average of five or pneumatic instruments. Sites that were targeted for instrument air conversions, or sites that produce sour gas, were not considered in this count. The engines at facilities eligible for vent gas capture may already have an Air Fuel Ratio Controllers (AFR), be eligible for an AFR, or have a lean burning engine if they are a newer facility.

The emissions reductions indicated a range from 912 to 8687 tonnes CO_2e per year (in 2009) per engine. Implemented across the 10,000 eligible sites in Canada, this results in greenhouse gas emissions reductions of up to 10,000,000 tonnes CO_2e per year.

Engines Coupled with Air Fuel Ratio (AFR) Controllers
Many engines that are operating in oil and gas facilities are “rich burn” engines, meaning that more fuel gas is used than is stoichiometrically necessary. These engines can be retrofitted with a device that controls and optimizes the ratio of air to fuel. Air-Fuel Ratio (AFR) controllers are generally only suited to older, rich burn engines, instead of newer, lean burn engines. Furthermore, a VGC (Vent Gas Capture) system can be paired with an AFR system.

The count of eligible engines is reduced from the total engine count in Alberta as newer engines are, in most cases, already lean burn systems. Other factors that further limit the use of AFR systems include engine tuning and other process-specific challenges, and in some cases, other energy efficiency projects may be more appropriate compared to AFR controls. Besides that AFR controls will also reduce N_2O emissions.

The installation of an air-fuel ratio controller results, on average, of reductions of 600 tonnes CO_2e per year per engine. This estimation comes from vendor information, producer projects and Cap-Op inventory.

The installation of an AFR control system is also explained in EPA’s Fact Sheet 104: “Install Automated Air/Fuel Ratio Controls”.

6.3 Reciprocating compressor piston rod packing

6.3.1 Introduction

Reciprocating compressors leak gas during normal operation. Areas of high leak frequency include flanges, valves, and fittings located on compressors. The highest volume of gas loss, however, is associated with piston rod packing systems.

Packing systems are used to maintain a tight seal around the piston rod, to prevent leaking of the gas that is compressed to high pressure in the compressor cylinder, while allowing the rod to move freely. Figure 26 and Figure 27 below show a typical compressor rod packing system.

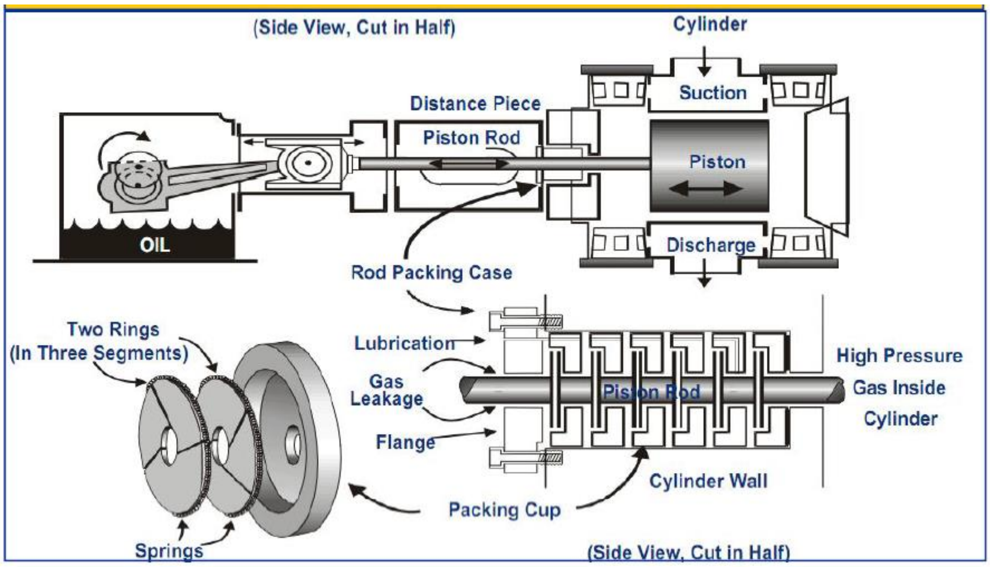

Figure 26 Typical compressor rod packing system (EPA, 2016 August 31st e, p. 3)

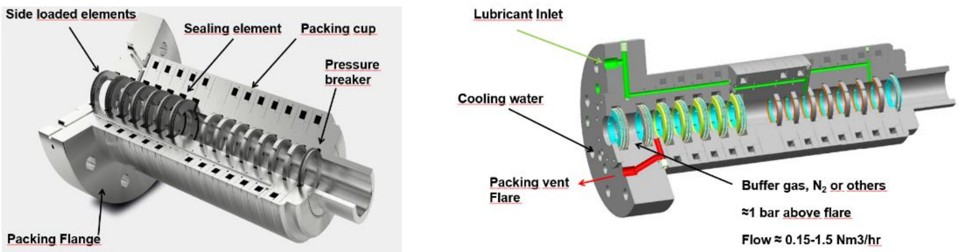

Figure 27 Example of a typical stuffing box (Source: Burckhardt Compression)

A compressor rod packing consists of a series of flexible rings that fit around the shaft to create a seal against leakage. The packing rings are lubricated with circulating oil to reduce wear, help seal the unit, and draw off heat. Other cooling methods include air cooling, water jacketing, and circulating coolants inside the packing box. Packing rings are held in place by a set of packing cups, normally one for each pair of rings, and kept tight against the shaft by a surrounding spring. The number of cups and rings will vary depending dominantly on the compression

chamber pressures. A “nose gasket” on the end of the packing case prevents leaks around the packing cups.
Under the best conditions, new packing systems properly installed on a smooth, well-aligned shaft can be expected to leak a minimum of 0.1-10 Nm/hr^3 for lubricated piston rods and approximately 50% more for non-lubricated rods. Failed rods can show leakage rates that are 10 times or more than the normal rate.

In general the leakage will be higher for worn packings and piston rods, higher discharge pressures, large piston rod diameters, gas molecular weights, worn piston rods, for non-lubricated piston rods and for bad alignment. Leakage typically occurs from the following areas:

- Around the packing case through the nose gasket.
- Between the packing cups, which are typically mounted metal-to-metal against each other.
- Around the rings from slight movement in the cup groove as the rod moves back and forth.
- Between the rings and shaft.

Leaking gases are in many cases vented to the atmosphere through packing vents on the flange. More detailed information on vent systems of reciprocating compressors is discussed in section 6.5.3.
Another method for capturing emissions from reciprocating compressor rod packing vents is to manifold the vent line to a vapor recovery unit (VRU) system, see also section 6.5.4.

It is also possible to direct the vent gas to the suction side of the compressor. This can be done with a rather small compressor and in many cases a small size reciprocating compressor is used. The vent gas compressor will also have a leakage over the piston rod packing but this can be further reduced considerably by using a diaphragm type compressor leading to an emission free compressor.

A VRU is a simple system designed to capture vented gas streams, usually from tanks, that would otherwise go to the atmosphere. The main components of the system include a compressor and scrubber. If a VRU system is already in place at a facility with reciprocating compressors, it is often possible to route the vent streams to tanks, allowing the vented rod packing gas to be picked up by the VRU. The recovered gas can then be sold or routed for fuel or other meaningful use onsite. If the gas cannot be used productively, it can also be sent to a flare system. While flaring may have a higher cost than venting to the atmosphere, this practice can reduce methane and VOC emissions.

6.3.2 Emission reduction methods

6.3.2.1 Replacing piston rod packings (NSPS Subpart OOOOa requirements for rod-packings)

EPA recognized in the 2012 NSPS that methane emissions from reciprocating compressor seal leaks can be reduced substantially by replacement of worn-out rod packing on a periodic basis. The agency reports replacing packing before serious wear occurs can reduce emissions by 90-95%. However, depending on the degree of wear, and compressor maintenance history, emission reduction improvements would be less than 90-95% for an average compressor. Periodic replacements of rod packing materials is also a good operating and maintenance protocol: operators that carefully monitor and replace compressor rod packing systems on a routine basis can conserve additional gas for sale that would otherwise have been leaked and reduce piston rod wear, both of which increase profit.

It is estimated that reciprocating compressor emissions due to *seal leaks alone* to be approximately 10% of the total emissions in the chain occurs in the production segment, 28% in the processing segment, 24% in the transmission segment, and 18% in the storage segment.

As part of the 2012 NSPS rulemaking, EPA estimated the total amount of methane leaked and the amount of abatement that could be achieved from reciprocating compressors in each segment based upon the rule's requirements that rod packing systems be replaced every 36 months or every 26,000 operating hours. The agency calculated abatement opportunities of 63.2% for devices in the production segment, approximately 80% for those in both the processing and transmission segments, and 77.3% in the storage segment. These estimates were for new compressors; leak rates for existing compressors are likely higher.

EPA 2016 NSPS Subpart OOOOa

The 2016 New EPA's Source Performance Standard (NSPS) Subpart OOOOa requires operators the following for all existing reciprocating compressors in all four segments of the oil and gas sector, from wellheads to gas distribution systems. The full requirements are given in § 60.5385a of the 40 CFR Part 60, Subpart OOOOa, (Standards of Performance for Crude Oil and Natural Gas Facilities for which Construction, Modification or Reconstruction Commenced After September 18, 2015, (URL: https://www.law.cornell.edu/cfr/text/40/60.5385a):

(a) You must replace the reciprocating compressor rod packing according to either paragraph (a)(1) or (2) of this section, or you must comply with paragraph (a)(3) of this section.

(1) On or before the compressor has operated for 26,000 hours. The number of hours of operation must be continuously monitored beginning upon initial start-up of your reciprocating compressor affected facility, or the date of the most recent reciprocating compressor rod packing replacement, whichever is later.

(2) Prior to 36 months from the date of the most recent rod packing replacement, or 36 months from the date of start-up for a new reciprocating compressor for which the rod packing has not yet been replaced.

(3) Collect the methane and VOC emissions from the rod packing using a rod packing emissions collection system that operates under negative pressure and route the rod packing emissions to a process through a closed vent system that meets the requirements of § 60.5411a(a) and (d).

(b) You must demonstrate initial compliance with standards that apply to reciprocating compressor affected facilities as required by § 60.5410a(c).

(c) You must demonstrate continuous compliance with standards that apply to reciprocating compressor affected facilities as required by § 60.5415a(c).

(d) You must perform the reporting as required by § 60.5420a(b)(1) and (4) and the recordkeeping as required by § 60.5420a(c)(3), (6) through (9), and (17), as applicable.

6.3.3 *Rod seal/ packing vents – Adapted from CCAC's Technical guidance document number 4: Reciprocating compressor rod seal/packing vents (CCAC, 2017)*

Venting emissions can be reduced by routing gas to useful outlets, including a fuel gas system (if present), a Vapor Recovery Unit (VRU), or a compressor inlet. Alternatively, methane emissions can be reduced by flaring reciprocating compressor vent gas.

Recovering or flaring gas that leaks from rod packing may substantially reduce emissions. For facilities/operations that already have installed useful outlet(s) (e.g., VRU, fuel gas system) or flare(s), implementing this mitigation option would involve installing additional piping and valves to connect these systems to the compressor vents. In the case of a single on-site VRU, a facility may already have multiple gas lines manifolded to it, and one can add another line to the manifold from the reciprocating compressor.

Before installing the additional line, one must consider the process conditions such as incoming gas composition and volume from the compressor to ensure the VRU can accommodate the new gas stream. In evaluating potential inlet vent gas volume to the VRU, one must ensure that the VRU has sufficient capacity to accept the maximum anticipated volume from the compressor vent(s).

One can expect to reduce methane emissions by up to 95 percent from reciprocating compressor venting when routing rod packing emission to a VRU (the operating factor of a VRU) and by up to 99 percent when implementing a flare connection (assuming 99% flare efficiency).

Assuming a facility has an existing useful outlet such as a VRU, the cost of piping and installation costs would be the main associated expenses for this opportunity. The incremental operating and maintenance (O&M) cost would be negligible and mainly consist of routine inspection and maintenance as well as additional electricity costs associated with additional throughput to the VRU. With a low capital cost and high methane reduction value, if technically viable, implementing this technology could quickly benefit operators.

Routing gas that leaks from rod packing to a flare will not result in a direct economic benefit to the operator implementing this option. OGMP suggests that, when assessing this option, Partners consider the indirect benefits associated with this option (e.g. safety benefits, reputational risk mitigation).

6.3.3.1 *Monitoring & measuring piston rod packing leakage*

Leakage can be reduced through proper monitoring and a cost-effective schedule for replacing packing rings and piston rods. New ring materials and new designs for packings could further reduce emissions in the future.
Monitoring and replacing compressor rod packing systems on a regular basis can greatly reduce methane emissions to the atmosphere and save money. For instance, conventional bronze-metallic packing rings wear out and need to be replaced every three to five years. However, as packing deteriorates, leak rates can increase to the level at which replacing packing rings more frequently can be economically justified. In addition, more frequent ring replacement might actually extend the life of the compressor rod. Companies who institute a program of monitoring and cost-effective replacement are able to achieve several benefits:

- Reduced methane emissions.
- Gas savings from lower leakage rates.

- Extended service life of compressor rods.

The five steps to economic packing and piston rod replacement are:

- Step 1: Monitor and record baseline packing leakage and piston rod wear.
- Step 2: Compare current leak ratio to initial rate to determine the expected leak reduction.
- Step 3: Asses costs of replacement.
- Step 4: Determine economic replacement threshold.
- Step 5: Replace packing and rods when cost-effective.

Step 2 through 4 can be determined easily if the leak rates and replacement costs are known.

Monitoring of the packing leakage in step 1 is often done by a temperature measurement of the vent gas (higher temperatures indicate higher leakage), see also **Figure** 28 below.

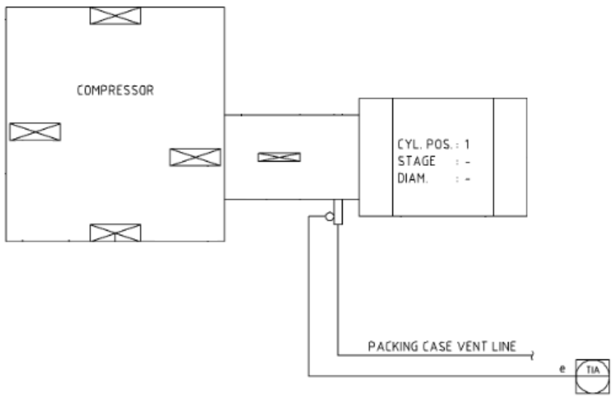

Figure 28 Indication of the location of the vent gas temperature measurement (source: Howden Thomassen Compression)

In-line leakage flow measurement can also be done but is not always easy and requires a high accuracy for lower flow rates. The vent line shall also be free of obstructions in case of high flow rates to secure safety.
The vent port on the packing case flange provides a means for gas leakage to escape to the atmosphere. However, gas can also flow along the rod and/or from the gasket at the end of the packing case, thus bypassing the packing cup vent and entering the distance piece. Consequently, where possible, measurements should encompass emissions from both the packing cup vent and distance piece. Some systems vent the packing cup into the distance piece, while others have separate vents.

Gas leakage can be measured with either a hand held or an installed measuring device. Before measurements are initiated, a check of the packing vent system should be undertaken. Failure to account for emissions escaping into the distance piece may result in an underestimation of packing-related emissions (by up to 40 percent), which could impact the economics of the decision process.
It is important to take measurements immediately after installing new seals (or new rods and seals). This measurement becomes the baseline for the new packing and can serve as a suitable default baseline for other cylinders and compressors of similar type, size, pressure, and age of rods. After installation of rings, specialized

personnel shall routinely monitor and record leakage rates and related operating conditions (pressure, lubrication, temperatures) over the entire life of the packing rings, usually on a monthly or quarterly basis.
Measuring of the flow shall be carried out therefore by trained employees or by a specialized company.

A typical scheme of measuring the vent line flow as shown in the paper “Packing Vent Monitoring (GMRC 2016) for each individual cylinder is shown in Figure 29. The field implementation is shown in Figure 30. The applied flow meter was a mass flow meter which was easy to install and rather inexpensive. The functionality is simple and has no moving parts and similar devices are recommended to use by the EPA in their fugitive emission studies

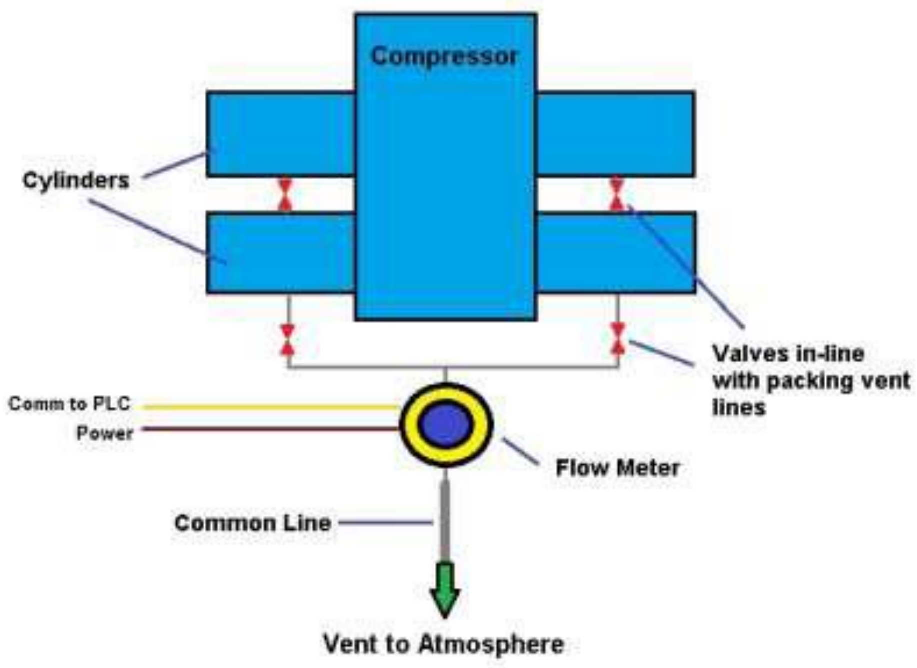

Figure 29 Principle of the measuring scheme (GMRC 2016)

Figure 30 Field installation of individual vent flow lines for each cylinder (GMRC 2016 Atmos Energy)

Rods can be monitored periodically during ring replacements by documenting shaft dimensions and surface roughness where the rod contacts the packing rings. Piston rods wear more slowly than packing rings, having a life time depending on the machine and operation conditions.
Rods wear “out-of-round” or taper when poorly aligned, which affects the fit of packing rings against the shaft (and therefore the tightness of the seal) and the rate of ring wear. An “out-of-round” shaft not only seals poorly, allowing more leakage, but also causes uneven wear on the seals, thereby shortening the life of the piston rod and the packing seal. The leakage attributable to rod wear is determined by the change in the baseline leakage rate after each successive ring replacement (assuming same operating conditions and ring type). This increase in baseline leakage can be used to establish an economic threshold for replacing the piston rod.

Development of a novel liquid reciprocating piston rod packing
Southwest Research Institute (GMRC 2017) has carried out a project for the development of a novel liquid reciprocating compressor packing seal to reduce methane emissions from a reciprocating compressor packing by 95%. The leakage rate can vary widely for different compressors clearly depending on a variety of factors other than just the age of the packing or sinking of the piston rod. It is clear to operators that even with new packing installed, some compressors have higher emissions than others, and a correlation needs to be established between the compressor leakage rate, operating conditions, and compressor geometry when determining acceptable leakage rates.
To provide the leakage basis for this project, a benchmark test was performed to measure the leakage from a 37 kW Ariel reciprocating compressor that will be used for the testing comparisons throughout the project.

Dynamic testing was performed over a speed range of 300-900 rpm operating with air in a closed flow loop. A control valve was used to vary the pressure ratio from 1.5 to 3.

A rotameter was used to measure the packing leakage flow from the compressor cylinder through the packing seal. A secondary Coriolis meter was used to provide verification of the accuracy of the measurement. The rotameter was calibrated with an accuracy of 2% for the range of the recorded leakage flow rate. Emission testing results showed that the packing acts as an orifice. Leak rates were directly correlated with the mean in-cylinder pressure rather than the compressor flow rate. Therefore, higher operating pressures result in higher leakage rates (given the same packing and rod size) independent of the flow rates.

6.3.4 Additional options in reducing emissions for reciprocating compressors

Partners in the Natural Gas STAR Program (EPA, 2016 August 31st) have not reached a consensus on standard emission reductions that can be achieved by changing compressor rod packing. Many variables are cited as affecting potential savings, including cylinder pressure, fit and alignment of packing parts, and amount of wear on the rings and rod shaft, as well as company-internal decision criteria. However, Partners agree that identifying a replacement threshold for replacing packing rings and piston rods is a practical method to reduce methane emissions from reciprocating compressors.
New materials can improve the life and performance of certain equipment and provide companies with additional savings through reducing leakage and repair and replacements costs.

The options are:

Rod packing rings
Carbon-impregnated Teflon is gradually replacing bronze metallic rings. Teflon is expected to last about one year longer than the conventional bronze rings. However, it shall be noted that other factors, including proper installation, cooling, and lubrication, might play a greater role in the service life of a ring.

Upgraded piston rod
New or existing compressor rods coated with tungsten carbide have proven to increase service life for rods by reducing wear, as well as making them effective for “static-seal” installations (see Lessons Learned study, “*Reducing Emissions When Taking Compressors Off-Line*”). Chrome coating is also used to reduce wear.

Three-ring rod packing
A three-ring rod packing system shown in Figure 31 is becoming more widespread. The rings are typically installed in one of the last two cups. The primary benefit of this arrangement is that this design can usually be installed without any replacement or modification of the packing case cup.

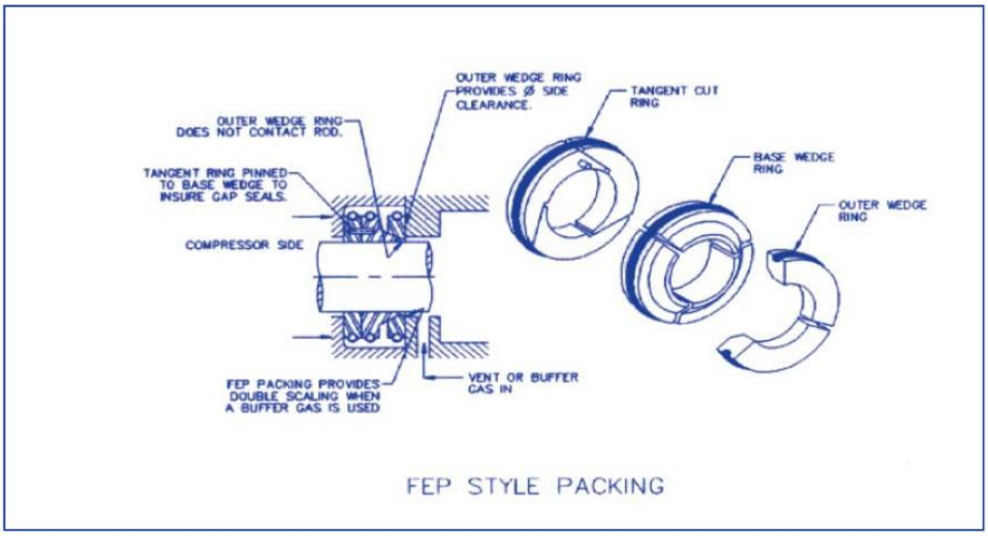

Figure 31 Three-Ring Fugitive Emission Rod Packing Assembly (source EPE)

6.3.5 INGAA Comments (INGAA 2014) on EPA's Compressor White paper (EPA, 2014 April)

The Interstate Natural Gas Association of America (INGAA), a trade association of the interstate natural gas pipeline industry, submitted comments on the EPA's five white papers.
These comments focus on the EPA's technical white paper, "Oil and Natural Gas Sector Compressors" (Compressor Paper). INGAA has submitting separate comments on three papers (Compressors, Leaks and Pneumatics) that address sources applicable to the interstate natural gas transmission and storage (T&S) sector.

In the Compressor Paper (EPA, 2014 April) EPA summarized its current understanding of vented VOC and methane emissions from this source category, and its understanding of available mitigation techniques and the cost, effectiveness and application of these techniques in the oil and natural gas sector.

1. In response to the Compressor Paper specifically, INGAA offers the following comments EPA should consider additional mitigation approaches for rod packing. Specifically, INGAA recommends condition-based maintenance for rod packing as an alternative to maintaining or replacing rod packing on a prescribed schedule.
2. EPA should review the data for centrifugal compressors. There is a significant disparity in reported emissions between the National Inventory and EPA's Subpart W for centrifugal compressors. EPA should resolve this issue before contemplating mitigation methods.
3. EPA should acknowledge that almost all new centrifugal compressor units use dry seals and therefore wet seals as a source of emissions should no longer be a focal point of the discussion.

We will discuss in this section the condition-based maintenance for rod packings.

According to INGAA's comments (INGAA 2014), EPA's Compressor Paper fails to, and should, include condition-based maintenance for rod packing. This is used by some companies as an alternative to maintaining / replacing rod packing at a prescribed interval.

Reliability studies have shown that many different mechanisms can affect the need for maintenance or contribute to the failure of a component (e.g., packing wear that increases emissions). INGAA strongly recommends including condition-based maintenance for rod packing as a viable alternative to mitigate methane emissions instead of a specific time interval of e.g. every 3 years or 25.000 hours.

Condition-based maintenance practices may extend the operation of functional rod packing and preclude premature and wasteful rod packing maintenance or replacement. In other cases, it will identify rod packing where premature wear warrants maintenance on a more frequent basis than the prescribed interval. It also encourages the development of innovative rod packing technologies (GMRC 2017). This option considers current practices being used by operators, improvements to rod packing design, and the evolving technology.

The EPA Natural Gas STAR program includes a lessons learned document “Reducing Methane Emissions from Compressor Rod Packing System,” which provides an example for condition based maintenance practices. Rod packing gas leaks are periodically monitored and the value of the incremental leaked gas (relative to post-maintenance/replacement leak rates) is compared with the discounted rod packing maintenance/replacement cost. When the incremental lost gas value exceeds the maintenance/replacement cost, the rod packing maintenance/replacement is cost-effective. This same general philosophy can be applied using a different basis for the repair decision, such as a defined leak rate or change in leak rate over time.

Changing compressor rod packing at a set interval is discussed in the EPA Compressor Paper as a means of reducing methane emissions. INGAA supports this approach provided the operating company is allowed the flexibility to establish a packing replacement interval coordinated with regular scheduled maintenance.
The desired outcome of a rod packing replacement protocol is to prevent methane emissions to the environment, but the frequency of replacement must consider the blowdown emissions that occur each time the packing is replaced. Companies understand the value of rod packing monitoring and maintenance/replacement programs, and such programs have been instituted as part of safety and standard maintenance practices.
EPA requests more details on mitigation techniques, including prevalence, but those answers are not known. For example, a survey would be required to understand the prevalence and common procedures for rod packing condition-based maintenance. In general, condition based maintenance grounded on periodically measuring rod packing leak rate typically will show a relatively flat leak rate over time, followed by an increase in leak rate when rod packing begins to fail.

6.4 Reciprocating compressor cylinder unloaders: EPA Factsheet #106 (EPA, 2016 August 31st f)

Compressor cylinder unloaders are used to reduce the machine's start-up load, to prevent an overload when there is an upset in operating conditions, and to control gas volumes due to fluctuations in rate requirements. Many older reciprocating engine-powered compressors are equipped with outdated or worn cylinder unloaders that continuously leak natural gas even when regularly maintained. A useful tool to detect emissions and show that unloaders leak gas is regular surveys with infrared (IR) cameras. One Natural Gas Partner initiated a project to replace the cylinder unloaders at some of its compressor stations with a design that utilizes a balanced piston that avoids chatter and minimizes the pressure required for operation. Reduced chatter reduces the contact, friction, and wear which results in reduced emissions. Reduced pressure means a reduced driving force for emissions.
Faulty unloaders can be a source of fugitive methane emissions to the atmosphere from leaking O-rings, covers, pressure packing, and frequent maintenance. Unloaders have also been identified as one of the top causes of unscheduled reciprocating compressor shutdowns. There are unloaders that utilize multiple sealing elements to reduce emissions while its plug-type design avoids the inherent operational problems and breakage associated with finger-type unloaders.

One of Natural Gas Partners reported that a total of 15623 Nm^3 per year of methane emissions were eliminated by replacing the worn unloaders on four compressors with those of a new design at one of their compressor stations.

6.5 Vent and Flare Systems

6.5.1 Flaring versus venting

The term gas flaring indicates the combustion of gas (without energy recovery) in an open flame that burns unceasingly at the top of flare stacks.
Using a flare to control emissions from tanks involves connecting the vents of a tank or tank battery to the bottom of the flare stack. The vapours from oil and condensate tanks are sent to the flare, and air is also added to provide oxygen for combustion. The vapours and air are ignited by natural gas pilot flames, and much of the HAP (Hazardous Air Pollutants), VOC, and methane content of the tank vapours can be destroyed. The destruction efficiency for flares can vary greatly depending on residence time, temperature profile, mixing, and other factors. Properly designed and operated flares have been reported to achieve 98% destruction efficiencies.

Applying 98% destruction efficiency results in potential emission reductions. The reductions are substantial and would provide large benefits to the ozone and PM (Particulate Matter), Hazardous Air Pollutants (HAPs), and greenhouse gas emission inventory. The use of flares, however, also has several drawbacks. One of these is that tank vapor flares need a continuous supply of pilot light natural gas, and reports have estimated pilot light gas consumption at around 0.6 Nm^3/hr per flare.

Besides the practice of gas flaring, there is also that of gas venting. Gas venting is the discharge of unburned gases into the atmosphere, often carried out in order to maintain safe conditions during the different phases of the treatment process. During venting operations methane, carbon dioxide, volatile organic compounds, sulphur compounds and gas impurities are released. In many cases gases that are being vented could be burnt rather than dispersed into the atmosphere; this would partially reduce the environmental impact in terms of greenhouse gases, because the gases would be oxidised to form carbon dioxide, which has a global warming potential 28 (on a time scale of 100 years) times lower than methane. That means that flaring gives less emissions than venting.

6.5.2 Enclosed flares

The simplest enclosed combustion device is an enclosed flare. An enclosed flare is simply meant to hide the flame and does not make a particular effort to increase combustion efficiency or reduce emissions. The flames from enclosed flares are usually not visible from the outside, except during upset conditions, making them less objectionable to the surrounding community compared to open (unenclosed) flares. An example is shown in Figure 32 below.

Figure 32 Examples of enclosed flare systems (source: Zeeco Products & Industries)

Enclosed flares provide cooling and combustion air through natural draft. The enclosed flare burner is simple and can be an anti-flashback type, a high-pressure type or a forced-draft type. A forced-draft type of device is used when the process gas has a tendency to produce smoke. It utilizes a blower to provide 20–40% of the stoichiometric air to the fuel gas near the burner tip. Enclosed flares typically operate at around 98% destruction efficiency.

Destruction efficiency is defined as the difference between the amount of pollutants entering the system and the amount of pollutants exiting the system divided by the mass of pollutants entering the system, expressed as a percentage. Depending on the pollutants to be destroyed, a minimum destruction efficiency is needed to meet regulations. Thus, the selection of the combustion equipment depends on the destruction efficiency needed.

In order to reach higher levels of destruction efficiency, we start off with an enclosed flare design and add temperature control and assist gas. This can be called a vapor combustor, or in some cases, a thermal oxidizer. The vapor combustor can maintain higher temperatures in the chamber, which allows it to maintain a destruction efficiency of up to 99.9%. Residence time is typically around 0.7 seconds for these types of combustors.

A thermocouple is used to monitor system temperature and control the opening of the louvers or the flow of assist gas to maintain a desired chamber temperature of 760 to 980 °C. Different burners can be used, including forced-draft burners for smokeless combustion of heavy hydrocarbons, anti-flashback burners and low NO_x (oxides of nitrogen) burners.

6.5.3 Vent and drain systems for reciprocating compressors according to the API 618

Besides that process gas will leak from the cylinder through the piston rod packing via the distance price to the air, the process gas can also flow to the crank case as shown in Figure 33. This situation can lead to an explosive gas mixture.

Purge systems for the piston rod packing and distance piece can be used for reciprocating compressors to lower (fugitive) emissions of the process gas.
An example of the typical flow path of the purge (vent) gas and process gas through a piston rod packing is shown in Figure 34 (GEP, Ariel).

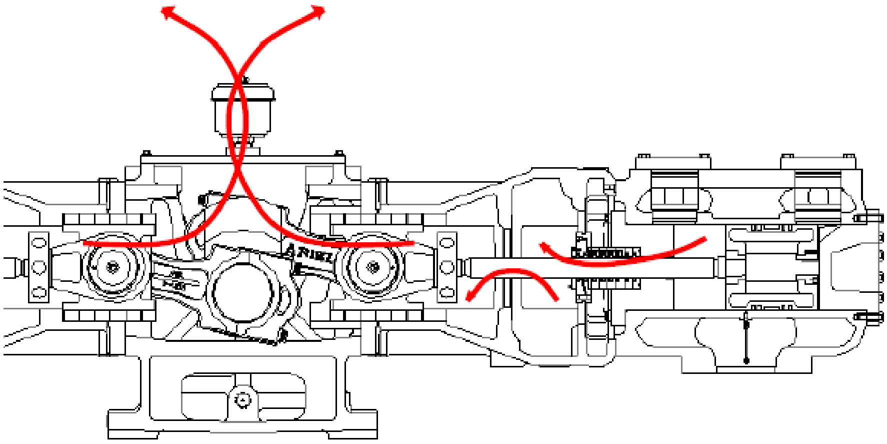

Figure 33 Process gas leaking to the crankcase (source GEP, Ariel).

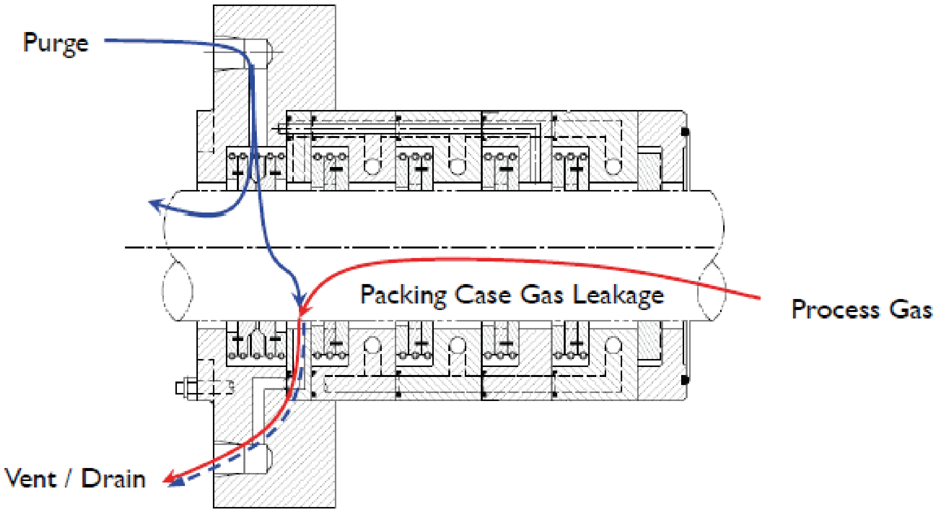

Figure 34 Flow path of the purge (vent) gas and process gas through a piston rod packing (source GEP, Ariel).

In the API Standard 618 a description is given of how this system shall be designed. According to the 5th edition of the API Standard 618, the purpose of a distance piece and drain system, working in conjunction with packing, buffer system and partitions, accomplishes several functions, including:

a. confining and collecting the normal leakage from compressor rod pressure packing and carrying the leakage to a safe location;
b. preventing process gas, toxic gas or hazardous gas leakage into the area around the machine;
c. preventing contamination of the crankcase lube oil;
d. atmospheric fugitive emission control;
e. confining and collecting large leakage in the event of compressor pressure packing failure, and directing the leakage to a safe location;

f. helping to prevent an explosive atmosphere from developing in the crankcase;
g. preventing excessive liquid accumulation in the distance piece;
h. avoiding gas leakage to sewer systems;
i. allowing the operator to monitor and determine the condition of compressor rod pressure packing.

The API Standard 618 states:

> If specified, to reduce process gas emissions to an absolute minimum, the cylinder pressure packing shall include venting and buffer gas cups with side-loaded packing rings in the adjacent cups.

The API Standard 618 provides several pictures of the vent and drain system for a single and double distance piece configuration. Figure 35 shows an example of the API Standard 618 with the P&ID diagram (API Figure I.1) of the vent and drain system of a double distance piece compartment (GEP, Ariel).

It shall kept in mind that as the packing rings wear and the packing case vent flow increases, the vent pressure can exceed the purge pressure, allowing gas to enter the distance piece. This requires that the distance piece vent always be considered a primary vent.

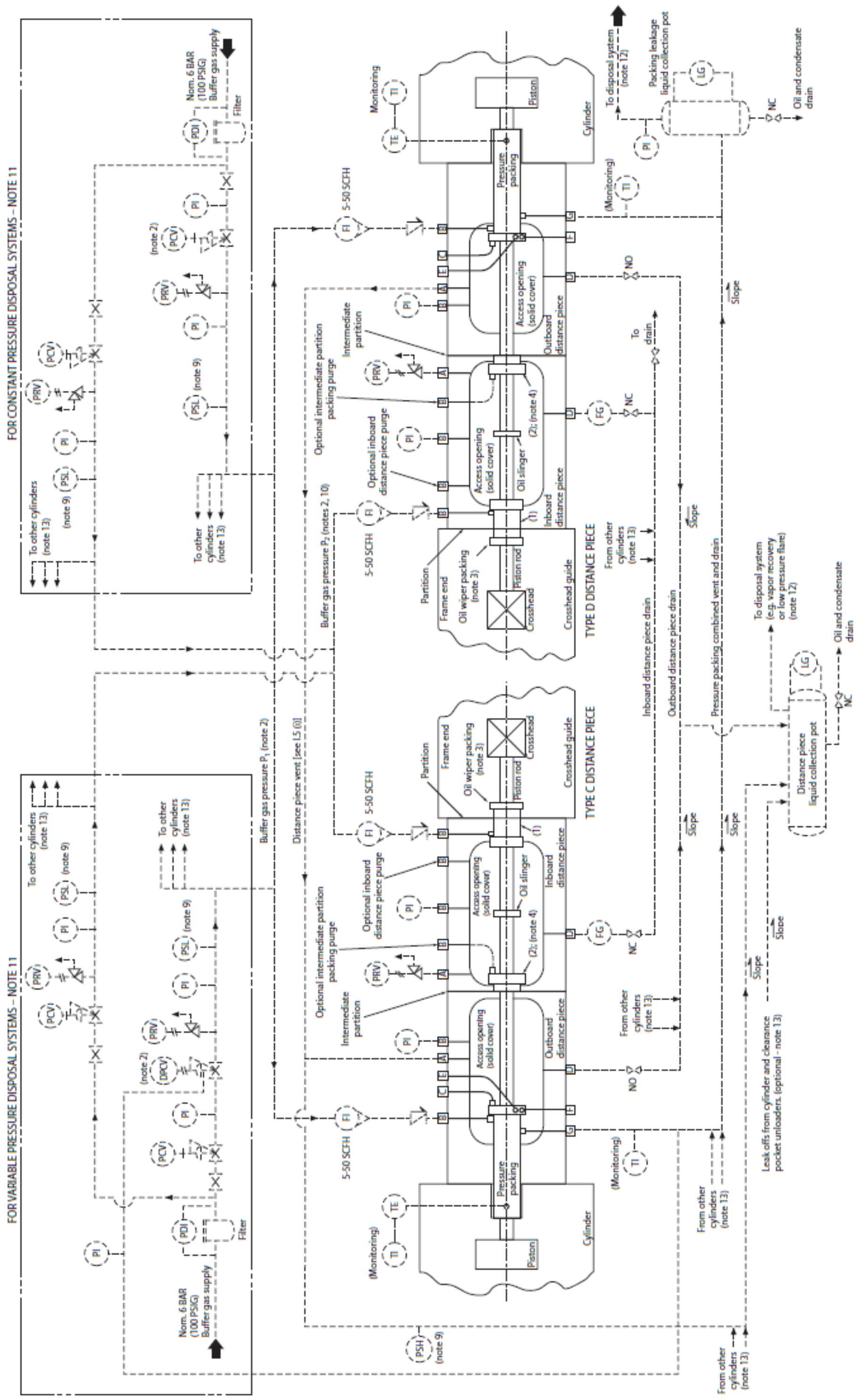

Figure 35 Figure I.1 of the API 618: Typical Buffered Single Compartment Distance Piece Vent, Drain, and Buffer Arrangement to Minimize Process Gas Leakage

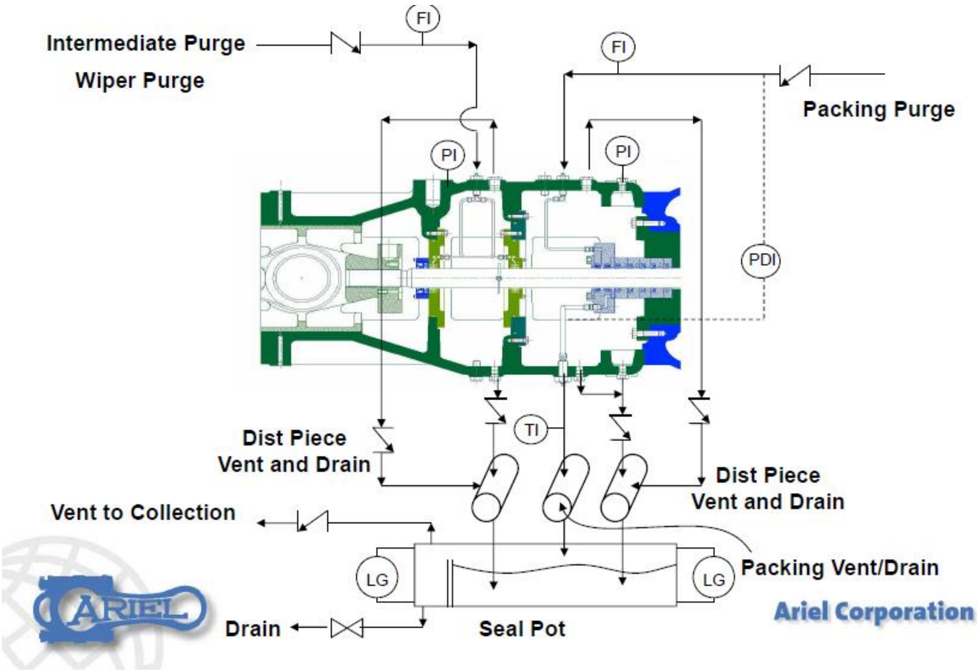

Figure 36 Example of the vent and drain line PI&D of a double distance compartment (source: GEP, Ariel).

Venting to atmosphere has been common with non‐toxic or non‐lethal gasses. However, venting to atmosphere is not acceptable for toxic or lethal gasses and is becoming increasingly restricted for pipeline natural gas due to EPA greenhouse gas (GHG) regulations. At some point, it may be necessary to vent all gas vents to a flare (GMRC 2017).

As a more emission friendly alternative, the vent gas can be also be routed a vapor recovery unit, see also section 6.5.4 , but it can also be routed back directly to the suction side of the compressor. This can be done with a rather small compressor and in many cases a reciprocating is used. The vent gas compressor will also have a leakage over the piston rod packing but this can further be reduced by using a diaphragm type compressor.

Whether for venting to a flare or to atmosphere, a list of considerations that have been found in *The GMRC Guideline for high‐speed reciprocating compressor packages for natural gas transmission & storage applications (GMRC 2017)* is very helpful and the listing is:

1. It is necessary to vent all distance piece compartments. Vent and drain lines should be sized to handle worst case leakage rates without causing the distance piece internal pressure to exceed about 10 inch of water (0.254 barg) unless higher pressures are permitted by the compressor manufacturer specifications. Typical packing leakage rates are in the range of 5 to 10 SCFH (8.5-17 Nm^3/hr per pressure packing case when packing rings are new, but may reach 100 SCFH (170 Nm^3/hr), or even higher, per packing case, when rings are worn. The compressor manufacturer should be consulted for guidance on maximum potential packing leakage rates and maximum allowable distance piece internal pressures.

2. Independently vent primary vents and drains from any secondary ones. Install all vents and drains to prevent collection of liquids that could cause either gas or liquid build-up. When applicable, design vents and drains to accommodate gas that is heavier than air (not a concern on natural gas pipeline and storage applications).
3. Packing drain/vent lines from multiple packing cases are normally connected to a common drain tank or header as shown in Figure 37. The vent connections should be configured so that gas cannot transfer from one vented compartment to another. Check valves can be used, but they can foul up due to contaminants in the oil and gas mixture. A liquid check valve in an oil separation pot or seal trap is a very effective means of isolating vents from a common waste oil tank.

   Location of the waste oil tank (on skid or off skid) needs to be carefully considered and coordinated with all parties – end user, packager, EPC - in the package and building design phase.

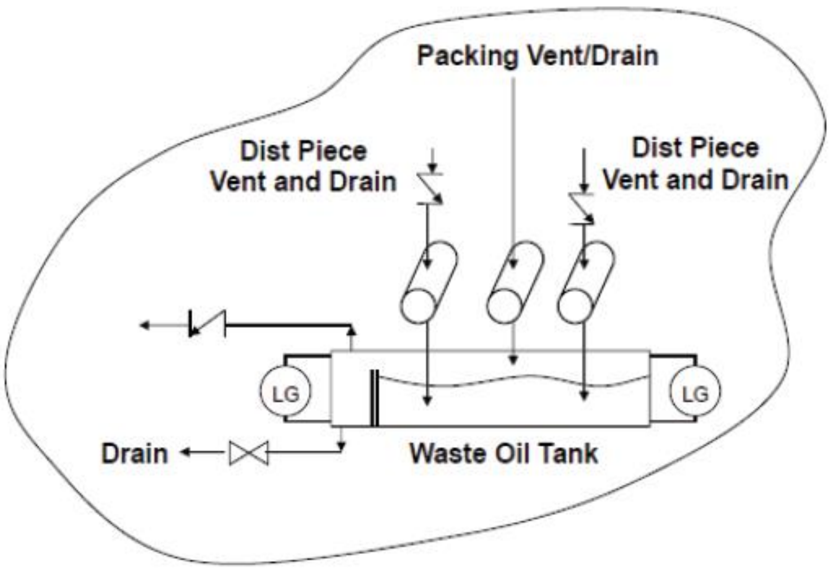

Figure 37 Common vent/drains connected to waste oil tank

4. Pressure drop needs to be minimized in the drain and vent lines. All compressor packing vents and drains should typically be at least 1 inch (25.4 mm) diameter, but not smaller than the size of the distance piece connections furnished on the compressor.
5. Drain manifolds need to slope continually toward the drain pots and the waste oil tank, avoiding low level traps where oil could pool and collect.
6. The packing vent/drain connection should not be tied to the distance piece drain prior to entering the oil separation pot, as the packing vent flow can go back through the drain connections to vent through the top of the guides. This will not allow the oil to drain properly from the distance piece.
7. Lube oil needs to be separated from the packing vent gas.
8. A check (non-return) valve must be installed on the final vent line, whether to flare or to atmosphere.
9. Where packing leakage rates are to be monitored, the vents should be piped into a single vent header terminating at the edge of the skid, with valves and flow meter. If the flow meter restricts the flow rate in a way that would result in increasing the distance piece pressure to an excessive level, an automatic

pressure relief/bypass valve should be connected in parallel around the flow meter.

Figure 38 shows a preferred arrangement for periodic monitoring of multiple vent line flows using a single flow meter with manual valves. The schematic shows how to isolate and monitor flow from an individual packing vent.

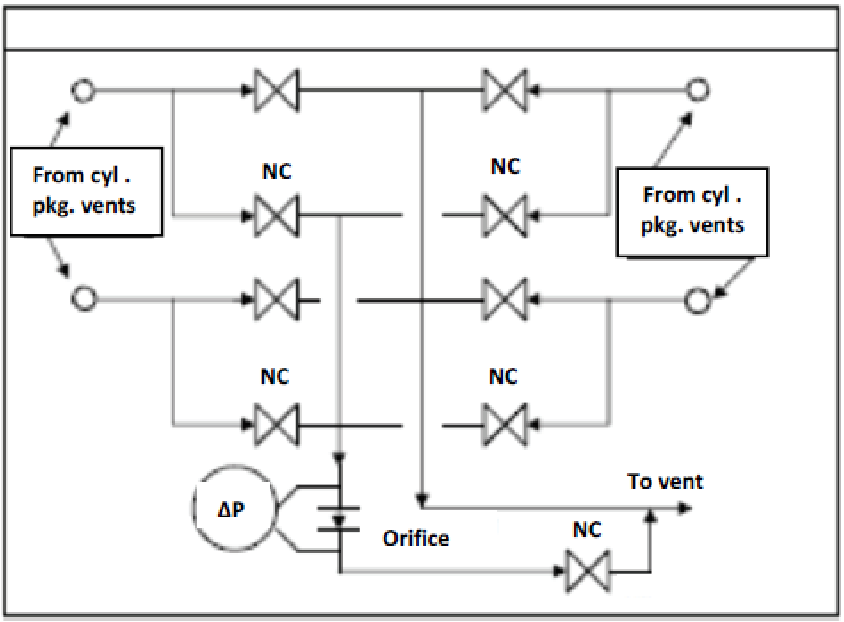

Figure 38 Multiple packing vent monitoring schematic

10. When common vents are used on two stage compressor packages, the first stage vents should have check valves. Similar practice applies to compressors with more than two stages.
11. All packing drains may be piped to a common drain header terminating at the edge of the skid. For two stage compressor packages, check valves should be installed on the first stage drains.
12. If oil mist eliminators are used on engine crankcase or other vents, closely follow the manufacturer’s specifications for installation of piping upstream and downstream of the mist eliminator.
13. Skid oil containment should be the following or equivalent based on packager’s successful experience: a drip lip of (minimum) ¼ inch x 2 inch (6.4x51 mm) flat bar welded to the deck plate around the entire perimeter of the engine/compressor skid; and a skid drain of 1.5 inch (38 mm) diameter (minimum) provide at each corner of the skid with threaded pipe connection for interface to drain system.

6.5.4 Vapor recovery units (reuse vent gas)

A VRU, or vapor recovery unit, is a compression system used to collect and compress low volume gas streams for injection into the suction of a larger compressor, a meter run, a local site fuel gas system or directly into a gas gathering line.

Mechanical VRUs consist of a driver motor or engine that supplies the power to the compressor. They are often used by oil and gas operations to recover vent gas.

The advantages of a VRU are:

- It is economic attractive because it can make money for a facility. Sending the natural gas recovered to the sales pipeline increases the facility's total volume of gas sold.
- VRUs reduce air pollution emissions since they recover vent gas that would be emitted to atmosphere or burned in a flare.
- Assist in meeting air permit limits.
- Using VRUs to capture vent gas can reduce current and future risks and liability associated with greenhouse gas emissions.

The most commonly used mechanical compressors used for VRUs include:

- Flooded rotary screw.
- Rotary sliding vane.

Less commonly used VRUs include:

- Vapor Jet Pump– non mechanical method using pressurized water to recover and compress gas.
- Reciprocating compressors are used more often in dry gas applications but some specific type of reciprocating compressors are better suited to wet gas and can be used in VRU service.

The following parameters shall be considered in the design of a VRU:

- Variable flow.
- Variable pressure.
- Variable molecular weight.
- "Dirty gas".
- Corrosive service.

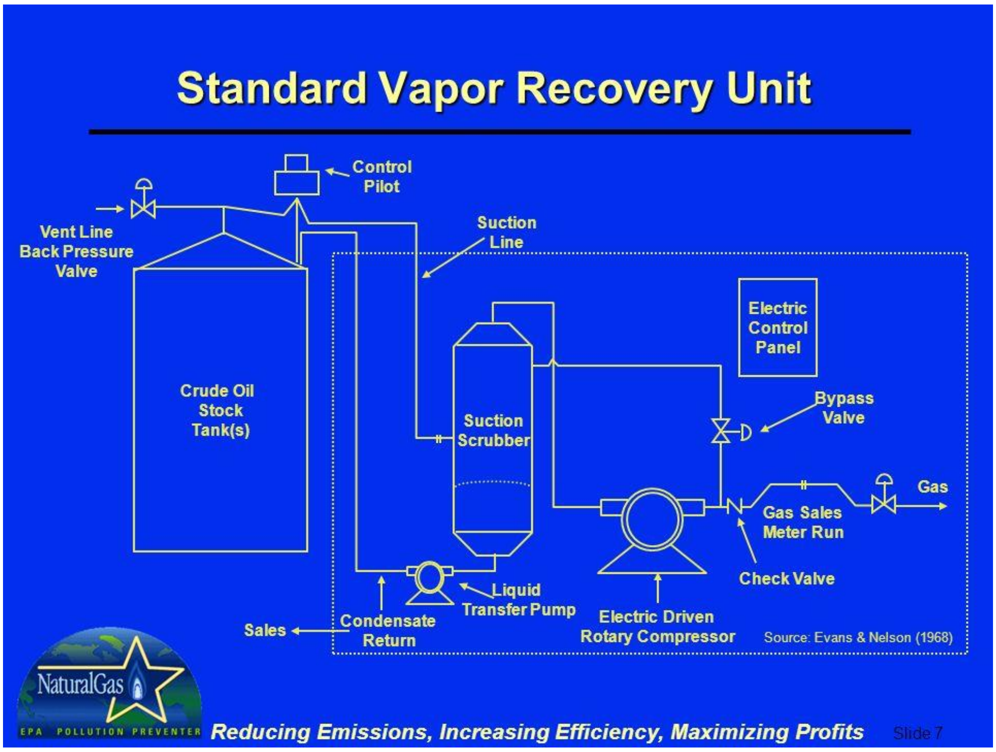

Figure 39 - Typical flow scheme of a VRU (source: EPA NG Star)

Figure 40 - Photo of a typical VRU (source: https://hy-bon.com/blog/faq-about-vapor-recovery-units/)

6.6 Taking compressors off-line for maintenance (UGS systems) (EPA, 2016 August 31st h)

6.6.1 Introduction

Compressors must periodically be taken off-line for maintenance, operational stand-by, or emergency shut down testing, and as a result, gas may be released to the atmosphere from a number of sources.

When compressor units are shut down, typically the high pressure gas remaining within the compressors and associated piping between isolation valves is vented to the atmosphere (‘blowdown’) or to a flare. In addition to blowdown emissions, a depressurized system may continue to leak gas from faulty or improperly sealed unit isolation valves. Compressors for Underground Gas Storage (UGS) systems can operate on a daily basis and especially these compressor systems have in general high venting rates.

The Natural Gas STAR Partners have found that simple changes in operating practices and in the design of blowdown systems can save money and significantly reduce methane emissions by keeping systems fully or partially pressurized during shutdown. Though pressurized systems may also leak from the closed blowdown valve and from the reciprocating compressor rod packing, total emissions can be significantly reduced due to the fact that the pressure difference over the isolating valves is reduced. It is estimated that the emission from a pressurized system is approximately a factor 3 lower during shut-down than the “blowdown” scenario.

The number of times a compressor is taken off-line for normal operations depends on its operating mode. Some compressors are designated as base load and these compressors are operated most of the time, and might be taken off-line only a few times per year for maintenance for instance. Down time for base load compressors averages 500 hours per year. Other compressors operate for peak load service for UGS systems. These units drop off the system (shut down) as market demand decreases. Peak load compressors may be operated for less than 50 percent of the year, but cycling on- and off-line many times per year.

The largest source of methane emissions associated with taking compressors off-line is from depressurizing the system by venting all the gas that remains within the compressor and the piping associated with the compressor. The gas volume released during a compressor blow down depends on several factors including the size of the compressor, the pipeline pressure, and the pipe volume contained between unit isolation valves.

It should be noted that all options discussed in this section require blowdown of a compressor before it can be taken on-line again. The main difference between the baseline scenario (venting all the gas during blow down) and maintaining it depressurized) and the options keeping the compressors pressurised is the timing of the blowdown and the volume of the blowdown, for example, if the blowdown gas is routed to the fuel gas system (if present).

Unit isolation valves are another source of methane emissions from off-line depressurized compressors. Large unit valves are used to isolate the compressor from the pipeline and can leak significant amounts of methane. Unit valves have acceptable ranges of leakage specified by design tolerances for this type of valve. Unit isolation valves are periodically maintained to reduce leakage, but the limited accessibility of such valves can result in increased leakage between scheduled maintenance.

If the compressor is kept pressurized while off-line, emissions from compressor rod packings and blowdown valves can be observed. Seals on compressor piston rods will leak during normal operations, but this leakage increases approximately 50% when a compressor is idle with a fully pressurized suction line. Leaks occur through gaps between the seal rings and their support cups, which are closed by the dynamic movement of the piston rod and lubricating oil (see EPA's *Lessons Learned: Reducing Methane Emissions from Compressor Rod Packing*). Vent and flare system valves can also leak from pressurized systems at a rate of ≈255 Nm^3 per hour.

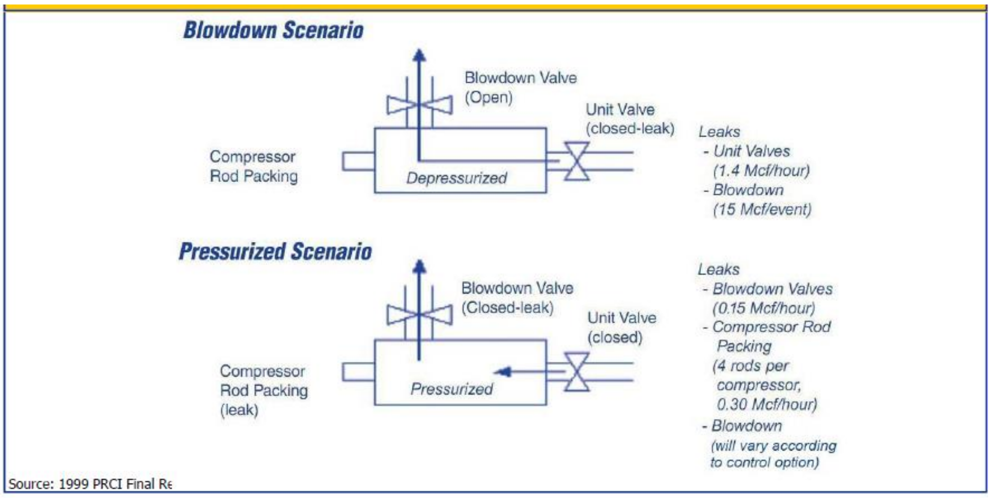

Figure 41 Compressor diagram for a blowdown and pressurized scenario (EPA, 2016 August 31st h)

Natural Gas STAR Partners have significantly reduced methane emissions from compressors taken off-line by implementing changes in maintenance and operating procedures as well as installing new equipment. The practices recommended by Natural Gas Star Partners are summarized in the next section on technical solutions.

6.6.2 *Technical solutions*

The four recommended practices by the Natural Gas STAR Partners for reducing emissions when taking compressors off-line are:

1. Maintain pipeline pressure on the compressor during shutdown
As shown in Figure 41 above, leakage from the compressor seal and closed blowdown valve will increase for the pressurized system, but is still less than anticipated leakage at the unit isolation valve for a depressurized system. It has been reported that total fugitive gas emissions will be reduced by as much as 68 percent, compared to leakage that would occur through the unit valve if the compressors were offline and depressurized.

2. Keep the compressor at fuel gas pressure (if present) and connect to the fuel gas system
Connecting the blowdown vent or flare lines to the fuel gas system allows the gas that is purged when taking a compressor off-line to be routed to a useful outlet. The pressure of an off-line compressor equalizes to fuel line gas pressure (typically 7-10 bar). At the lower pressure of the fuel line, it is reported that the total leakage from the compressor system is reduced by more than 90 percent, compared to leakage that would occur through the unit valve if the compressor were offline and depressurized. Leakage across the unit valves into the compressor continues to feed the fuel system via the vent connection, rather than vent to the atmosphere or flare in the fully depressurized system.
This procedure is described more into detail EPA’s fact sheet 401 dated 2011: “Inject Blowdown Gas into Low Pressure Mains or Fuel Gas System”.

3. Keep the compressor at pipeline pressure and install a static seal on the compressor rods

A static seal on the compressor rods can eliminate rod packing leaks during shutdown periods with the compressor still pressurized. A static seal is installed on each rod shaft outside the conventional packing. An automatic controller activates when the compressor is shutdown to wedge a gas-tight seal around the shaft; the controller deactivates the seal on start-up. The process gas is used for this purpose.

The new leakage rate would represent a reduction of 89% of the emissions that would take place if the compressor were to be kept off-line and depressurized.

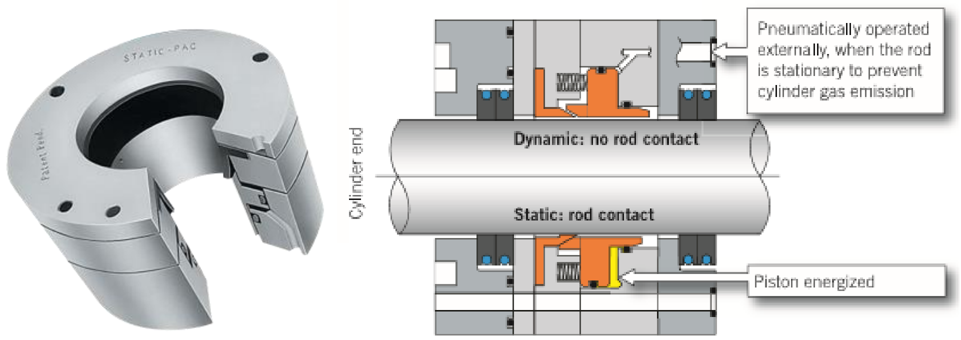

Figure 42 Examples of a static seal (left: Cook; right: Hoerbiger)

4. Install an Ejector

An ejector is a venturi nozzle that uses high-pressure gas as motive fluid to draw suction on a lower pressure gas source, discharging into an intermediate pressure gas stream. The ejector can be installed on vent connections up and down stream of a partly closed valve, or between the discharge and suction of a compressor which creates the necessary pressure differential. The captured gas and the motive gas are then routed to the compressor suction or fuel gas system.

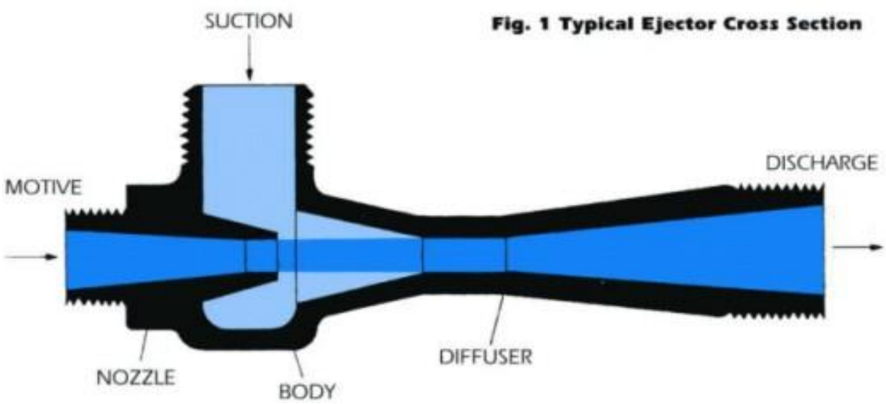

Figure 43 Example of an ejector (source: Northvale Korting)

6.6.3 Economics

Keeping compressors fully pressurized when off-line achieves immediate payback, there are no capital costs and emissions are avoided by reducing the net leakage rate. Routing blowdown vent lines to the fuel gas system (if present), or to a lower pressure gas line reduces fuel costs for the compressor or other facility equipment, in addition to avoiding blowdown emissions. Benefits of these practices include fewer bulk gas releases, lower leak rates, and lower fuel costs, with a payback in many cases of less than a year.

The decision steps are:

- Identify blowdown alternatives.
- Calculate the quantity and value of methane emissions from the base line (depressurized) scenario.
- Calculate the costs and savings of alternatives.
- Conduct economic analysis.

An efficient operating practice is to avoid fully depressurizing compressors until they are to be taken online again.

The option of installing static seals provides added gas savings when used together with the option of maintaining the compressor at pipeline pressure) by limiting fugitive gas emissions when maintaining a pressurized system.

The option of installing an ejector, will recover blowdown gas that would otherwise have been vented and allow the operator to direct it to a useful outlet. In addition, this option can capture leakage and route it to a useful outlet, making it possible to be implemented in combination with any of the other options.

Other emission reduction measures which are found are:

Venting before maintenance
Venting before maintenance is another opportunity to recover methane. It has been shown (Lechtenböhmer et al. 2007) that current pipeline venting can be reduced 50% by decreasing the line pressure beforehand e.g. by shutting the valve upstream of the pipeline segment and continuing to operate the downstream compressor. A line segment can be further depressurised before it is vented by using portable pull-down compressors. This practice has achieved a 90% reduction in line venting at estimated investment cost of Euro 35 per tonne of CO2 equivalent (Robinson et al., 2003).

Using portable compressors
Portable compressors can be used to pump the gas from a closed section into the suction piping of a compressors, see Figure 44 below. In this way the gas will not be vented to the air leading to lower emissions and a costs benefit for the customer by using the gas which is normally vented.

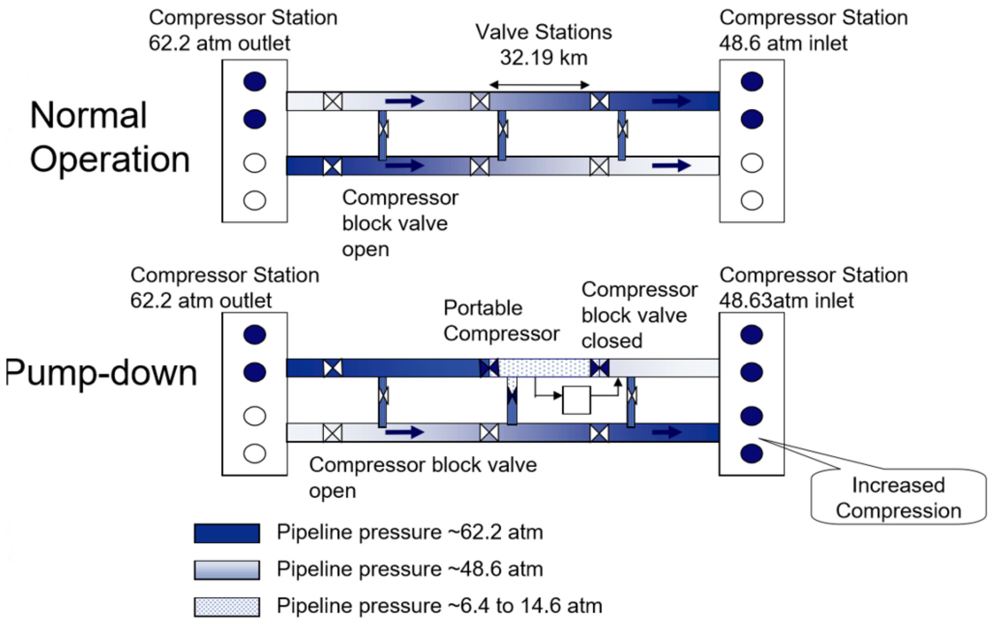

Figure 44 Scheme of using portable compression to reduce pipeline blowdown emissions

6.7 Pneumatic control devices

6.7.1 Introduction

Pneumatic control devices are responsible for a significant share of the fuel. Every year, within a natural gas system, a single unit of pneumatic control valve instrumentation typically releases 15000 N/m^3 (GE Workshop, 2012) per year of natural gas into the atmosphere.

According to the EPA, “retrofit or complete replacement of worn units can provide better system-wide performance and reliability and improve monitoring of parameters such as gas flow, pressure”.

Older pneumatic devices require larger gas bleed rates for process control, while devices introduced in the 90s achieve the same result without the high bleed rates and generally at the same capital and operating costs. Other options are devices using instrument air, mechanical, or electric devices. Thus low bleed pneumatic devices are appropriate measures to reduce methane. Due to the rising value of gas as a sales commodity and as a carbon credit, retrofit or early replacement programs are very attractive.

Pneumatic equipment in the oil and gas industry uses pressurized gas to create mechanical action. In this section we focus specifically on pneumatic controllers. Pneumatic controllers, or “PCs,” are automated instruments that control various process conditions of natural gas, such as liquid level, pressure, pressure difference, and temperature. A typical P&ID showing a liquid level controller (LLC) and pressure controller (PC) is shown in Figure 45.

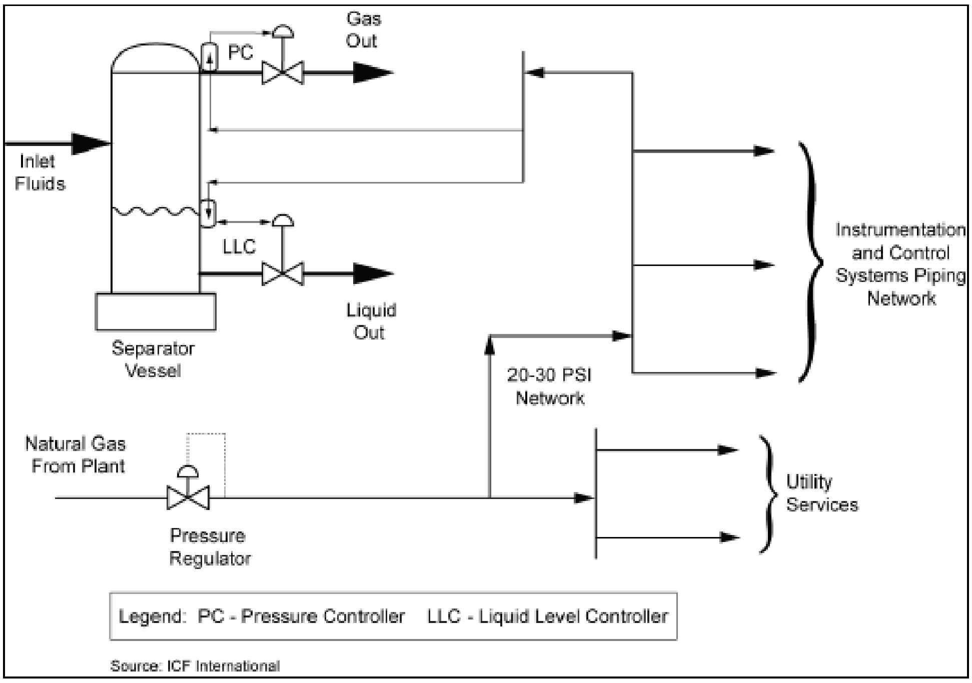

Figure 45 Natural Gas Pneumatic Control System (source: Oil and Natural Gas Sector Pneumatic Devices Report for Oil and NATURAL Gas Sector Pneumatic Devices, Review Panel 2014", Prepared by U.S. EPA Office of Air Quality Planning and Standards (OAQPS).

Many PCs in the oil and gas sector use pressurized natural gas as their energy source and vent some quantity of that gas into the atmosphere in normal operation. These devices include continuously emitting devices (either high-bleed or low-bleed PCs), snap-acting or intermittent devices (which emit gas in periodic releases), and no-bleed devices, which are self-contained units that release gas to downstream pipelines rather than into the atmosphere. PCs that are powered by some source other than pressurized natural gas, such as electricity, solar power, or instrument air, also do not vent gas into atmosphere.

This section provides an analysis of control measures requiring operators to replace existing high-bleed and intermittent-bleed PCs with low-bleed devices. Calculations (EPA, 2014 June 16th) demonstrate that these measures would achieve large methane emission reductions.

Accounting for these revenues and savings, the measures described below would generate annual savings to operators in oil and gas production ranging from Euro 250 to over Euro 900 depending on the type of PC at issue.

Most of the material as given in this section is derived from EPA's white paper on reducing emission (EPA 2014, April) of Pneumatic devices and from, a review of this white paper by the Sierra Club Natural Resources Defence Council (EPA, 2014 June 16th) and EPA's fact sheet "*Convert Gas Pneumatic Controls to Instrument Air",* (EPA 2016 August 31st i).

6.7.2 Types of Pneumatic Controllers

Based on the source of power, two types of pneumatic controllers are defined for this section:

- Natural gas-driven pneumatic controller means a pneumatic controller powered by pressurized natural gas.
- Non-natural gas-driven pneumatic controller means an instrument that is actuated using other sources of power than pressurized natural gas; examples include solar, electric, and instrument air.

Natural gas-driven pneumatic controllers come in a variety of designs for a variety of uses. For the purposes of this white paper, they are characterized primarily by their emissions characteristics:

Continuous bleed pneumatic controllers
These controllers have a continuous flow (which may vary in time) of pneumatic supply natural gas to the process control device (e.g., level control, temperature control, pressure control) where the supply gas pressure is modulated by the process condition, and then flows to the valve controller where the signal is compared with the process setpoint to adjust gas pressure in the valve actuator. A typical control valve configuration is shown in Figure 46.
Continuous bleed controllers are subdivided into 2 types based on their bleed rate:

- Low bleed, having a bleed rate of less than or equal to 0.17 Nm^3/hr (6scfh).
- High bleed, having a bleed rate of greater than 0.17 Nm^3/hr (6 scfh).

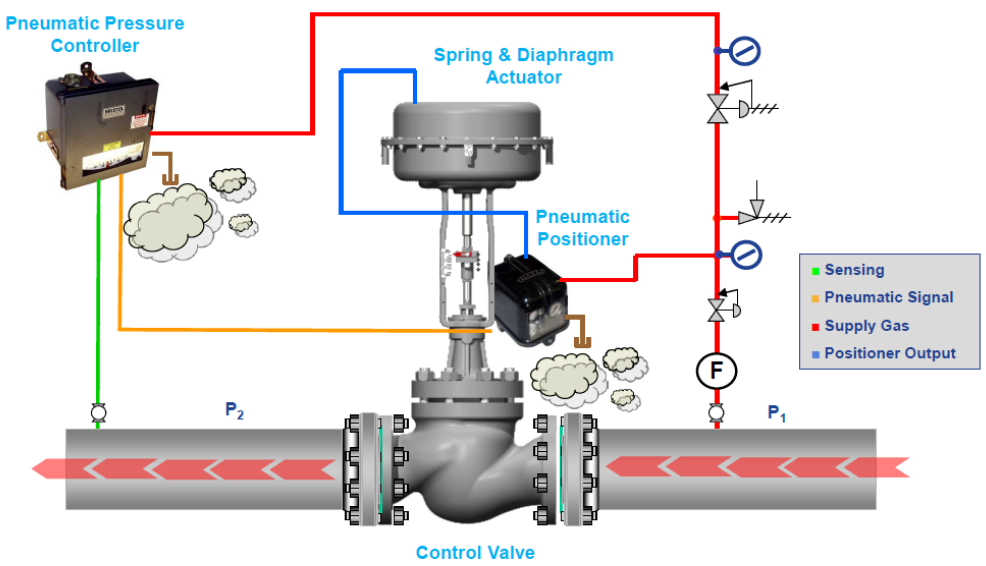

Figure 46 Typical (high bleed) control valve configuration

Continuous bleed controllers also vent an additional volume of gas during actuation in addition to the device continues bleed stream. Continuous bleed device also depend, in part, on the frequency of activation and the amount of gas vented during activation and so also the emissions.

Intermittent pneumatic controller
These controllers do not vent continuously. These natural gas-driven pneumatic controllers do not have a continuous bleed, but are actuated using pressurized natural gas. They release gas when they open or close a valve or as they throttle the gas flow. Thus, the actual amount of emissions from an intermittent controller is dependent on the amount of natural gas vented per actuation and how often it is actuated.

In general, intermittent controllers serve functionally different purposes than bleed controllers and, therefore, cannot replace bleed controllers in most (but not all) applications.

Pneumatic pumps
Pneumatic pumps are devices that use gas pressure to drive a fluid by raising or reducing the pressure of the fluid by means of a positive displacement, a piston or set of rotating impellers. Pneumatic pumps are generally used at oil and natural gas production sites where electricity is not readily available (GRI/EPA, 1996 June). The supply gas for these pumps can be compressed air, but most often these pumps use natural gas from the production stream (GRI/EPA, 1996 June).

Non-natural gas-driven pneumatic controllers
These controllers can be used in some applications. These controllers can be mechanically operated or use sources of power other than pressurized natural gas such as compressed air.

Instrument air system are only feasible at oil and natural gas locations that have electrical service sufficient to power an air compressor. At sites without electrical service sufficient to power an instrument air compressor, mechanical or electrically powered pneumatic controllers can be used. Non-natural gas-driven controllers do not directly release methane or VOCs, but may have secondary impacts related to generation of required electrical power.

Additional information on pneumatic controllers can be found in the reports as summarized in Table 6.2.

Table 6.2 - Summary of Major Sources of Pneumatic Controller and Pump Information (source: Oil and Natural Gas Sector Pneumatic Devices Report for Oil and NATURAL Gas Sector Pneumatic Devices, Review Panel 2014", Prepared by U.S. EPA Office of Air Quality Planning and Standards (OAQPS).

Report Name	Affiliation	Year of Report	Activity Factor	Pneumatic Controllers	Pneumatic Pumps
Methane Emissions from the Natural Gas Industry (GRI/EPA, 1996c)	Gas Research Institute / EPA	1996	Nationwide	X	X
Estimates of Methane Emissions from the U.S. Oil Industry (ICF Consulting, 1999)	EPA	1999	Nationwide	X	
Inventory of Greenhouse Gas Emissions and Sinks: 1990-2012 (U.S. EPA, 2014)	EPA	2014	Nationwide/ Regional	X	X
Greenhouse Gas Reporting Program (U.S. EPA, 2013)	EPA	2013	Basin	X	X
Measurements of Methane Emissions from Natural Gas Production Sites in the United States (Allen et al., 2013)	Multiple Affiliations, Academic and Private	2013	Nationwide	X	
Determining Bleed Rates for Pneumatic Devices in British Columbia (Prasino, 2013)	The Prasino Group	2013	British Columbia	X	
Air Pollutant Emissions from the Development, Production, and Processing of Marcellus Shale Natural Gas (Roy et al., 2014)	Carnegie Mellon University	2014	Regional (Marcellus Shale)	X	
Economic Analysis of Methane Emission Reduction Opportunities in the U.S. Onshore Oil and Natural Gas Industries (ICF, 2014)	ICF International	2014	Nationwide	X	X

6.7.3 Available reduction methods

Several techniques to reduce emissions from pneumatic controllers have been developed over the years. This summary provides a summary of these techniques for reducing emissions from pneumatic controllers including replacing high bleed controllers with low bleed or zero bleed models, driving controllers with instrument air rather than natural gas, using non-gas-driven controllers, and enhanced maintenance.

The comments on the EPA's white papers by the Sierra Club (EPA, 2014 June 16th) indicated the following estimated reductions:

A. Converting Pressure Transmitters from high-bleed to low bleed:
   - Oil and gas production facilities: 82%
   - Gas transmission and storage: 88%

B. Converting Pressure Transmitters from intermittent to low bleed:
   - Oil and gas production facilities: 18%

It also states that if captured gas sales and operating costs reductions are included, economic attractiveness of these measures improves and in fact, in most cases, the control measures will generate positive cash flow for operators.

A table of a summary of alternative mitigation techniques for pneumatic controllers are given in “Oil and Natural Gas Sector Pneumatic Devices Report for Oil and NATURAL Gas Sector Pneumatic Devices, Review Panel 2014”, Prepared by U.S. EPA Office of Air Quality Planning and Standards (OAQPS).

Low Bleed Pneumatic Controllers

Low bleed controllers provide similar functional control as high bleed controllers, but have lower continuous bleed emissions. An example is shown in Figure 47. In the transmission segment of the USA, the average achievable reductions per device are estimated around 3.7 tons and 0.08 tons for methane and VOC, respectively. As defined in EPA’s white paper, a low bleed controller can emit up to 0.17 Nm^3/hr, but this is higher than the expected emissions from the typical low bleed controllers available on the current market.

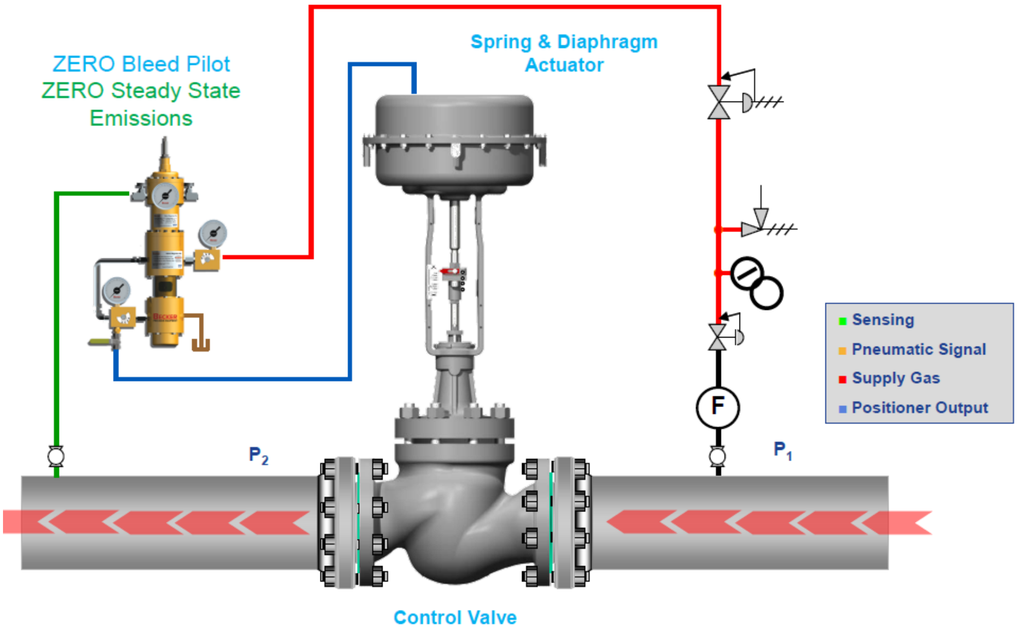

Figure 47 Typical low bleed configuration (source: GE Workshop, 2012)

There are certain situations in which replacing and retrofitting are not feasible, such as instances where a minimal response time is needed, cases where large valves require a high bleed rate to actuate, or a safety isolation valve is involved. Replacing high bleed pneumatic with low bleed controllers is infeasible in situations where a process condition may require a fast or precise control response so that it does not stray too far from the desired set point.

A slower-acting controller could potentially result in damage to equipment and/or become a safety issue. An example of this is on a compressor where pneumatic controllers monitor the suction and discharge pressure and actuate a recycle when one or the other is out of the specified target range. Another scenario where fast and precise control is necessary includes transient (non-steady) situations where a gas flow rate may fluctuate widely or unpredictably. In this case, a responsive high bleed device may be required to ensure that the gas flow can be controlled in all situations.

Temperature and level controllers are typically present in control situations that are not prone to fluctuate as widely or where the fluctuation can be readily and safely accommodated by the equipment. Therefore, such processes may be appropriate for control from a low bleed device, which is slower acting and less precise.
Safety concerns can limit the appropriateness of low bleed controllers in specific situations where any amount of bleeding is unacceptable. Emergency valves are often not controlled with bleeding controllers (e.g., neither low bleed nor high bleed), because it may not be acceptable to have any amount of bleeding in emergency situations.

Pneumatic controllers are designed for process control during normal operations and to keep the process in a normal operating state.
If an Emergency Shut Down (ESD) or Pressure Relief Valve (PRV) actuation occurs, the equipment in place for such an event is spring-loaded, or otherwise not pneumatically powered.

During a safety issue or emergency, it is possible that the pneumatic gas supply will be lost. For this reason, control valves are deliberately selected to either fail open or fail closed, depending on which option is the failsafe.

Zero Bleed Pneumatic Controllers
Zero bleed pneumatic controllers are self-contained closed-loop natural gas-driven controllers that vent to the downstream pipeline rather than to the atmosphere. An example is shown in Figure 48.

These closed loop devices are considered to emit no natural gas to the atmosphere. However, they can be used only in applications with very low pressure and, therefore, may not be suitable to replace continuous bleed pneumatic controllers in many applications. Some applications where they may suitable include gathering, metering and regulation stations, power plant and industrial feed, and city gate stations/distribution. To date, the EPA has not obtained any information on the cost of zero bleed controllers or their prevalence in the field.

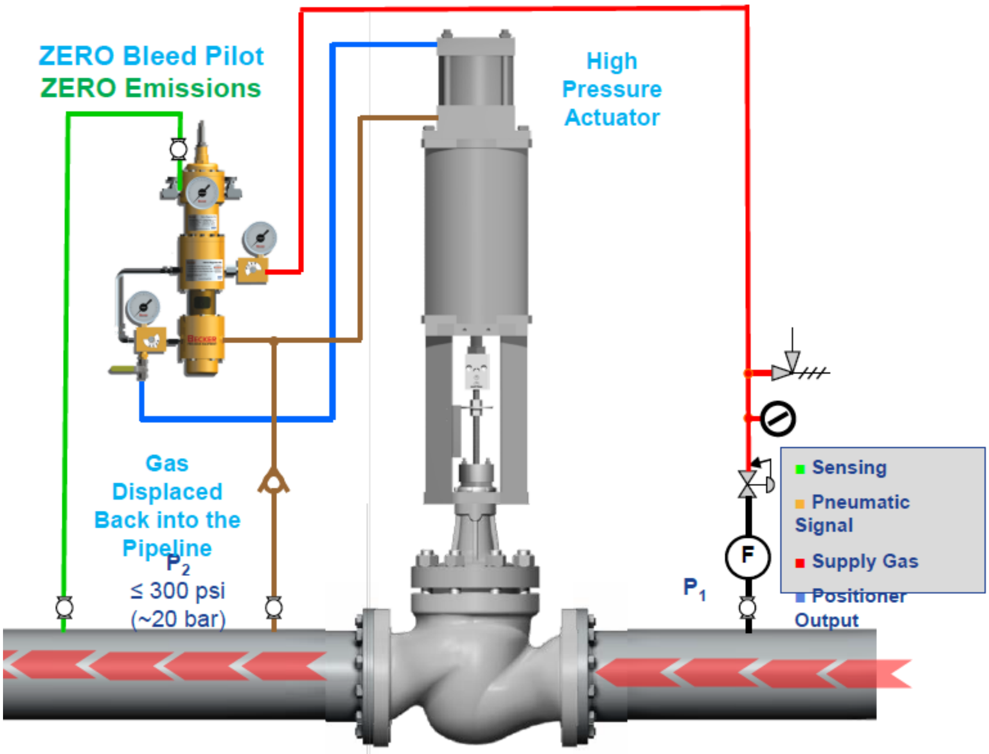

Figure 48 Typical zero bleed configuration (source: GE Workshop, 2012)

Instrument air system

The major components of an instrument air conversion project include the compressor, power source, dehydrator, and volume tank as shown in the P&ID diagram of a compressed instrument air system is presented in Figure 49.

The following is a description of each component as described in the Natural Gas STAR document (EPA, 2016 August 31st i), "Lessons Learned: Convert Gas Pneumatic Controls to Instrument Air".

Compressors used for instrument air delivery are available in various types and sizes, from centrifugal (rotary screw) compressors to reciprocating piston (positive displacement) types. The size of the compressor depends on the size of the facility, the number of control devices operated by the system and the typical bleed rates of these devices. The compressor is usually driven by an electric motor that turns on and off, depending on the pressure in the volume tank. For reliability, a full spare compressor is normally installed. A minimum amount of electrical service is required to power the compressors.

A critical component of the instrument air control system is the power source required to operate the compressor. Because high-pressure natural gas is abundant and readily available, gas pneumatic systems can run uninterrupted on a 24-hour, 7-day per week schedule. The reliability of an instrument air system, however, depends on the reliability of the compressor and electric power supply. Most large natural gas plants have either an existing electric power supply or have their own power generation system. For smaller facilities and in remote locations, however, a reliable source of electric power can be difficult to ensure. In some instances, solar-powered battery operated air compressors can be effective for remote locations, which reduce both methane emissions and energy consumption. Small natural gas powered fuel cells are also being developed.

Dehydrators, or air dryers, are also an integral part of the instrument air compressor system. Water vapor present in atmospheric air condenses when the air is pressurized and cooled, and can cause a number of problems to these systems, including corrosion of the instrument parts and blockage of instrument air piping and controller orifices.

The volume tank holds enough air to allow the pneumatic control system to have an uninterrupted supply of high-pressure air without having to run the air compressor continuously. The volume tank allows a large withdrawal of compressed air for a short time, such as for a motor starter, pneumatic pump, or pneumatic tools, without affecting the process control functions.

Compressed air may be substituted for natural gas in pneumatic systems without altering any of the parts of the pneumatic control. The use of instrument air eliminates natural gas emissions from natural gas powered pneumatic controllers. All other parts of a gas pneumatic system will operate the same way with instrument air as they do with natural gas.

The use of instrument air eliminates natural gas emissions from the natural gas-driven pneumatic controllers; however, these systems may only be used in locations with access to a sufficient and consistent supply of electrical power. Instrument air systems are also usually installed at facilities where there is a high concentration of pneumatic control valves and the presence of an operator that can ensure the system is properly functioning (EPA, 2016 August 31st i).

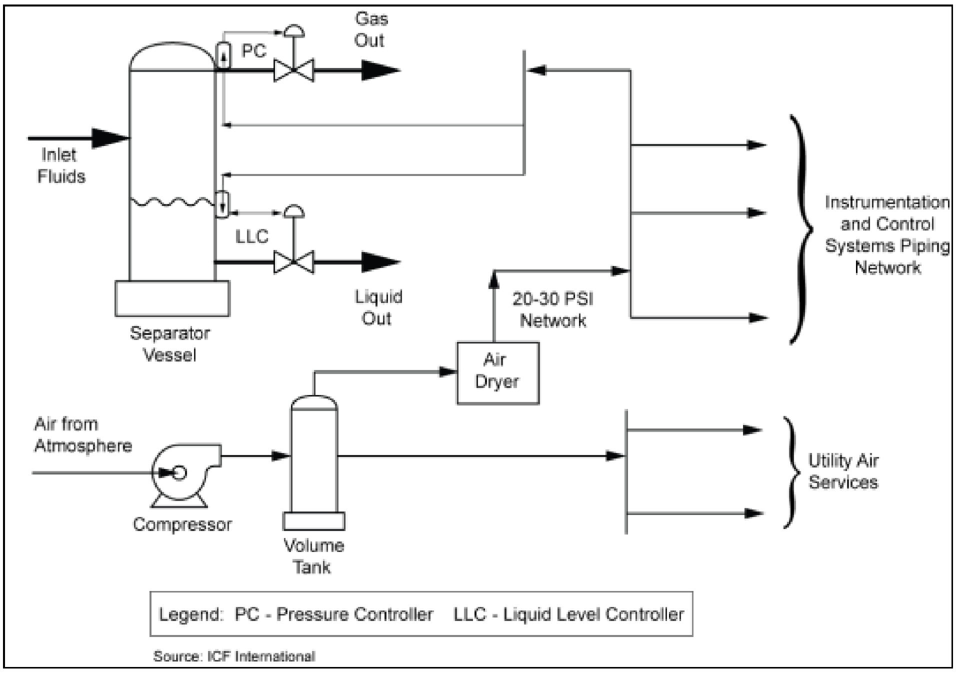

Figure 49 Compressed Instrument Air System (EPA, 2014 April).

Mechanical and Solar-Powered Systems in Place of Bleed Controller
Mechanical controls have been widely used in the natural gas and petroleum industry. They operate using a combination of levers, hand wheels, springs and flow channels with the most common mechanical control device being a liquid-level float to the drain valve position with mechanical linkages (EPA, 2016 August 31st i). Another device that is increasing in use is electronic control instrumentation. Electricity or small electrical motors (including solar powered) have been used to operate valves and therefore do not bleed natural gas into the atmosphere (EPA, 2016 August 31st i). Solar control systems are driven by solar power cells that actuate mechanical devices using electric power. As such, solar cells require some type of backup power or storage to ensure reliability.

Application of mechanical controls is limited because the control must be located in close proximity to the process measurement. Mechanical systems are also incapable of handling larger flow fluctuations (EPA, 2016 August 31st i). Electric-powered valves are only reliable with a constant supply of electricity. These controllers can achieve 100% reduction in emissions where applicable.

6.7.4 NSPS (OOOOa) requirement for pneumatic controllers

The 2016 New EPA's Source Performance Standard (NSPS) Subpart OOOOa requires operators the following for all existing reciprocating compressors in all four segments of the oil and gas sector, from wellheads to gas distribution systems. The full requirements are given in § 60.5380a of the 40 CFR Part 60, Subpart OOOOa, (Standards of Performance for Crude Oil and Natural Gas Facilities for which Construction, Modification or Reconstruction Commenced After September 18, 2015, (https://www.law.cornell.edu/cfr/text/40/60.5390a) which is as follows:

> For each pneumatic controller affected facility you must comply with the GHG and VOC standards, based on natural gas as a surrogate for GHG and VOC, in either paragraph (b)(1) or (c)(1) of this section, as applicable. Pneumatic controllers meeting the conditions in paragraph (a) of this section are exempt from this requirement.
>
> (a) The requirements of paragraph (b)(1) or (c)(1) of this section are not required if you determine that the use of a pneumatic controller affected facility with a bleed rate greater than the applicable standard is required based on functional needs, including but not limited to response time, safety and positive actuation. However, you must tag such pneumatic controller with the month and year of installation, reconstruction or modification, and identification information that allows traceability to the records for that pneumatic controller, as required in § 60.5420a(c)(4)(ii).
>
> (b)
> (1) Each pneumatic controller affected facility at a natural gas processing plant must have a bleed rate of zero.
> (2) Each pneumatic controller affected facility at a natural gas processing plant must be tagged with the month and year of installation, reconstruction or modification, and identification information that allows traceability to the records for that pneumatic controller as required in § 60.5420a(c)(4)(iv).

(c)

(1) Each pneumatic controller affected facility at a location other than at a natural gas processing plant must have a bleed rate less than or equal to 6 standard cubic feet per hour.

(2) Each pneumatic controller affected facility at a location other than at a natural gas processing plant must be tagged with the month and year of installation, reconstruction or modification, and identification information that allows traceability to the records for that controller as required in § 60.5420a(c)(4)(iii).

(d) You must demonstrate initial compliance with standards that apply to pneumatic controller affected facilities as required by § 60.5410a(d).

(e) You must demonstrate continuous compliance with standards that apply to pneumatic controller affected facilities as required by § 60.5415a(d).

(f) You must perform the reporting as required by § 60.5420a(b)(1) and (5) and the recordkeeping as required by § 60.5420a(c)(4).

6.8 Leak Detection And Repair (LDAR)

6.8.1 Introduction

Leak detection and repair (EPA, 2007 October) is a work practice designed to identify leaking equipment so that emissions can be reduced through repairs. LDAR programs are focussing on VOC's and use EPA's Method 21 (see also section 6.8.2).
A component that is subject to LDAR requirements must be monitored at specified, regular intervals to determine whether or not it is leaking. Any leaking component must then be repaired or replaced within a specified time frame.

A leak is detected whenever the measured concentration exceeds the threshold standard for the applicable regulation. Leak definitions vary by regulation, component type, service (e.g. light liquid, heavy liquid, gas/vapor, etc.) and monitoring interval.
Most NSPS (New Source Performance Standards) heave a leak detection of 10.000 ppm. Many NESHAP (National Emission Standards for Hazardous Air Pollutants) use a 500 or 1000 ppm. May equipment leak regulations also define a leak based on visual inspections an observations (such as fluid dripping, spraying, misting or clouding from the around components, sound (such as hissing), and smell.
The LDAR requirements specify weekly visual inspections of pumps, agitators, and compressors for indicating of liquids from the seals of turbo compressors.

When the LDAR requirements were developed, EPA estimated that petroleum refineries could reduce emissions from equipment leaks by 63% by implementing a facility LDAR program. Additionally, EPA estimated that chemical facilities could reduce VOC emissions by 56% by implementing such a program. The benefits of an LDAR program are:

- Increasing Safety for Facility Workers and Operators.
- Decreasing Exposure for the Surrounding Community.
- Reducing Product Losses.
- Potentially Reducing Emission Fees.
- Avoiding Enforcement Actions.

The EPA has determined that leaking equipment, such as valves, pumps, and connectors, are the largest source of emissions of volatile organic compounds (VOCs) and volatile hazardous air pollutants (VHAPs) from petroleum refineries and chemical manufacturing facilities. The Agency has estimated that approximately 70367 tons per year of VOCs and 9357 tons per year of HAPs have been emitted from equipment leaks in the USA.

Emissions from equipment leaks exceed emissions from storage vessels, wastewater, transfer operations, or process vents. VOCs contribute to the formation of ground-level ozone. Ozone is a major component of smog, and causes or aggravates respiratory disease, particularly in children, asthmatics, and healthy adults who participate in moderate exercise. Ozone can be transported in the atmosphere and contribute to nonattainment in downwind areas.

Some species of VOCs are also classified as VHAPs. Some known or suspected effects of exposure to VHAPs include cancer, reproductive effects, and birth defects. The highest concentrations of VHAPs tend to be closest to the emission source, where the highest public exposure levels are also often detected.

Some common VHAPs emitted from refineries and chemical plants include acetaldehyde, benzene, formaldehyde, methylene chloride, naphthalene, toluene, and xylene.

A portable instrument is used to detect VOC leaks from individual sources. EPA does not specify the instrument detector type but it must meet the specifications and performance criteria as described by EPA. A leak definition concentration based on a reference compound is specified in each applicable regulation. This method is intended to locate and classify leaks only, and is not to be used as a direct measure of mass emission rate from individual sources.

Figure 50 Example of a LDAR measurement

6.8.2 *EPA's Method 21 (EPA, 2007 October)*

To reduce the VOC's emissions, the EPA has developed Method 21 for the determination of VOC for leaks from process equipment. These sources include, but are not limited to, valves, flanges and other connections, pumps and compressors, pressure relief devices, process drains, open-ended valves, pump and compressor seal system degassing vents, accumulator vessel vents, agitator seals, and access door seals.

In general, EPA has found significant widespread noncompliance with Leak Detection and Repair (LDAR) regulations and more specifically, noncompliance with EPA's Method 21 requirement.

In 1999, EPA estimated that, as a result of this noncompliance, an additional 40,000 tons of VOCs are emitted annually from valves at petroleum refineries in the USA alone. The EPA has released a best practice document in 2007 "Leak detection and Repair, A Best Practice, EPA October 2007". This document is intended for use by regulated entities as well as compliance inspectors to identify some of the problems identified with LDAR programs focusing on EPA's Method 21 requirements and describe the practices that can be used to increase the effectiveness of an LDAR program. Specifically, this document explains:

- The importance of regulating equipment leaks.
- The major elements of an LDAR program.

- Typical mistakes made when monitoring to detect leaks.
- Problems that occur from improper management of an LDAR program.
- A set of best practices that can be used to implement effective an LDAR program.

The document is very comprehensive, easy to use and describes all important steps which are necessary to carry out an adequate LDAR program. This Best Practice document (ldarguide.pdf) is strongly recommended and can be found on EPA's website: http://epa.gov/sites/production/files/2014 02/documents

6.8.3 Sources, causes and control of equipment leak

Table 3.1 of the EPA's Best Practice Document is shown in Figure 51 and shows the primary sources of emissions from components subject to equipment leak regulations. In a typical facility, most of the emissions are from valves and connectors because these are the most prevalent components and can number in the thousands. The major cause of emissions from valves and connectors is seal or gasket failure due to normal wear or improper maintenance.

Previous EPA studies have estimated that valves and connectors account for more than 90% of emissions from leaking equipment with valves being the most significant source as shown in Figure 52 (Table 3.1 of the Best Practices document). Newer information suggests that open-ended lines and sampling connections may account for as much as 5-10% of total VOC emissions from equipment leaks.

Table 3.1 – Sources of equipment leaks.

Pumps are used to move fluids from one point to another. Two types of pumps extensively used in petroleum refineries and chemical plants are centrifugal pumps and positive displacement, or reciprocating pumps.	**Leaks from pumps** typically occur at the seal.
Valves are used to either restrict or allow the movement of fluids. Valves come in numerous varieties and with the exception of connectors, are the most common piece of process equipment in industry.	**Leaks from valves** usually occur at the stem or gland area of the valve body and are commonly caused by a failure of the valve packing or O-ring.
Connectors are components such as flanges and fittings used to join piping and process equipment together. Gaskets and blinds are usually installed between flanges.	**Leaks from connectors** are commonly caused from gasket failure and improperly torqued bolts on flanges.
Sampling connections are utilized to obtain samples from within a process.	**Leaks from sampling connections** usually occur at the outlet of the sampling valve when the sampling line is purged to obtain the sample.
Compressors are designed to increase the pressure of a fluid and provide motive force. They can have rotary or reciprocating designs.	**Leaks from compressors** most often occur from the seals.
Pressure relief devices are safety devices designed to protect equipment from exceeding the maximum allowable working pressure. Pressure relief valves and rupture disks are examples of pressure relief devices.	**Leaks from pressure relief valves** can occur if the valve is not seated properly, operating too close to the set point, or if the seal is worn or damaged. Leaks from rupture disks can occur around the disk gasket if not properly installed.
Open-ended lines are pipes or hoses open to the atmosphere or surrounding environment.	**Leaks from open-ended lines** occur at the point of the line open to the atmosphere and are usually controlled by using caps, plugs, and flanges. Leaks can also be caused by the incorrect implementation of the block and bleed procedure.

Figure 51 Summary of sources of equipment leaks (source: Table 3.1 of the EPA's Best Practice Document [1]Leak detection and Repair, A Best Practice" (EPA 2007 October)

Table 3.3 – Uncontrolled VOC emissions at a typical facility.

Component	Average Uncontrolled VOC Emissions (ton/yr)	Percent of Total Emissions
Pumps	19	3
Valves	408	62
Connectors	201	31
Open-ended lines	9	1
Sampling connections	11	2
Pressure relief valves	5	1
Total	653	

Source: Emission factors are from Protocol for Equipment Leak Emission Estimates, EPA-453/R-95-017, Nov 1995, and equipment counts in Table 3.2.

More recent data indicates that open-ended lines and sampling connections each account for approximately 5-10% of total VOC emissions.

Figure 52 Summary of uncontrolled VOC emissions at a typical facility (source: Table 3.2 of (EPA 2007 October))

6.8.4 *How are emissions from equipment leaks reduced?*

Facilities can control emissions from equipment leaks by implementing a leak detection and repair (LDAR) program or by modifying/replacing leaking equipment with leak free components. Most equipment leak regulations allow a combination of both control methods.

Leaks from open-ended lines, compressors, and sampling connections are usually fixed by modifying the equipment or component. Emissions from pumps and valves can also be reduced through the use of leak free valves and pumps without seals. Common leak free valves include bellows type valves of which an example is shown in Figure 53 and diaphragm valves of which an example is shown in Figure 54. Common pumps without seals are diaphragm pumps, canned motor pumps, and magnetic drive pumps. Leaks from pumps can also be reduced by using dual seals with or without barrier fluid.

Leak free valves and pumps without seals are effective at minimizing or eliminating leaks, but their use may be limited by materials of construction considerations and process operating conditions. Installing leak free and equipment without seals may be a wise choice for replacing individual, chronic leaking components.

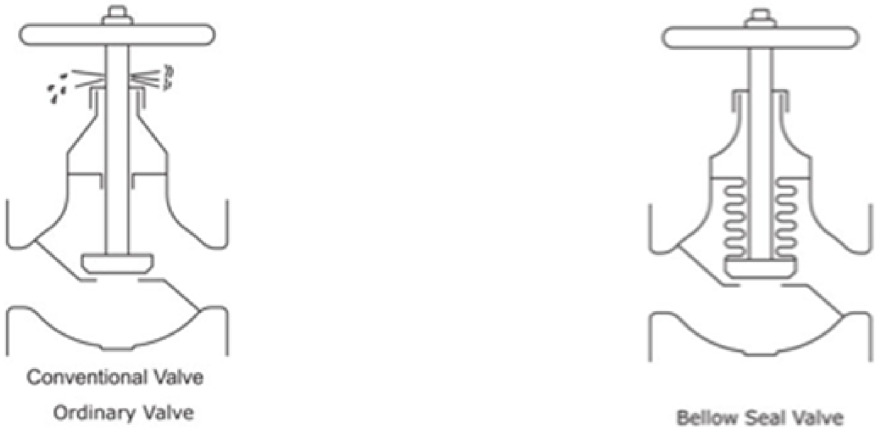

Figure 53 Example of a normal valve (left) and bellow type valve (right) (source: Bellow Seal)

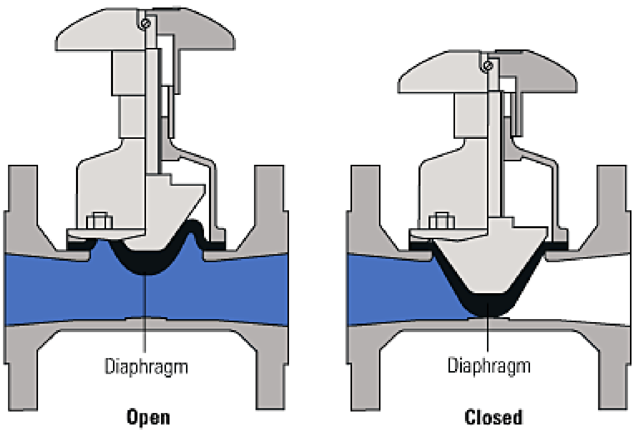

Figure 54 Example of a diaphragm type valve (source: IEEE)

6.8.5 *What regulations incorporate LDAR programs?*

LDAR programs are required by many New Source Performance Standards (NSPS), National Emission Standards for Hazardous Air Pollutants (NESHAP), State Implementation Plans (SIPs), the Resource Conservation and Recovery Act (RCRA), and other state or local requirements. Annex A gives the table with 25 federal regulations that require a formal LDAR program with method 21. Annex B gives the 28 other federal regulations that require some Method 21 monitoring, but do not require LDAR programs to be in place.

NSPS (40 CFR Part 60) equipment leak standards are related to fugitive emissions of VOCs and apply to stationary sources that commence construction, modification, or reconstruction after the date that an NSPS is proposed in the Federal Register. NESHAP (40 CFR Parts 61, 63, and 65) equipment leak standards apply to both new and existing stationary sources of fugitive VHAPs.

RCRA (40 CFR Parts 264 and 265) equipment leak standards apply to hazardous waste treatment, storage, and disposal facilities. In the USA many state and local air agencies incorporate federal LDAR requirements by reference, but some have established more stringent LDAR requirements to meet local air quality needs.

6.8.6 Elements of an LDAR program

The requirements among the regulations vary, but all LDAR programs consist of the following five basic elements:

1. Identifying components.
2. Leak detection.
3. Monitoring components.
4. Repairing components.
5. Recordkeeping.

All these elements are discussed in detail in Section 5 of the Best Practice (BP) document (EPA, 2007 October). For each element, Section 5 outlines the typical LDAR program requirements, common compliance problems, problems found through field inspections, and a set of best practices used by facilities with effective LDAR programs.

6.9 Direct Inspection and Maintenance at Compressor Stations (DI&M) (EPA, 2016 August 31st j; EPA, 2016 August 31st k)

6.9.1 Introduction

Implementing a directed inspection and maintenance (DI&M) program is a proven, cost-effective way to detect, measure, prioritize, and repair equipment leaks to reduce *methane* emissions. A DI&M program begins with a baseline survey to identify (see section 5.3.3 for methods) and quantify leaks (see 5.3.4 for methods). Repairs that are cost-effective to fix are then made to the leaking components. Subsequent surveys are based on data from previous surveys, allowing operators to concentrate on the components that are most likely to leak and are profitable to repair.

Baseline surveys of Natural Gas STAR partners transmission compressor stations found that the majority of fugitive methane emissions are from a relatively small number of leaking components. Data collected from Natural Gas STAR partners demonstrates that 95 percent of these methane emissions are from 20 percent of the leaky components at compressor stations.

A DI&M program at compressor stations can reduce methane emissions and yield significant savings by locating leaking components and focusing maintenance efforts *on the largest leaks* that are profitable to repair. Subsequent emissions surveys are directed towards the site components that are most likely to leak, as well as cost-effective to find and fix.

DI&M programs begin with a comprehensive baseline survey of all equipment components at the compressor stations. Operators first *identify* leaking components and then *measure* the emissions rate for each leak. The repair cost for each leak is evaluated with respect to the expected gas savings and other economic criteria such as payback period. The initial leak survey results and equipment repairs are then used to direct subsequent inspection and maintenance efforts.

The main differences of an DI&M and LDAR program are:

- DI&M is used mainly for methane and LDAR is used for VOC's (according EPA's method 21).
- LDAR is only a leak detection method (exceeding a certain threshold value, or visible observations). DI&M first identifies a leak and also measures for each leak the emissions rate.

6.9.2 Steps in a DI&M program

A DI&M program is implemented in four steps:

1. Conduct a baseline survey.
2. Record the results and identify candidates for cost-effective repair.
3. Analyse the data, make the repairs, and estimate methane savings.
4. Develop a survey plan for future inspections and follow-up monitoring of leak-prone equipment.

Step 1: Conduct a baseline survey

A DI&M program typically begins with baseline screening to identify leaking components. As the leaking components are located, accurate leak rate measurements are obtained using bagging techniques, a high volume sampler, or Toxic Vapor Analysers that have site-specific concentration correlations. Companies have found that leak measurement using a high volume sampler is cost-effective, fast, and accurate. More detailed information on leak detection instruments can be found in section 5.3.3.

A baseline survey that focuses only on leak screening is substantially less expensive. However, leak screening alone does not provide the information needed to make cost-effective repair decisions. Partners have found that follow-up surveys in an ongoing DI&M program cost 25-40% less than the initial survey because subsequent surveys focus only on the components that are likely to leak and are economic to repair. For some equipment components, leak screening and measurement can be accomplished most efficiently during a regularly scheduled DI&M survey program. For other components, simple and rapid leak screening can be incorporated into ongoing operation and maintenance procedures. Some operators train maintenance staff to conduct leak surveys, others hire outside consultants to conduct the baseline survey.

Step 2: Record results and identify candidates for repair

Leak measurements collected in Step 1 must be evaluated to pinpoint the leaking components that are cost-effective to repair. Leaks are prioritized by comparing the value of the natural gas lost with the estimated cost in parts, labour, and equipment downtime to fix the leak. Some leaks can be fixed on the spot by simply tightening a connection. Other repairs are more complicated and require equipment downtime or new parts. For these repairs, operators may choose to attach identification markers, so that the leaks can be fixed later if the repair costs are warranted. Repair costs for components such as valves, flanges, connections, and open-ended lines are likely to be determined by the size of the component, with repairs to large components costing more than repairs to small components. Some large leaks may be found on equipment normally scheduled for routine maintenance, in which case the maintenance schedule may be advanced to repair the leak at no additional cost.

As leaks are identified and measured, operators should record the baseline leak data so that future surveys can focus on the most significant leaking components. The results of the DI&M survey can be tracked using any convenient method or format.

The information that operators may choose to collect include:

- An identifier for each leaking component.
- The component type (for example, blowdown open ended line).
- The measured leak rate.
- The survey date.
- The estimated annual gas loss.
- The estimated repair cost.

This information will direct subsequent emissions surveys, prioritize future repairs, and track the methane savings and cost-effectiveness of the DI&M program.

Step 3: Analyse data and estimate savings
Cost-effective repair is a critical part of successful DI&M programs because the greatest savings are achieved by targeting only those leaks that are profitable to repair. In all cases, the value of the gas saved must exceed the cost to find and fix the leak. Partners have found that an effective way to analyse baseline survey results is to create a table listing all leaks, with their associated repair cost, expected gas savings, and expected life of the repair. Using this information, economic criteria such as net present value or payback period can be easily calculated for each leak repair. Partners can then decide which leaking components are economic to repair.

Step 4: Develop a Survey Plan for Future DI&M
The final step in a DI&M program is to develop a survey plan that uses the results of the initial baseline survey to direct future inspection and maintenance practices. The DI&M program should be tailored to the needs and existing maintenance practices of the facility.

An effective DI&M survey plan should include the following elements:

- A list of components to be screened and tested, as well as the equipment components to be excluded from the survey.
- Leak screening and measurement tools and procedures for collecting, recording, and accessing DI&M data.
- A schedule for leak screening and measurement.
- Economic guidelines for leak repair.
- Results and analysis of previous inspection and maintenance efforts which will direct the next DI&M survey.

Operators should develop a DI&M survey schedule that achieves maximum cost-effective methane savings yet also suits the unique characteristics of a facility (e.g., the age of the compressors, the number and size of reciprocating and centrifugal compressors in service, the line pressure and the fuel gas pressure). Some companies schedule DI&M surveys based on the anticipated life of repairs made during the previous survey. Others base the frequency of follow up surveys on maintenance cycles or the availability of resources. Since a DI&M program is flexible, if subsequent surveys show numerous large or recurring leaks, the operator can increase the frequency of the DI&M follow-up surveys. Follow-up surveys may focus on components repaired during previous surveys, or on the classes of components identified as most likely to leak.

The potential gas savings from implementing DI&M programs at compressor stations will vary depending on the size, age, equipment, and operating characteristics of the compressor stations. Natural Gas STAR partners have found that the initial expense of a baseline survey is quickly recovered in gas savings (EPA, 2016 August 31st j).

Lessons Learned of DI&M programs
DI&M programs can reduce survey costs and enhance profitable leak repair. Targeting problem stations and components saves time and money needed for future surveys and helps identify priorities for a leak repair schedule.

The principal lessons learned from Natural Gas STAR partners are:

- A relatively small number of large leaks contribute most of a compressor station's fugitive emissions.
- Screening concentrations do not accurately identify the largest leaks, nor do they provide the information needed to identify which leaks are cost-effective to repair. Effective leak measurement techniques must be used to obtain accurate leak rate data.
- A cost-effective DI&M program will target the components that are most likely to leak and are economic to repair.
- Natural Gas STAR partners have also found that some compressor stations are more leak-prone than others. Tracking of DI&M results may show that some compressor stations may need more frequent follow-up surveys than other stations.
- Partners have found it useful to look for trends, asking questions such as "Do gate valves leak more than ball valves?" and "Does one station leak more than another?"
- Re-screen leaking components after repairs are made confirms the effectiveness of the repair. A quick way to check the effectiveness of a repair is to use the soap screening method.
- Institute a "quick fix" step that involves making simple repairs to simple problems (e.g., loose nut, valve not fully closed) during the survey process.
- Develop a system for repairing the most severe leaks first, incorporating repair of minor leaks into regular O&M practices.
- Focus future surveys on stations and components that leak most.
- Record methane emissions reductions at each compressor station and include annualized reductions in Natural Gas STAR Program reports.

6.9.3 Economic replacement considerations. Adapted from NG Star (EPA, 2014 August 31st) and Technical Guidance Documents (CCAC, n.d.)

An example of the economic replacement of a piston rod packing is given by: (EPA, 2016 August 31st e). The economics of this mitigation technology include equipment replacement costs and gas savings by leak reduction. Replacing/maintaining reciprocating compressor equipment is considered economical based on results of a cost-benefit analysis of the value of gas saved (based on leak measurement) and expected costs associated with equipment maintenance/replacement. When determining the associated costs related to equipment maintenance/replacement, the costs associated with production stops shall considered if such stops are required to carry out the replacement.

The equipment replacement costs vary among different reciprocating compressor components. For packing rings, the number of compressor cylinders, number of cups per cylinder, and the ring material determine the cost of replacement. Piston rods might also need replacing, depending on condition. Worn (pitted, corroded, out-of-round) rods will also shorten the life of rings. The payback period of this replacement will vary depending on the expected leak reduction value.

Once the expected leak reduction and cost of replacements have been determined, Partners can determine an “economic replacement threshold” that will indicate when replacing packing rings (and rods, if necessary) is cost-effective. A simple method is to apply discounted cash flow principles to calculate the economic replacement (ER) threshold. This can be calculated with the following equation:

$$\mathrm{Er} = \frac{\mathrm{C_r D_f}}{\mathrm{HG_p}} \; [\mathrm{m^3/hr}]$$

Where:

E_r = Economic replacement (Nm^3/hr)
C_r = Cost of replacement (Euro)
D_f = Discount factor (-)
H = Hours of compressor operation per year
G_p= Gas price ($Euro/m^3$).

The discount factor term is used for capital recovery for equal annual revenues and is calculated using the following equation:

$$D_f = \frac{i(1+i)^n}{(1+i)^n - 1}$$

Where:

i = discount rate (expressed as a decimal).
n = the payback period selected in year

Assuming a packing ring replacement cost of Euro 1620, plus an equal cost for labour, the calculated leak reduction that will be economic for payback periods (n) of 1, 2, 3, 4 and 5 years at a discount rate of 10% (i = 0.1) is shown in Table 6.3. For this example, the Euro 1620 ring replacement costs plus Euro 1620 labour costs can be paid back in one year with an expected leak reduction of 0.89 m^3/hr.

For additional information, see the Natural Gas STAR technical Document: “Reducing Methane Emissions from Compressor Rod Packing Systems” (https://www.epa.gov/sites/production/files/2016-06/documents/ll_rodpack.pdf) (EPA, 2016 August 31st e)

Table 6.3 Example of an economic replacement threshold for packing rings

Expected leak reduction (m3/hr)	**Payback period (years)**
0.89	1
1.78	2
2.67	3
3.56	4
4.45	5

6.9.4 Example of a DI&M project (Lechtenböhmer et al., 2007)

In 2003 a comprehensive measurement campaign of the Russian Northern and Central export pipelines was carried out by Wuppertal Institute in cooperation with Max- Planck Institute for Chemistry (with support of Gazprom, E.ON-Ruhrgas and VNIIGAZ Institute). The purpose of the campaign was to close the gaps in the available data and improve the knowledge of the methane emissions from the gas export grid in Russia (Lechtenböhmer et al., 2007). Based on the results of the measurement campaign, this paper surveys the existing options for mitigation actions. The extensive works of the Natural Gas STAR International Program, a voluntary partnership between the US EPA and natural gas operators to reduce methane emissions, illustrate that gas capture projects are profitable due to the increased throughput and increased efficiency.

It was shown that unintentional leaks from the natural gas infrastructure account for 66.5% of methane losses from Russia's gas transmission including compressor seal emissions. The majority of the methane is lost by a small number of components. For example, leak survey results from 13 compressor stations found that 0.5% of the components caused more than 90% of the emissions. Leak inspections can take advantage of this finding.

Periodic inspections can be directed only at problem areas specific to a facility where significant leaks can be found that are cost-effective to repair. This mitigation option requires an investment for inspection and for repair of any discovered leaks. Both are largely labour costs and usually provide very quick paybacks on the investment (less than 12 months) if the volume of gas saved is quantified and a value assigned to it.

The Rusagas Carbon Offset Project between TransCanada and Gazprom performed directed inspection and maintenance at two Russian compressor stations, where they achieved emission reductions of about 50% as a test for possible Joint Implementation-projects (Venugopal, 2003). In addition, Cherkasy Transgas of Ukraine achieved reductions of almost two third at two compressor stations (Mandra and Novakivska, 2003). Robinson et al. (2003) give a 13% reduction, based on Natural Gas STAR International company experience and they estimate the costs for the Russian situation at only 0.2 US$ per tonne of CO2 equivalent reduced. The total potential for Russia estimated by Venugopal (2003) is more than 400×10^6 m^3 gas per year. Regarding the approximately 249×10^6 m^3 gas per year emitted from leakages at compressors and intersections at pipelines the total potential might be even bigger.

6.10 References

(CCAC) Climate & Clean Air Coalition. (n.d.). Oil and Gas Methane Partnership Technical Guidance Documents. Retrieved July 9, 2018, from http://ccacoalition.org/en/content/oil-and-gas-methane-partnership-technical-guidance-documents

(CCAC) Climate & Clean Air Coalition. (2017). *Technical Guidance Document Number 4: Reciprocating Compressors Rod Seal/Packing Vents*. Retrieved from http://www.ccacoalition.org/en/resources/technical-guidance-document-number-4-reciprocating-compressors-rod-sealpacking-vents

(EPA) Environmental protection agency. (2007 October). *Leak Detection and Repair: A Best Practices Guide*. Retrieved from https://permanent.access.gpo.gov/gpo9828/ldarguide.pdf

(EPA) Environmental protection agency. (2014, April). *Comments: Oil and Natural Gas Sector Pneumatic Devices Report for Oil and NATURAL Gas Sector Pneumatic Devices, Review Panel 2014"*, Prepared by U.S. EPA Office of Air Quality Planning and Standards (OAQPS).

(EPA) Environmental protection agency. (2014, June 16th). *Comments: White papers on methane and VOC emissions in the oil and natural gas sector*. Retrieved from https://www.nrdc.org/sites/default/files/ene_14061901a.pdf

(EPA) Environmental protection agency. (2016 August 31st c). *Install Electric Compressors*. Retrieved from https://www.epa.gov/natural-gas-star-program/install-electric-compressors

(EPA) Environmental protection agency. (2016 August 31st d). *Install Electric Motor Starters*. Retrieved from https://www.epa.gov/natural-gas-star-program/install-electric-motor-starters

(EPA) Environmental protection agency. (2016 August 31st e). *Reducing Methane Emissions from Compressor Rod Packing Systems*. Retrieved from https://www.epa.gov/natural-gas-star-program/reducing-methane-emissions-compressor-rod-packing-systems

(EPA) Environmental protection agency. (2016 August 31st f). *Replace Compressor Cylinder Unloaders*. Retrieved from https://www.epa.gov/natural-gas-star-program/replace-compressor-cylinder-unloaders

(EPA) Environmental protection agency. (2016 August 31st g). *Replacing Wet Seals with Dry Seals in Centrifugal Compressors, Lessons Learned*. Retrieved from https://www.epa.gov/natural-gas-star-program/replacing-wet-seals-dry-seals-centrifugal-compressors

(EPA) Environmental protection agency. (2016 August 31st h). *Reducing Emissions When Taking Compressors Off-Line*. Retrieved from https://www.epa.gov/natural-gas-star-program/reducing-emissions-when-taking-compressors-line

(EPA) Environmental protection agency. (2016 August 31st i). *Convert Gas Pneumatic Controls to Instrument Air, Lessons Learned*. Retrieved from https://www.epa.gov/natural-gas-star-program/convert-gas-pneumatic-controls-instrument-air

(EPA) Environmental protection agency. (2016 August 31st j). *Directed Inspection and Maintenance at Compressor Stations*. Retrieved from https://www.epa.gov/natural-gas-star-program/directed-inspection-and-maintenance-compressor-stations

(EPA) Environmental protection agency. (2016 August 31st k). *Directed Inspection and Maintenance at Gas Processing Plants and Booster Stations*. Retrieved from https://www.epa.gov/natural-gas-star-program/directed-inspection-andhttps://www.epa.gov/natural-gas-star-program/directed-inspection-and-maintenance-gas-processing-plants-and-booster-maintenance-compressor-stations

(EPA) Environmental protection agency. (2016, August 31st a). *Factsheet 101: Replace Gas Starters with Air or Nitrogen*. Retrieved from https://www.epa.gov/natural-gas-star-program/replace-gas-starters-air-or-nitrogen

(EPA) Environmental protection agency. (2016, August 31st b). *Factsheet 102: Reduce Natural Gas Venting with Fewer Compressor Engine Startups and Improved Engine Ignition*. Retrieved from https://www.epa.gov/natural-gas-star-program/reduce-natural-gas-venting-fewer-compressor-engine-startups-and-improved

(EPA) Environmental protection agency. (2017, May 4). *Recommended Technologies to Reduce Methane Emissions.* Retrieved June 29, 2018, from https://www.epa.gov/natural-gas-star-program/recommended-technologies-reduce-methane-emissions

Armendariz, A. (2009). *Emissions from Natural Gas Production in the Barnett Shale Area and Opportunities for Cost-Effective Improvements*. Retrieved from https://www.edf.org/sites/default/files/9235_Barnett_Shale_Report.pdf

Cap-Op Energy. (2013). *Alberta's upstream oil and gas assets inventory study: Opportunities to reduce greenhouse gas emissions at existing distributed facilities*. Retrieved from http://www.capopenergy.com/uploads/1/1/7/8/11781696/alberta_upstream_inventory_report_final_2013.pdf

(GEP) Gas Electric Partnership, *"Fugitive Emissions Control on Reciprocating Compressors"* by Dan Hannon from Ariel Corporation. Retrieved from http://ccacoalition.org/en/content/oil-and-gas-methane-partnership-technical-guidance-documents

GE Workshop. (2012, April 19). *Reducing Emissions Through Retrofitting of High Bleed Devices*. Retrieved July 9, 2018, from https://www.epa.gov/sites/production/files/2016-04/documents/giernoth.pdf

GMRC Conference (2016) *"Packing Vent Monitoring System"* Paper number 22 (Atmos Energy)

GMRC Conference (2017) "Baseline Emissions Measurements from Reciprocating Compressor Packing", S. Simons et.al.

GMRC (2017) *Guideline for high - speed reciprocating compressor packages for natural gas transmission & storage applications* (2017)

GRI/EPA (1996 June). *Methane Emissions from the Natural Gas Industry*. Retrieved from https://www.epa.gov/natural-gas-star-program/methane-emissions-natural-gas-industry

INGAA (2014) Comments on EPA Compressor White Paper

Lechtenböhmer, S., Dienst, C., Fischedick, M., Hanke, T., Fernandez, R., Robinson, D., . . . Gillis, B. (2007). Tapping the leakages: Methane losses, mitigation options and policy issues for Russian long distance gas transmission pipelines. *International Journal of Greenhouse Gas Control*, *1*(4), 387-395. Retrieved from https://www.sciencedirect.com/science/article/pii/S1750583607000898

US Forest Service (2011). *Emission reduction techniques for oil and gas activities*. Retrieved from https://www.fs.fed.us/air/documents/EmissionReduction-072011x.pdf

A The "Bigger Picture" of emissions as impacts on climate

A.1 Introduction: a spectrum

The climate aspect to gas emissions is one of the foremost reasons for this report's existence. However, during this chapter, the climate perspective will prove to be much more nuanced and broad than initially expected. In fact, we will find the need to distinguish the prevailing, more catastrophic climate predictions, as *one* mode of the climate perspective. Although this mode has gained large momentum, occupying the mainstream narrative, the exploration of the climate perspective will not begin with one or the other mode. Instead, this chapter will approach the subject as a *spectrum* of varying methods, opinions and predictions.

A.2 Understanding the climate system and temperature predicting

The earth's climate is a complex unbalanced system of many factors. However, one of these factors may be sensitive to compressor emissions: the atmosphere's composition.

The content of earth's atmosphere is influenced by many different human and non-human factors. Currently, the emissions of various substances caused by human activities are known to change the atmosphere's composition. Therefore, humans may affect the chaotic climate systems, which urges scientist and emitters to look more closely into the matter. Since emissions from compressor systems may be significant, this industry too is pressed to get a better understanding of the climate change and human emissions.

A good point to start our discussion is not with CO_2 or the greenhouse effect for that matter. Instead, let's take a step back and see the bigger picture: the *energy flows* in our climate system, as depicted in Figure 55 below. This schematic is explained by a comprehensive climate-science-introduction from a recent paper by three senior climate experts, Happer, Koonin and Lindzen:

> The earth's climate system is a giant heat engine, reflecting about 30% of the incoming sunlight, absorbing the rest, and then radiating an almost equal amount back into space as heat, driving the winds, precipitation, and ocean currents in the process. Note that the natural energy flows are measured in 100's of W/m2 (Watts per square meter) and, as shown in the lower left-hand corner, there is a claimed net imbalance of 0.6 [0.2, 1.0] W/m2 warming the planet. (Happer, Koonin & Lindzen, 2018, p. 3)

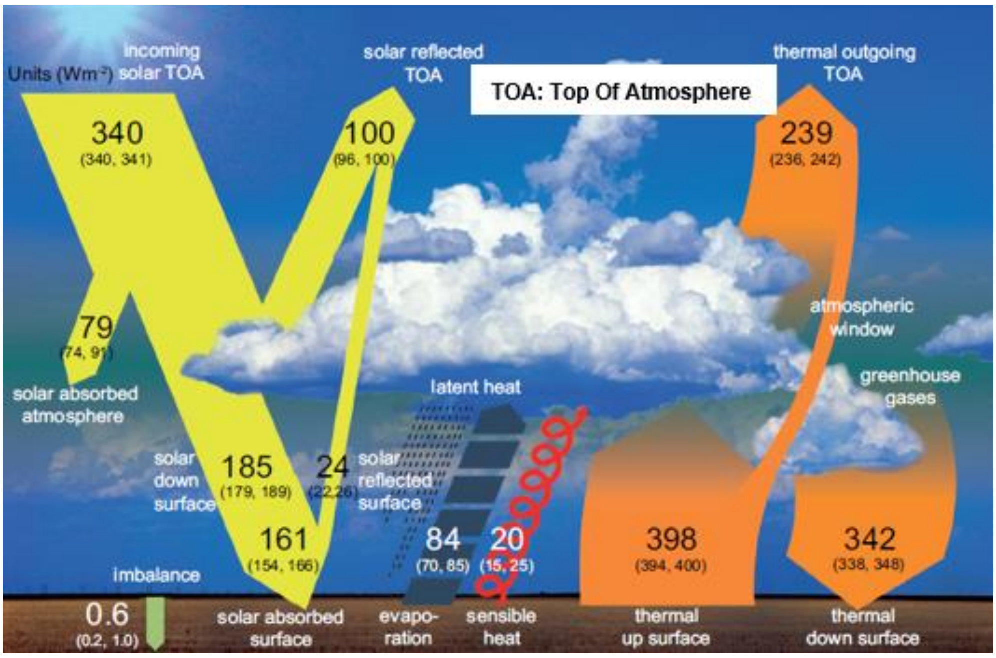

Figure 55 Schematic of the atmosphere's heat and energy system. Units in radiative forcing W/m². (IPCC, 2013, p. 181)

As one can readily see, even from the simplified schematic, this complex climate system is influenced by a *multitude* of factors, only *one* of which the greenhouse effect. In this (in)famous effect, greenhouse gases (GHGs) absorb certain wavelengths of infrared light, causing a conversion into heat i.e., *radiative forcing* (RF) *in W/m²*.

To get a better understanding of Figure 55, we may use its depiction of absolute quantities of energy (in W/m²) to get a sense of the potential and actual human impact on the energy system. Provided by the famous Intergovernmental Panel on Climate Change (IPCC), Figure 56 below shows the nominal radiative forcing (RF) of anthropogenic (human) GHG emissions, since 1750. While the WMGHG (well-mixed greenhouse gases) are thought to have a positive RF, the “Other Anthrop.”-emissions are aerosols that have a negative RF. The cumulative red bar shows, with a 50% error range, that total human emissions since 1750 contributed about 1.1 to 3.4 W/m²: less than 1% of the natural energy flows in the climate system. On the other hand, it should be noticed well that the anthropogenic emissions have rapidly increased during the last century and are still rising. Besides that, the effect is becoming larger due to the accumulation of the emissions.
This anthropogenic RF, combined with all the other factors at play in the atmosphere energy *balance,* contributes to the deficit of 0.6 W/m² depicted in the lower left side in Figure 55.

Note that the terminology of ‘*balance’* does not imply some sort of static equilibrium of the climate system. Instead, the balance of the climate’s energy system is highly elastic and seldomly an exact zero-sum (Happer et al., 2018).

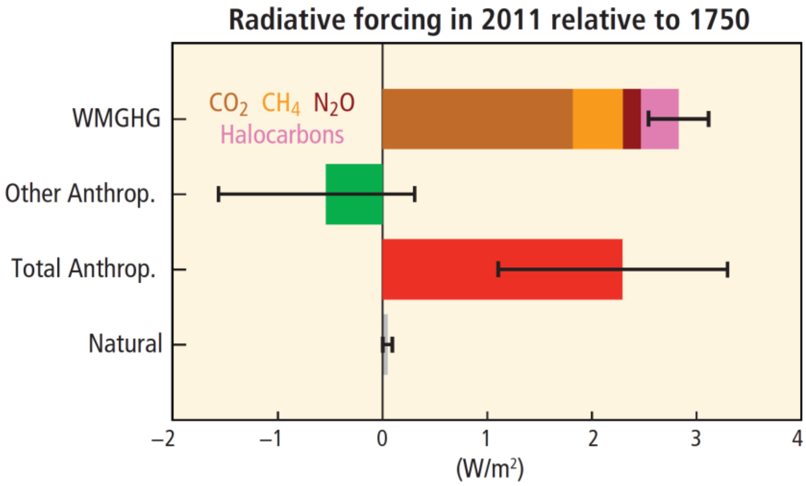

Figure 56 Radiative forcing of climate change during the industrial era (1750-2011). WMGHG are well-mixed greenhouse gases, excluding water vapour (H_2O). (IPCC, 2014, p. 45)

Let us take a second look at the greenhouse effect, for knowing its *existence* is one thing, but gauging its exact *impact* is another. It is precisely on this issue, the estimation of *impact*, where scientists still disagree. Let us therefore analyse how various climate experts consider with the greenhouse effect's *climate impact*.

The greenhouse effect is largely determined by the inherent *properties* and *quantities* of different greenhouse gases. The most important GHGs are water vapour (H_2O), carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The radiative forcing they produce in the atmosphere is determined by their range of infrared light absorption, which are displayed in grey in Figure 57 below.

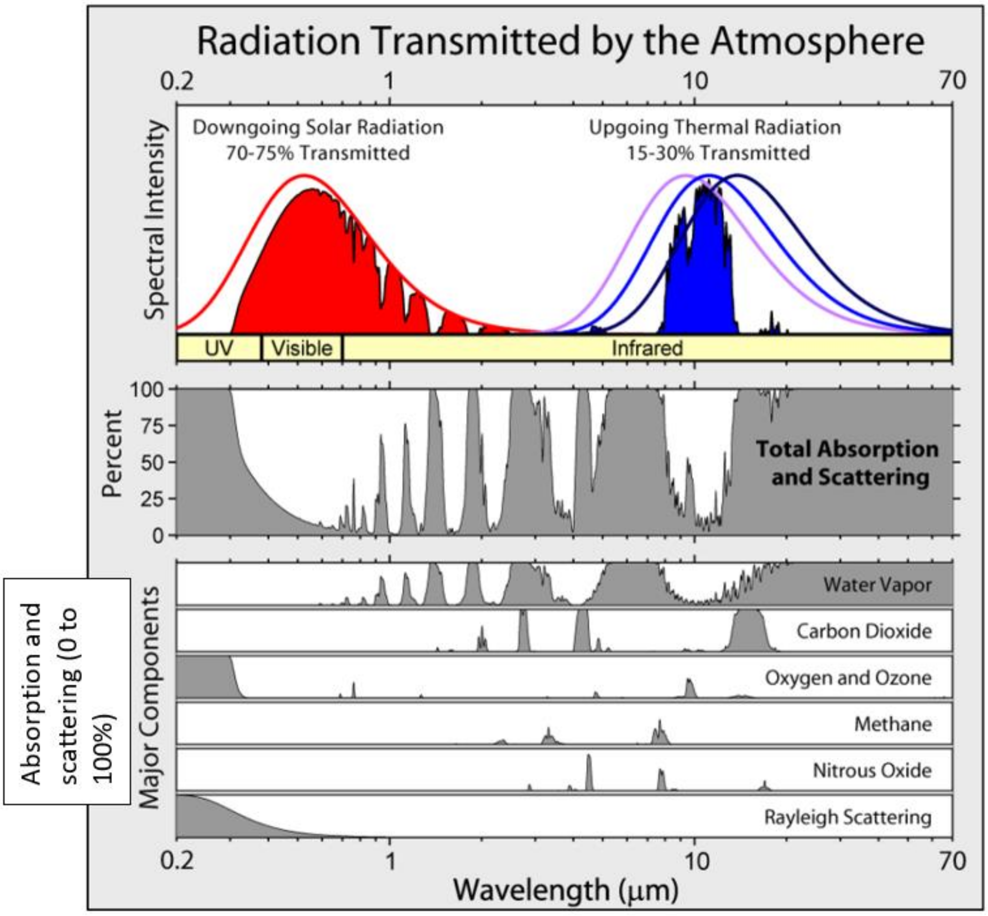

Figure 57 Spectra of main GHG molecules. Most importantly are the grey areas which indicate which parts of the spectra are absorbed by the major GHG gases. The coloured graph is the idealized solar spectrum. Adapted from (Barret Bellamy Climate, n.d.)

As indicated by *water vapour's* large grey surface, it has by far the greatest *absorption range*, which combined with its high *atmospheric concentration* (~1 to 4% of total volume), makes water vapour the most important greenhouse gas. For all other GHGs, both their *absorption range* (the grey area in above figure) and *atmospheric concentrations* are significantly lower. Visualised as pixels below in Figure 58, the ambient carbon dioxide volume concentration is currently 400 ppmv (parts-per-million volume) (0.04% of total volume) while methane concentrations are 1800 ppbv (0.00018% of total volume) (Center for Sience Education, 2012).

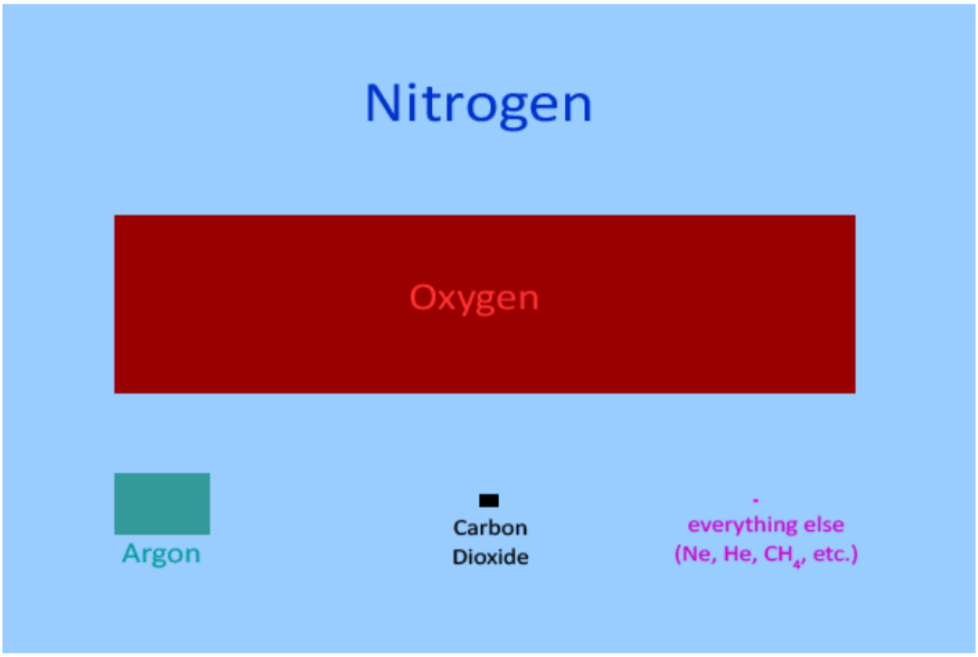

Figure 58 Atmospheric air concentrations in parts per million volume, where volume is visualised in pixels, with one pixel representing one part of the figure's million parts. Nitrogen 78%, oxygen 21%, argon ~1%, carbon dioxide 0.04% (400ppmv) and everything else less than 0.0028% (28 ppmv). Note the exclusion of water vapour, which normally has 1 to 4% of total volume. (Center for Sience Education, 2012)

As such, due to the low atmospheric concentrations of most GHGs and their small absorption ranges, their direct *radiative forcing* (and therefore their climate impact) is quite small, a fact all climate scientists agree upon. They disagree however, on the key issue of the existence of a *positive water vapour feedback mechanism*, a feedback loop which enlarges a small temperature change to a much greater one (Gray, 2016; Lindzen, 2009; Lindzen 2014). Through this positive feedback mechanism, a small increase in RF by the less potent GHGs would increase the earth's humidity, increasing the levels of the most potent GHG (water vapour) and thereby inducing a much more significant RF. It is the existence of this positive feedback mechanism of water vapour on which scientists disagree, and which either *validates* or *rejects* catastrophic temperature predictions.

Attempts to *predict* temperature far into the future is a large part of the contemporary climate- narrative. Such predictions first attempt to estimate radiative forcing changes associated with changing GHG concentrations, and subsequently transpose the radiative forcing into concrete temperature changes. However, each step is associated with decreasing accuracy as assumptions on complex climate mechanisms become more influential. To quantify these predictions, there are several metrics, one popular being the Equilibrium Climate Sensitivity (ECS), which *predicts* what the average temperature change would be for a *doubling* of a certain GHG. The ECS estimated by IPCC models that predict catastrophic temperature increase, range from 1.5°C to 4.5°C (IPCC, 2013). Key to these estimates is the assumption of a *positive* water vapour feedback. This assumption, and more complex parameters, result in the temperature models in Figure 59 below, which shows the IPCC predictions of global average temperature increase for four GHG-concentration scenarios. The IPCC's worst-case scenario (RCP8.5) represents a *tripling* of current GHG concentrations by 2100, resulting in an increased *radiative forcing* of 8.5 W/m^2 resulting in a *global temperature* increase between 2.5°C to 5.5°C (IPCC, 2013). By their same calculations, scenario RCP2.6 shows the estimated temperature change (>1°C) if GHG levels remain close to their current concentrations.

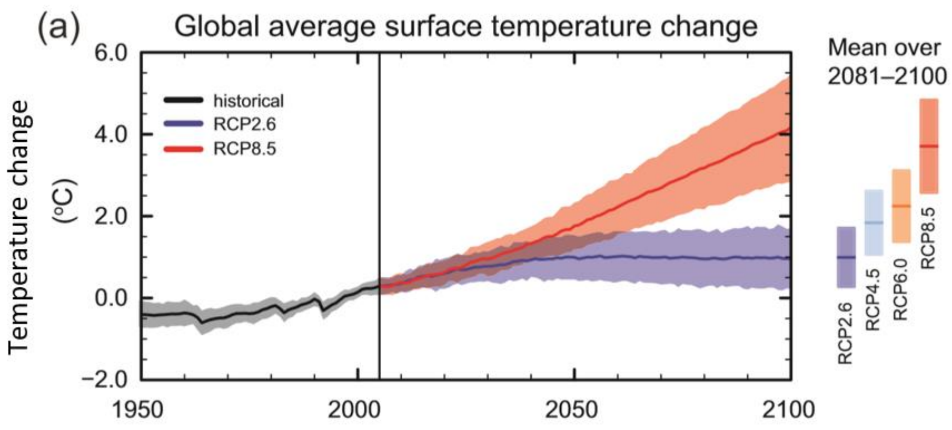

Figure 59 Multi-model simulated time series from 1950 to 2100 for (a) change in global annual mean surface temperature relative to 1986-2005. Assuming a positive water vapour feedback. With RCP8.5 as the worst-case tripling of GHG concentrations. And with RCP2.6 as no further increase in GHG. (IPCC, 2013, p. 21)

However, some scientist like Richard Lindzen and Bill Gray, consider the IPCC's temperature models to be much too sensitive to GHG concentration fluctuations. Lindzen and Gray estimate the climate sensitivity to be much lower, and even suggest the water vapour feedback mechanism to be *negative*, meaning that the warming of the atmosphere results in a de-moisturizing, lowering levels of the most potent GHG, water vapour. This negative feedback mechanism assumes the earth's energy system to be much more stable, and makes for mild warming effects due to human GHG emissions. These experts estimate the ECS (a doubling of GHG concentrations) to be 0.3°C, a great contrast with IPCC's 4.5°C (Lindzen, 2009, 2014). This varied spectrum of temperature predictions is illustrative of the previously mentioned spectrum of climate perspectives, where there are many so-called 'sceptics' who make *non*-catastrophic climate predictions.

However, all climate predictions models are inherently problematic due to the extensive complexity of the climate system. All scientist, 'sceptic' or not, emphasize the uncertainty of models, and even the IPCC stated:

> "In climate research and modelling, we should recognize that we are dealing with a coupled non-linear chaotic system, and therefore that the long-term prediction of future climate states is not possible" (IPCC, 2007, chapter 14.2.2.2).

A.3 Measurements and reduction efforts

Although predictions and models prove inherently difficult, *measurements and data* provide *more* certainty.
Measurements of the global concentrations of current and historical GHG are more accurate than models, and also invoke less debate. Across the varied spectrum of climate perspectives, it is known that the atmospheric concentrations of various GHG are on the rise, with CO_2 concentrations going from 0.018% (180 ppmv) in the pre-industrial era (before the year 1750) , to the current 0.04% (400 ppmv) levels, which is doubled in 170 years (EPA, 2017, January 23rd).

Greenpeace co-founder Patrick Moore affirms that this rise is largely contributable to human activity, and he illustrates that other GHG sources such as the largest recent volcanic eruption of Mount Pinatubo emitted only 2% of annual human-related CO_2 emissions (Moore, 2016). However, there is more to CO_2 emissions than their (negative) role as a GHG. In fact, Moore suggests that human CO_2 emissions has a huge positive aspect, namely that they *helped* prevent a global disaster that had been coming for 140 million years. During this period (exhibited below in Figure 60 as the Cretacrous until Holocene) CO_2 concentrations were on a steady *decline* as carbon was steadily stored from the air into the earth's crust and sea. CO_2 levels went from 0.3% (3000 ppmv) towards the *dangerously low level* of 0.015% (150 ppmv) at which most plant growth is *stunted*, directly threatening all plant-*based* life forms. This deadly decline was reverted when human activities, re-emitted the stored carbon from the earth's crust back into the atmosphere. This increased CO_2 concentrations towards a much more *life sustaining level* while additionally, the mild warming potentially postponed the next cyclical ice-age (Moore, 2016).

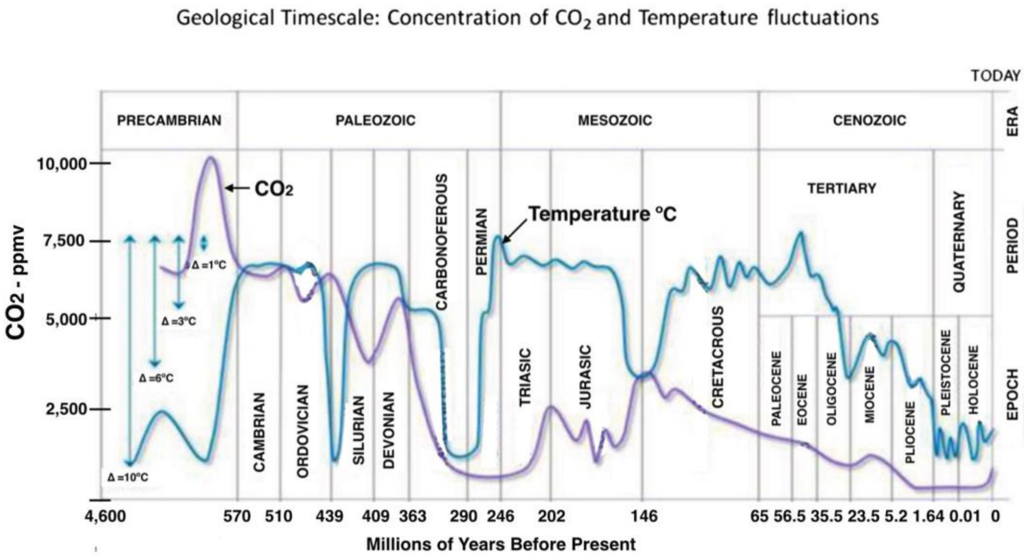

Figure 60 Graph of global temperature and atmospheric CO_2 concentration over the past 600 million years. For context, the Palaeocene period marked the end of the dinosaur's era, while at the end of the Pleistocene period, the first homo sapiens evolved (0,3 million years ago). (Moore, 2016, p.7)

A.4 Methane, VOCs, and Global Warming Potentials (GWP)

Methane is a gas often handled by recips in the natural gas industry, and emissions through leakage and venting are potentially impactful. Let us therefore look at the science behind methane's role in the earth's climate. Our discussion will also provide the opportunity to explore some more climate metrics that attempt to quantify the impact of emissions.

Methane emissions are part of the global methane cycle, which consists of various *sources* and *sinks* that make for a complex and dynamic equilibrium. As shown in the schematic of Figure 61 below, *sources* of methane are both human and non-human while the *removal (sink)* of methane happens primarily through chemical reactions, for example the oxidation of CH_4 into H_2O and CO_2.

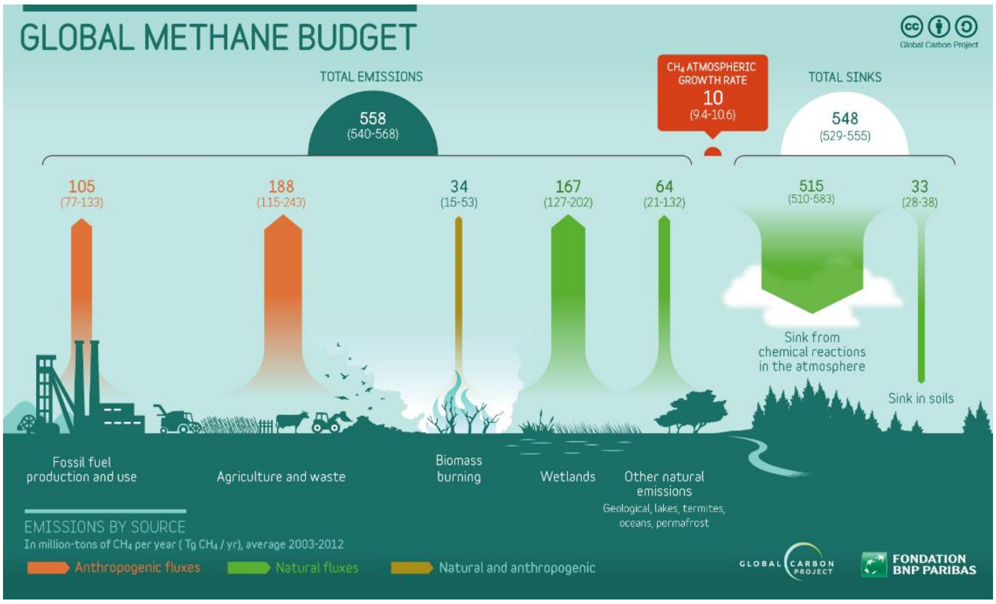

Figure 61 Global methane cycle schematic, in million-tonnes of CH_4 per year, average 2003-2012 (Global Carbon Project, 2016)

As seen in Figure 61 above, currently total methane sources are greater than the sinks, causing a growth in atmospheric concentrations since approximately 1700. This has resulted in a net increase of atmospheric concentrations from 700 ppbv (parts-per-billion volume) (0,00007% of atmospheric air volume) in 1700, to 1860 ppbv (0.000186% of atmospheric air volume) in 2017 (2 °C Institute, n.d.).

In the dominant (IPCC) climate narrative, CO_2 takes the main stage, while *non-carbon-dioxide-GHG* emissions like methane emissions are assessed using the popular metric of Global Warming Potential (GWP). This metric attempts to simplify how the climate is affected by different types of GHG, by comparing it to the climate impact of CO_2 (EPA, 2017, February 14th). Metrics like GWP were initially developed to simplify communication of a complex problem and illustrate how difficult that problem truly was (CMR & GTI, 2018). However, once published, the metrics made their way into mainstream science and government policy, and have been there ever since (CMR & GTI, 2018). Because such metrics are simplifications, which contain many complex parameters, it is crucial to understand their technical basis, and the advantages and disadvantages. Because we have already done the same on the metrics of radiative forcing and Equilibrium Climate Sensitivity (ECS), a nuanced understanding of GWP will be established relatively easily.

Global Warming Potential is defined as "the time-integrated radiative forcing due to a pulse emission of a given component relative to a pulse emission of an equal mass of CO_2" (CMR & GTI, 2018, p. 12). For example, one tonne of CH_4, according to the IPCC, will have the same radiative forcing as 28 tonnes of CO_2 in a 100-year perspective. The climate impact of one tonne methane is then expressed as 28 tonnes CO_2 equivalent ('eq.' or 'e'). Due to the metric's time integration, a short-lived atmospheric gas like methane (lifetime of 12.4 years) will have increased *impact* as the *time horizon* decreases from 100 to 20 years, shown in Figure 62 below. It must be noted that GWP is calculated using the nominal radiative forcing, which passes on its complexities and uncertainties (CMR & GTI, 2018). As such, since the most commonly used GWP values come from the IPCC, they will therefore reflect their respective assumptions, such as the *positive* water vapour feedback mechanism (discussed in Figure 58).

Table A.1 below shows the IPCC's calculated values for the most important GHG on a 20 and 100-year timescale. Most commonly referenced, are the values of the 100-year timeline, which are indicated as GWP100. Additionally, the table shows the metric of Global Temperature Change Potential (GTP), which some believe to be a more accurate metric than GWP (MRC & GRI, 2018). The GTP is the change in global mean surface temperature at a particular point in time in response to an emission pulse relative to that of CO_2 (MRC & GRI, 2018, p. 13). Proponents of the usage of GTP believe it represents more accurately the impact of short-lived species on the climate. However, the GTP introduces even more complex parameters as it models not only the radiative forcing of a given GHG increase, but also the corresponding temperature increase, encouraging over-simplification of the complex climate system (EPA, 2017, February; MRC & GRI, 2018). Although issues like the negativity/positive water vapour feedback mechanism are already interwoven with *GWP* calculations, the *GTP* would rely even more strongly on such complex and disputed issues.

Table A.1 Global warming potentials from the IPCC's fifth assessment report (AR5). (IPCC 2014)

		GWP		GTP	
	Lifetime (yr)	**Cumulative forcing over 20 years**	**Cumulative forcing over 100 years**	**Temperature change after 20 years**	**Temperature change after 100 years**
CO_2	b	1	1	1	1
CH_4	12.4	84	28	67	4
N_2O	121.0	264	265	277	234
CF_4	50,000.0	4880	6630	5270	8040
HFC-152a	1.5	506	138	174	19

The reported values by the IPCC often change for each assessment report (AR) they publish, every 7 years or so. Therefore, one often finds different values across literature and policies. For example, the US EPA still uses the values from AR4, 2007, rather than the table above's values from AR5 2013.

An elaborate list of various GHGs and their GWPs can be found at: http://www.ghgprotocol.org/sites/default/files/ghgp/Global-Warming-Potential-Values%20%28Feb%2016%202016%29_1.pdf

Methane's GWP is shown in more detail in Figure 62 below . Note the importance of the longevity of a compound, which makes GWP values either unchanging, decreasing or increasing over time.

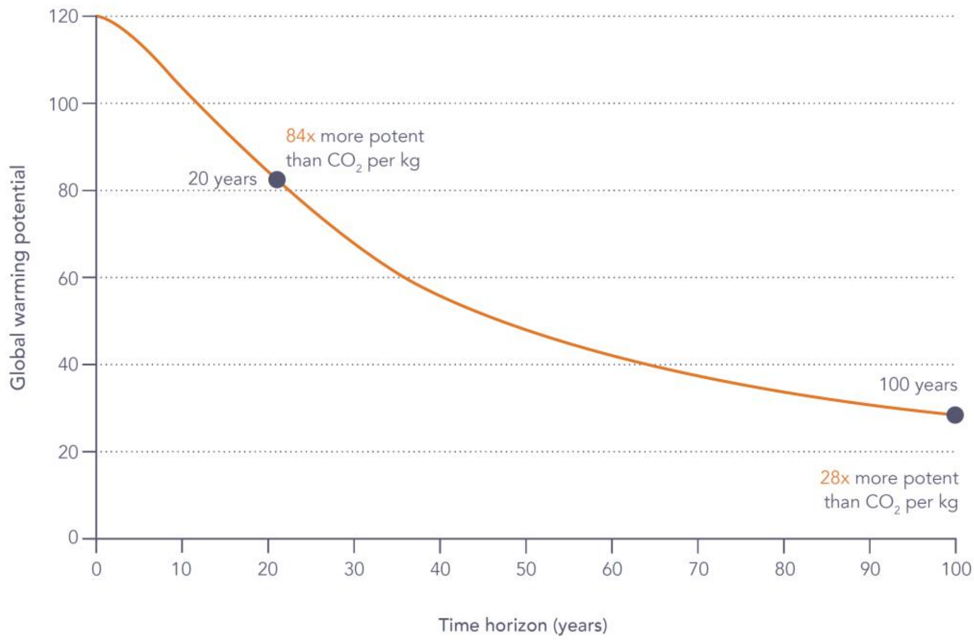

Figure 62 Illustration of the changing GWP of methane over time. (Balcombe, Anderson, Speirs, Brandon & Hawkes, 2015, p. 15)

As a last short topic, we can note the overlap between the categories of greenhouse gasses (GHG) and volatile organic compounds (VOCs). Some VOCs are also a GHG, often with high GWP values, yet due to much lower concentrations they are often less relevant. To be clear, VOC is a category for volatile organic particles, while the GHG category is a classification for particles with a radiative forcing property. Often VOCs are used in both the climate *and* health perspective. Note, however, that VOCs are not *necessarily* detrimental to neither health nor greenhouse gases.

Beside VOCs, there are many more particles that *can* have both a health and climate impact, which is not always a *warming* climate impact. Figure 63 below shows the IPCC's estimates of the effects of reductions ("controls") on ozone pollutants and fine particles (particulate matter). The figure shows that the *reduction* of ozone pollutants like nitrogen oxides and VOCs may cause a *negative* radiative forcing (a cooling effect), just like the reduction of most particulate matter. This illustrates how emissions relating to temperature differ greatly from emissions relating to air quality: sometimes clean air requires emission reductions that increase radiative forcing.

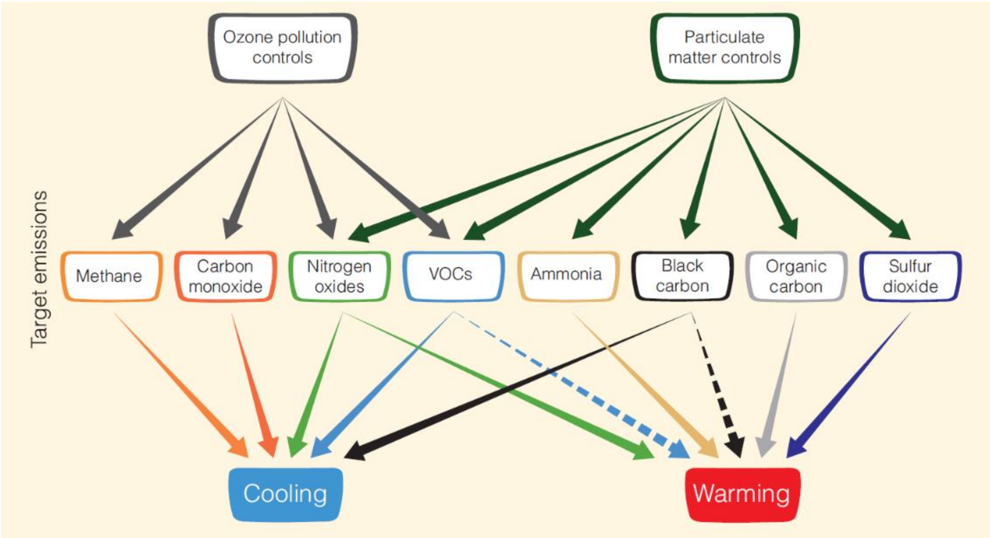

Figure 63 Schematic diagram of the temperature impact of pollution controls (reductions) of smog-causing particulate matter and ozone pollutants. Solid black line indicates known impact; dashed line indicates uncertain impact. (IPCC, 2013, p. 684)

A.5 References

(CMR) Center for Methane Research, & (GTI) Gas Technology Institute. (2018). *An introduction to methane and the center for methane research*. Retrieved from http://www.gastechnology.org/CMR/Documents/Intro_to_Methane_021318.pdf

(EPA) Environmental protection agency. (2017, April 12). Technical Overview of Volatile Organic Compounds. Retrieved March 19, 2018, from https://www.epa.gov/indoor-air-quality-iaq/technical-overview-volatile-organic-compounds

(EPA) Environmental protection agency. (2017, March 16). Initial List of Hazardous Air Pollutants with Modifications. Retrieved March 15, 2018, from https://www.epa.gov/haps/initial-list-hazardous-air-pollutants-modifications

(EPA) Environmental protection agency. (2017, January 23). Atmospheric Concentrations of GHG. Retrieved March 14, 2018, from https://www.epa.gov/climate-indicators/climate-change-indicators-atmospheric-concentrations-greenhouse-gases

(EPA) Environmental protection agency. (2017, February 14). Understanding Global Warming Potentials. Retrieved March 19, 2018, from https://www.epa.gov/ghgemissions/understanding-global-warming-potentials

(EPA) Environmental protection agency. (2017, December 7). Ozone pollution. Retrieved March 20, 2018, from https://www.epa.gov/ozone-pollution

(EPA) Environmental protection agency. (2018, March 8). Criteria Air Pollutants. Retrieved March 15, 2018, from https://www.epa.gov/criteria-air-pollutants

(IPCC) Intergovernmental panel on climate change. (2013). *Climate change 2013: The physical science basis. Working Group I contribution to the IPCC Fifth Assessment Report*. Retrieved from http://www.ipcc.ch/report/ar5/wg1/

(IPCC) Intergovernmental panel on climate change. (2014). *Climate change 2014: Synthesis report. Contribution of working groups I, II and III to the fifth assessment report (AR5) of the intergovernmental panel on climate change.* Retrieved from https://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full.pdf

2 C° Institute. (n.d.). Atmospheric CH4 Levels Graph [Dataset]. Retrieved March 14, 2018, from http://www.methanelevels.org/

Balcombe, P., Anderson, K., Speirs, J., Brandon, N., & Hawkes, A. (2015). *Methane and CO2 emissions from the natural gas supply chain: An evidence assessment*. Retrieved from https://www.sustainablegasinstitute.org/wp-content/uploads/2015/09/SGI_White_Paper_methane-and-CO2-emissions_WEB-FINAL.pdf?noredirect=1

Barret Bellamy Climate. (n.d.). Greenhouse gas spectra. Retrieved March 20, 2018, from http://www.barrettbellamyclimate.com/page15.htm

Buzsewski, B., Kesy, M., Ligor, T., & Amann, A. (2007). *Human exhaled air analytics: biomarkers of diseases*. Retrieved from https://onlinelibrary.wiley.com/doi/abs/10.1002/bmc.835

Center for science education. (2012, January 1). Carbon Dioxide 400 ppm Atmospheric Concentration Diagrams. Retrieved July 2, 2018, from https://scied.ucar.edu/carbon-dioxide-400-ppm-diagrams

Global Carbon Project. (2016, December 12). Global Methane Budget. Retrieved March 19, 2018, from http://www.globalcarbonproject.org/methanebudget/index.htm

Goldstein, A., & Galbally, I. (2007). *Known and Unexplored Organic Constituents in the Earth's Atmosphere*. Retrieved from https://pubs.acs.org/doi/abs/10.1021/es072476p

Happer, W., Koonin, S. E., & Lindzen, R. S. (2018). *Exhibit A*. Retrieved from http://co2coalition.org/2018/03/21/william-happer-steven-e-koonin-and-richard-s-lindzens-response-to-judge-william-h-alsups-tutorial-questions/

Jeff, L. (2014, February 13). Assessment of Equilibrium Climate Sensitivity and Catastrophic Global Warming Potential Based on the Historical Data Record. Retrieved March 15, 2018, from https://wattsupwiththat.com/2014/02/13/assessment-of-equilibrium-climate-sensitivity-and-catastrophic-global-warming-potential-based-on-the-historical-data-record/

Lindzen, R. (2014, April 10). MIT Professor Richard Lindzen: Climate Models vs. Measured Values [Video file]. Retrieved March 15, 2018, from https://www.youtube.com/watch?v=rXw_HipM9Eg

Watts, A. (2014, February 26). A case of the vapours: source of 'climate-active' organic aerosol particles pinned down. Retrieved July 2, 2018, from https://wattsupwiththat.com/2014/02/26/a-case-of-the-vapours-source-of-climate-active-organic-aerosol-particles-pinned-down/

Watts, A. (2018, March 27). NASA finds something else climate models are missing…. forcing from ‘Secondary Organic Aerosols. Retrieved March 28, 2018, from https://wattsupwiththat.com/2018/03/27/nasa-finds-something-else-climate-models-are-missing-forcing-from-secondary-organic-aerosols/

B Document and tools for the quantification of emissions

B.1 API 2009 Compendium

Many companies can benefit from guidance on the topic of quantification. Having a rough understanding of top-down, bottom-up, measurement and estimation is one thing, actually quantifying emissions is a second. Especially when regulation and mandatory reporting are associated with the quantification, it is important to confirm to the required reporting standards.

For this exact purpose, those in the natural gas and oil industry can turn towards the API 2009 Compendium, a guidance document on emission quantification, covering all associated topics like reporting, detection, and estimation, for many different sectors.

Note, however, that estimating greenhouse gas emissions is an evolving process. As such, the API *Compendium* is intended also to evolve. There is a process for ongoing review and updates, and revisions will be made at regular intervals to incorporate new information. In the interim, users are encouraged to check the documents referenced within the API *Compendium* for updates.

The third edition document is a compendium of currently recognized methods and provides details for all oil and natural gas industry segments to enhance consistency in emissions estimation. It shall be noted that the API Compendium is neither a standard nor a recommended practice for the development of emissions inventories. Rather, as the name implies, it represents a compilation of commonly used GHG emission estimation methodologies.

The overall objective of this document is to promote the use of consistent, standardized methodologies for estimating GHG emissions from oil and natural gas industry operations. As a result, this API Compendium recognizes calculation techniques and emission factors for estimating GHG emissions for oil and natural gas industry operations. These techniques cover the calculation or estimation of emissions from the full range of industry operations, from exploration and production through refining, to the marketing and distribution of products.

The API Compendium presents and illustrates the use of emission estimation methods for carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6) for all common emission sources, including combustion, vented, and fugitive. Decision trees are provided to guide the user in selecting a calculation or estimation technique that is based on considerations of materiality, data availability, and accuracy. It is also important to note that emission results can differ, in some cases significantly, depending on the specific approach(es) used to estimate emissions.

The API and the IPIECA (EXPLAIN OR REFER) took the first step to address inventory uncertainty and accuracy issues. As a result, a guiding document was developed under the name “Addressing uncertainty in oil and natural gas industry greenhouse gas inventories. Technical considerations and calculation methods” (hereafter referred to as the “Uncertainty Document”) (IPIECA & API, 2015). The purpose of this document is to augment existing industry guidance and provide technically valid approaches applicable for use by the global oil and natural gas industry to improve GHG emissions estimation robustness and data quality.

Additionally, the API and IPIECA provide a guiding document titled “Petroleum industry guidelines for reporting greenhouse gas emissions” hereafter referred to as *Guidelines* (IPIECA & API, 2011).

B.2 Software tool SANGEA™

The guidance for reporting of emissions, is not found only in manuals and documents such as the API 2009 Compendium. There are also software tools that make consistent and accurate reporting easier. One such program is the API SANGEA software tool, which builds upon the API Compendium.

SANGEA™ is a software program owned by the American Petroleum Institute (API). The objective of sponsoring SANGEA™ is to provide a user-friendly reporting tool to the oil and gas (O&G) industry and to encourage consistent reporting of GHG emissions.

API supported and distributed SANGEA™ (Version 3) expanding its use to O&G companies worldwide. In 2009, API published the updated Compendium 2009 (see Appendix B.1) with current industry best practices for estimating GHG emissions and the US EPA promulgated the Mandatory Reporting Rule (MRR) for GHG emissions for all industrial sources. With the development of new GHG emission accounting and reporting protocols and regulatory requirements, SANGEA™ version 3 software has become obsolete.

To continue its support of facilitating standardized emissions accounting and reporting methods, API sponsored the development of the new SANGEA™ (Version 4) with new calculation methodologies and requirements.

SANGEA™ software is a tool designed to assist petroleum and natural gas companies with estimating, managing and reporting greenhouse gas (GHG) emissions. It can also be used to track energy consumption and criteria pollutant emissions as well. Redesigned in 2012 by Trinity Consultants/T3, SANGEA™-4 includes the following functionalities:

- Applies API Compendium 2009 for GHG emission calculation methods
- Incorporates U.S. EPA Mandatory Reporting Rule (MRR) Subparts C, P, W, and Y (see also Table B.1) to comply with regulatory reporting requirements.
- Stores source parameters and operating data through established procedures.
- Calculates direct and indirect GHG emissions as well as criteria pollutants with embedded emission factors and equations.

- Tracks energy consumption and normalizes emissions on a production basis (e.g. ton GHG/bbl of product).
- Reports GHG emissions to comply with regulatory requirements and/or to track corporate performance metrics.

SANGEA™ gathers GHG emissions and energy usage data from exploration and production, gas processing, refining and marketing, petrochemicals, transportation, electricity consumption, manufacturing, coal mining, and other activities. The available source modules are summarised below in Table B.1.

Table B.1 Summary of available source modules in SANGEA™-4

SANGEA Source Modules	API Compendium 2009	USEPA MRR Subpart			
		C	P	W	Y
Acid Gas Removal (AGR)	√			√	
Combustion Control	√				
Dehydrator	√			√	
Equipment Leaks	√			√	√
Flare	√			√	√
Hydrogen Plant	√		√		
Indirect Emissions	√				
Liquid Loading	√				√
Miscellaneous	√				
Mobile and Transportation	√				
Oil and Gas Venting	√			√	
Refinery Process Units	√				√
Stationary Combustion	√	√		√	
Storage Tank	√			√	√
Sulfur Recovery Units (SRU)	√			√	
User Defined Sources	*				

* User defined sources allow users to create source types not covered under the protocols.

A guiding document on the SANGEA software provides several website links, including the compendium, and the EPA's reporting regulations. Compressor operators will find Subpart W relevant.

- American Petroleum Institute (API): http://www.api.org/oil-and-natural-gas/environment/climate-change)
- API Compendium 2009: http://www.api.org/~/media/files/ehs/climate-change/2009_ghg_compendium.pdf?la=en
- U.S Environmental Protection Agency (EPA) http://www.epa.gov/
- Resources for Subpart W: https://www.epa.gov/ghgreporting/subpart-w-petroleum-and-natural-gas-systems
- Resources for Subpart C: https://www.epa.gov/ghgreporting/subpart-c-general-stationary-fuel-combustion-sources
- Resources for Subpart Y: https://www.epa.gov/ghgreporting/subpart-y-petroleum-refineries
- Resources for Subpart P: https://www.epa.gov/ghgreporting/subpart-p-hydrogen-production

The paper of Hung-Ming (Trinity Consultants, 2012) provides an overview of SANGEA™-4 functions and features that were designed and developed for O&G

companies to streamline their GHG emissions reporting and recordkeeping processes. SANGEA is available for purchase via URL: http://www.api-sangea.org

EPA's Emission estimation tools (URL: https://www.epa.gov/air-emissions-factors-and-quantification/emissions-estimation-tools)
The EPA also provides several software tools for the estimation and reporting of emissions. These tools cover such fields as wastewater treatment, landfill gas emissions, VOC emissions from storage tanks. Table B.2 shows the overview of the EPA's different software tools.

Table B.2 EPA's Software tools for emission estimation (EPA, 2017 September 11th)

Emissions Estimation Tools

WebFIRE	The WebFIRE database includes EPA's recommended emissions estimation factors for criteria and hazardous air pollutants.

Emissions Estimation Tools- Documents
April 2015: Emission Estimation Protocol for Petroleum Refineries Version 3
Nov 2010: Refinery wastewater emissions tool spreadsheet
Dec 2010: Greenhouse Gas Emissions Estimation Methodologies for Biogenic Emissions from Selected Source Categories: Solid Waste Disposal Wastewater Treatment Ethanol Fermentation - DRAFT

Emissions Estimation Tools- Software	
TANKS	TANKS estimates volatile organic compound (VOC) and hazardous air pollutant (HAP) emissions from fixed- and floating-roof storage tanks.
SPECIATE	SPECIATE is EPA's repository of Total Organic Compound (TOC) and Particulate Matter (PM) speciated profiles for a variety of sources for use in source apportionment studies.
LandGEM	The Landfill Gas Emissions Model (LandGEM) is an automated estimation tool with a Microsoft Excel interface that can be used to estimate emissions rates for total landfill gas, methane, carbon dioxide, nonmethane organic compounds, and individual air pollutants from municipal solid waste landfills. It is available from the EPA's Clean Air Technology Center.
WATER9	WATER9, a wastewater treatment model, consists of analytical expressions for estimating air emissions of individual waste constituents in wastewater collection, storage, treatment, and disposal facilities; a database listing many of the organic compounds; and procedures for obtaining reports of constituent fates, including air emissions and treatment effectiveness.
PM Augmentation	May 2016. The PM Augmentation Tool helps to ensure completeness of PM inventories by correcting inconsistencies in submitted data and filling gaps where possible. PM Augmentation. The file is available on the Emissions Inventories page under **Emissions Inventory Tools**.