Natural Gas Industry Methane Emission Factor Improvement Study
Final Report
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Executive Summary

This report presents the work performed by the University of Texas at Austin, and URS Corporation, with the goal of updating default methane (CH_4) emission factors for selected processes and equipment used in the natural gas industry. The initial impetus of this study was to establish new emission factors that were both statistically superior to the 1996 Gas Research Institute (GRI) and U.S. EPA emissions inventory project (GRI and EPA, 1996) emission factors, and more relevant than the GRI/EPA factors (by including more recent samples). The default emission factors for various sources were compiled and synthesized for a variety of source categories, and new emission rate measurements were conducted for selected sources where existing data had large uncertainties or were thought to possibly be insufficiently representative of current practices and equipment.

The study focus was high emission rate leaks (fugitive leaks) from transmission, gathering/boosting, and gas processing reciprocating and centrifugal compressor components, including emissions from compressor vents (i.e., blowdown lines and compressor seals). Samples were collected from 66 reciprocating compressors and 18 centrifugal compressors, with a total of 48 reciprocating compressors at transmission compressor stations. Emissions from other fugitive sources such as valves, flanges, and other components were also measured in a few locations.

As found in other similar studies, the largest single emission sources at a compressor station are the compressor blowdown (BD) vent lines and the compressor seal vents.

The new measurements made for this project on fugitive components (i.e., valves, flanges, etc.) produced lower emission factors than the previous GRI/EPA study. This may be due to improved LDAR practices for accessible fugitive components that have been implemented by companies in the past two decades. For centrifugal transmission compressors this project found the average blowdown line emission factors were significantly lower than the GRI/EPA study, but found wet seal degassing vent emissions were much higher. For reciprocating transmission compressors, this project found average blowdown line emission factors that were significantly higher than the GRI/EPA study, and rod packing vent emissions that were also much higher.

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1.0 Introduction and Background

This report describes work conducted under a cooperative agreement sponsored by the U.S. Environmental Protection Agency (EPA). The work was performed by the University of Texas at Austin, and URS Corporation, with the goal of updating default methane (CH_4) emission factors for selected processes and equipment used in the natural gas industry. The default emission factors for various sources were compiled and synthesized for a variety of source categories, and new emission rate measurements were conducted for selected sources where existing data have large uncertainties or are insufficiently representative of current practices and equipment.

Methane is the primary component of natural gas and is also a potent greenhouse gas (GHG). About 32% of the U.S. anthropogenic CH_4 emissions have been attributed to natural gas systems, the highest emission source category (EPA, 2011). Published estimates of CH_4 emissions from the U.S. natural gas industry are based mostly on default average emission factors that were developed in the early 1990s and published in 1996 by the Gas Research Institute (GRI) and EPA (GRI and EPA, 1996).[1] In the intervening years, economic incentives and greater awareness of CH_4 as a GHG have inspired new emission reduction approaches that are not reflected in the 1996 GRI/EPA emission factors. Large uncertainties in some of the GRI/EPA emission factors resulted in some cases from small sample populations, variations in equipment design, and variations in equipment operating practices. Consequentially, these uncertainties may also affect the quality of emissions estimates derived from some of the existing default factors.

EPA, in collaboration with the American Petroleum Institute (API), the American Gas Association (AGA), and the Interstate Natural Gas Association of America (INGAA), identified a subset of the emission factors from the 1996 GRI/EPA reports believed to contribute the greatest uncertainty in the U.S. natural gas industry CH_4 emissions inventory. In 2008, EPA awarded a cooperative agreement to the University of Texas to update emission factors for the source categories listed below:

[1] The GRI/EPA study is documented in a 15 volume set. This report refers to the collective GRI/EPA study as well as specific volumes as necessary.

- Production: Well clean-ups, completion flaring, well workovers, and pipelines leaks;
- Processing: Fugitive emissions from reciprocating and centrifugal compressors;
- Transmission and Storage: Fugitive emissions from reciprocating and centrifugal compressors, pneumatic devices, and M&R stations; and
- Distribution: Residential customer meters, plastic mains, and services.

The objective for the project was initially to develop new emission factors for these sources that could be used to replace the existing emission factors, most of which were developed in the mid-1990's under the GRI/EPA program. An extensive search of publicly available GHG data for the emission sources of interest to this project was conducted; a summary of this review is included in Appendix A. The detailed literature review is available as an addendum to this report and on the project web site: (www.utexas.edu/research/ceer/GHG).

The GRI/EPA study gathered data in the early 1990's with the intent of characterizing CH_4 emissions from the U.S. natural gas industry. The goal of the GRI/EPA report was a single, accurate national estimate for total CH_4 emissions. Tight confidence bounds on the national total was important, but confidence bounds on any one of the myriad of individual sources could be wider (poorer). As a result, while the GRI/EPA study focused on understanding typical emission characteristics and extrapolating data gathered, for some strata of emission sources, data were gathered for a relatively few number of samples. The GRI/EPA study gathered measurements across broad ranges of technologies and operating practices for a discreet number of emissions sources as they existed in the early 1990s. This produced national average emissions factors which were applied to national level activity data. Table 1-1 summarizes the emission factors for the sources listed above and their contribution to sector and national emissions for the U.S. natural gas industry at the time of the GRI/EPA study.

Table 1-1. GRI/EPA Emission Factors Summary

Source	Emission Factor	Contribution to Sector Emissions, %	Contribution to Total National Emissions, %
Well Workovers (i.e., cleanups)	0.047 ± 459% tonne CH_4/well workover-yr	0.01% (± 1,298%)	
Gas Well Unloading	0.95 ± 344% tonne CH_4/unloading gas well-yr	6.7%	1.8% (± 380%)
Well Completions	0.014 ± 200% tonne CH_4/completion well-yr	0.027%	0.007% (± 201%)
Production Gathering Pipelines: Protected Steel	0.327± 85% tonne CH_4/leak-yr	7.8%	2.1% (± 108%)
Production Gathering Pipelines: Unprotected Steel	0.836 ± 93% tonne CH_4/leak-yr		
Production Gathering Pipelines: Plastic	1.61±166% tonne CH_4/leak-yr		
Production Gathering Pipelines: Cast Iron	3.85 ± 64% tonne CH_4/leak-yr		
Processing: Reciprocating compressors	78± 74% tonne CH_4/ reciprocating compressor-yr	61%	5.32% (± 95.1%)
Processing: Centrifugal compressors	148± 39% tonne CH_4/centrifugal compressor-yr		1.79% (± 91.4%)
Transmission: Reciprocating compressors	106± 68% tonne CH_4/ reciprocating compressor-yr	39%	12.1% (± 68.1%)
Transmission: Centrifugal compressors	212 ± 44% tonne CH_4/centrifugal compressor-yr		2.4% (± 43.7%)
Transmission: Continuous bleed pneumatics	8.915 ± 29% tonnes CH_4/device-yr	12%	4.5% (±60%)
Transmission: Pneumatic/hydraulic devices	0.1008 ± 112% tonne CH_4/device-yr		
Transmission: Turbine pneumatic devices	1.211 ± 276 tonne CH_4/ device-yr		
Transmission M&R Stations: transmission-to-transmission	7.62± 80% tonne CH_4/ transmission-to-transmission station-yr	3.9%	1.43% (± 1,000%)
Transmission M&R Stations: Farm taps	0.000597± 80% tonne CH_4/farm tap-yr		
Distribution: Residential meters	0.00265 ± 17% tonne CH_4/meter-yr	7.2%	1.76% (± 19.8%)
Distribution: Plastic mains	1.91± 166% tonne CH_4/leak-yr	6.4%	1.56% (± 282%)

Although the GRI/EPA project was not intended to be the basis for estimating CH_4 emissions from any particular company source, the data collected during this study provided (and continues to provide) the most comprehensive quantification of CH_4 emissions data for a variety of natural gas industry sources. While the GRI/EPA study serves as the basis for most natural gas industry CH_4 emission estimates worldwide, there have been some changes in the natural gas industry since the study was performed. New and improved technologies (such as horizontal drilling of unconventional gas sources), improved operating practices, government regulation of emissions, significant participation in voluntary programs like Natural Gas STAR, and economic conservation prompted by the rising price of natural gas are driving forces for reviewing and potentially updating specific emission factors.

1.1 Selection of Scope

Stakeholders for this study, which included the U.S. EPA, as well as some industry participants, determined that this study should focus primarily on the natural gas compressor station fugitive emissions from reciprocating and centrifugal compressors. Those were among a few sources in the GRI/EPA study with high overall emission rate and relatively wide confidence bounds. For all compressors in natural gas service, the highest source of fugitive emissions from compressor stations occurs in transmission stations, in particular the compressor vents (continuous leaks from blowdown lines vent stacks and from compressor seals). Therefore this study initially focused on transmission stations.

While this study focuses on transmission, some nearly identical compressors in gas processing were sampled as opportunistic surrogates, and in one region, some additional opportunistic data was gathered for upstream production gathering/boosting station compressor emissions.

The study focus was high emission rate leaks (fugitive leaks) from compressor components, including emissions from compressor vents (i.e., blowdown lines and compressor seals). Emissions from other fugitive sources such as valves, flanges, and other components were also measured in a few locations.

1.2 Technical Background

Compressors are used at various points along the natural gas collection, transportation, and delivery system to move gas by means of a pressure differential. Compressors at natural gas gathering/boosting stations are used to move gas from production to either central treatment facilities, to gas processing plants, or to transmission pipelines. Within a gas processing plant, compressors are used to draw gas to the plant and/or to move gas through various portions of the plant. In transmission, compressors are used to overcome the pressure drop that occurs in the long distances of the transmission pipeline.

Fugitive emissions include leaks from normally sealed components on the pressurized piping and equipment systems. Those include flanges, screwed fittings (connectors), valve stem packing (valves), pressure relief valves (PRV's), valve seats where one side of the closed valve is open to the atmosphere (open-ended lines [OELs]), and seals, such as compressor rod packing or rotating seals. The most significant fugitive emissions are associated with three sources: 1) centrifugal compressor seal oil gas, 2) reciprocating compressor piston rod packing systems, and 3) compressor blowdown line OELs.

For this study, fugitive emissions from centrifugal compressors and reciprocating compressors were measured at gathering/boosting facilities, gas processing plants, and transmission compressor stations. A photo of a centrifugal compressor wet seal degassing vent is shown in Figure 1-1 and a photo of compressor blown vents are shown in Figure 1-2.

Figure 1-1. Centrifugal Compressor Wet Seal Degassing Vent

Figure 1-2. Compressor Blowdown Vents

1.2.1 Centrifugal Compressors

Centrifugal compressors are widely used to handle large volumes of gas at high pressure. A centrifugal compressor, in its simplest form, consists of an impeller rotating within a casing, using centrifugal force to propel the gas to the outside of the casing at an increased pressure. A diagram of a centrifugal compressor is shown in Figure 1-3, and a photo is shown in Figure 1-4.

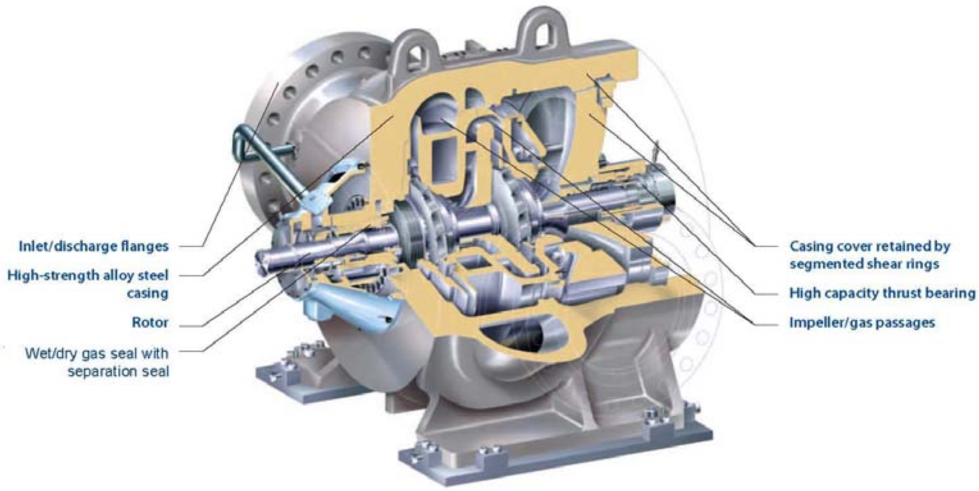


Figure 1-3. Centrifugal Compressor Schematic (Rolls Royce, 2010)

Figure 1-4. Centrifugal Compressor (foreground) with Turbine Driver (background)

Centrifugal compressors require seals around the rotating shaft to prevent gases from escaping where the shaft exits the compressor casing. These seals use oil, which is circulated under high pressure between three rings around the compressor shaft, forming a barrier against the compressed gas leakage. The center ring is attached to the rotating shaft, while the two rings on each side are stationary in the seal housing, pressed against a thin film of oil flowing between the rings to both lubricate and act as a leak barrier. "O-ring" rubber seals prevent leakage around the stationary rings. Very little gas escapes through the oil barrier; considerably more gas is absorbed by the oil under the high pressures at the "inboard" (compressor side) seal oil/gas interface, thus contaminating the seal oil. Seal oil is purged of the absorbed gas (using heaters, flash tanks, and degassing techniques) and recirculated. (EPA, 2006)

1.2.2 Reciprocating Compressors

A reciprocating compressor is a positive displacement device which employs pistons driven by a crank shaft to move gas. The pistons increase the pressure of the gas by reducing its volume.

Areas of high leak frequency from reciprocating compressors include flanges, valves, and fittings located on compressors, due to the high vibration. The highest volume of gas loss, however, is associated with two sources: 1) piston rod packing systems, and 2) compressor blowdown line OELs.

Packing systems are used to maintain a tight seal around the piston rod, preventing the gas compressed to high pressure in the compressor cylinder from leaking, while allowing the rod to move freely. A schematic of a reciprocating compressor is shown in Figure 1-5.

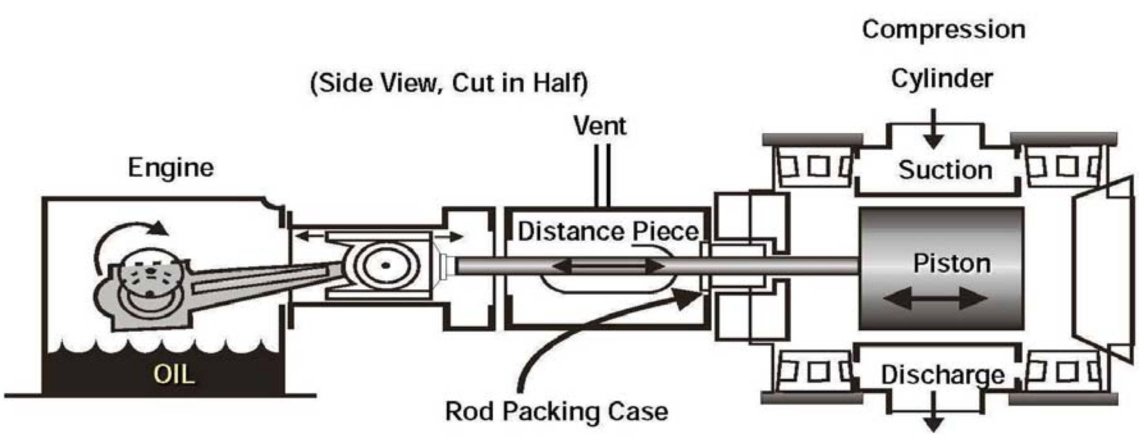


Figure 1-5. Reciprocating Compressor Schematic (EPA, 2006)

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. 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. A "nose gasket" on the end of the packing case prevents leaks around the packing cups. Higher leak rates are a consequence of fit, alignment of the packing parts, and wear. Leakage typically occurs from four 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; and
- Between the rings and shaft. (EPA, 2006)

Leaking gases are vented to the atmosphere either directly from the end of the packing seal, or through the compressor distance piece vent. Photos are shown in Figures 1-6 and 1-7. Sometimes, on larger compressors, these distance piece vents are piped together and joined into one larger vent line.

Figure 1-6. Reciprocating Compressors
(note the 2" rod packing line with orange elbows)

Figure 1-7. Reciprocating Compressor Rod Packing Vent (Gathering Service)
(1/2" tubing)

1.2.3 Blowdown Open-Ended Lines

The second significant source from compressors is large OELs. In particular, those OELs that are connected to the compressor blowdown vent line. The details of this source are described below.

Compressor blowdown OELs allow a compressor to be depressurized when idle, and typically leak when the compressor is operating or idle.

There are two primary modes of operation leading to different emission rates for compressor blowdown OELs. For this report, compressor blowdown emissions refer to the venting of natural gas contained inside the compressor. The first operating mode is when the blowdown valve is closed and the compressor is pressurized, either during normal operation or when idle. The second operating mode is when the blowdown valve is open. This occurs when the compressor is idle, isolated from the compressor suction and discharge manifolds, and the blowdown valve is opened to depressure the compressor. (Note: Fugitive losses do not include the vented emissions from depressuring the compressor.) A diagram of a typical compressor blowdown valve arrangement is presented in Figure 1-8.

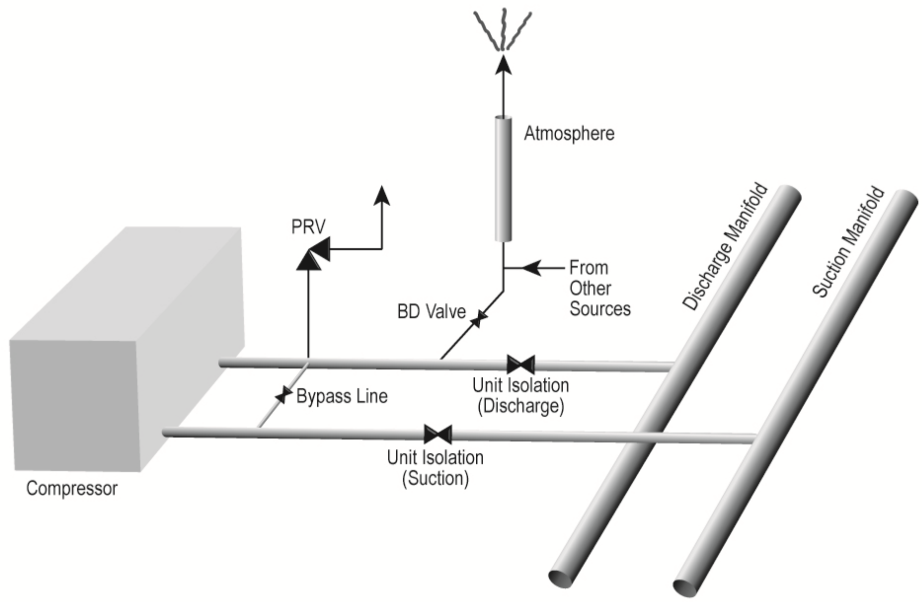


Figure 1-8. Typical Compressor Blowdown Arrangement (adapted from Hummel et. al, 1996)

1.3 Review of Existing Emission Factors

1.3.1 Transmission – Fugitive Emissions from Reciprocating and Centrifugal Compressors

Most fugitive emission measurements are conducted for a specific period of time (relatively short in comparison to annual operations), and assumed to leak continuously, at the same rate. However, compressor operations are different, in that they are often cycled for maintenance or due to changes in load requirements. Emission factors need to account for the portion of time that compressors are (1) not pressurized, (2) pressurized and running, and (3) pressurized and idle. When compressors are depressurized, most components are assumed not to have fugitive emissions. The exception is compressor blowdown lines, which can emit at higher rates when depressurized (note: fugitive losses do not include the vented emissions from depressuring the compressor).

The emission factors developed for the GRI/EPA study combined data from U.S. and Canadian measurements. The U.S. measurements for the depressurized blowdown fugitive emission factors were much higher than the pressurized blowdown factor, but this difference was not observed in the Canadian measurements. The GRI/EPA study found much higher emission rates for depressurized reciprocating compressors than for pressurized reciprocating compressors, as will be shown in Section 3.0 on Measurement Results and Analyses. The difference was attributed to compressor age, where compressors installed in the 1950's were found to have a statistically higher leak rate than other installation years. The emission factors in the GRI/EPA study are considered the primary industry reference for transmission compressor blowdown emissions

Emissions from compressor-related components were estimated separately due to differences in leakage characteristics for components subject to vibrational conditions. For example, compressor seal emission rates were determined for the following modes: (1) operating and pressurized, (2) idle and fully pressurized, (3) idle and partially pressurized, and (4) idle and depressured.

Transmission compressor emission factors from the GRI/EPA study are

5.55 ± 68% MMscf CH_4/reciprocating compressor-yr
= 106 tonne CH_4/ reciprocating compressor-yr

11.1 ± 44% MMscf CH_4/centrifugal compressor-yr
= 212 tonne CH_4/centrifugal compressor-yr

These emission factors are a summary per average compressor, and include individual sources such as seal leakage, starter line leakage, compressor PRV leakage, certain fugitive components on the compressors (such as cylinder valve covers and fuel valves) and blowdown open-ended-line leakage. The overall average component emission factors are based on the fraction of time associated with each operating mode for reciprocating and centrifugal compressors in gas transmission. The operating modes are shown in Table 1-2.

Table 1-2. Operating Modes of Compressors in Gas Transmission
(GRI and EPA, 1996, Table 4-20)

Operating Mode	Percent of Time Associated with Operating Mode	
	Reciprocating Compressor	Centrifugal Compressor
Pressurized: In Operation	45.2%	24.2%
Pressurized: Idle	33.9%	5.8%
Depressurized: Idle	20.9%	70.0%

Of the total CH_4 emissions from natural gas operations determined from the GRI/EPA study, transmission compressor fugitive emissions contributed 12.1% (± 68.1%) for reciprocating compressors and 2.4% (± 43.7%) for centrifugal compressors (39% of CH_4 emissions from transmission activities).

1.3.2 Processing– Fugitive Emissions from Reciprocating and Centrifugal Compressors

Component emission factors for the GRI/EPA study for compressors in gas processing plants were based on the screening data noted above for transmission compressors. Adjustments were made for the fraction of time reciprocating and centrifugal compressors are pressurized in gas processing (89.7% and 43.6% for reciprocating and centrifugal compressors, respectively). In addition, it was found that approximately 11% of compressors in gas processing have blowdown valves and PRVs routed to a flare rather than vented to the atmosphere.

Component counts for gas processing plants, including the compressors, were based on data from 21 sites compiled through the GRI/EPA study and three separate studies.

Gas Processing compressor emission factors from the GRI/EPA study are:

4.09± 74% MMscf CH_4/reciprocating compressor-yr
= 78 tonne CH_4/ reciprocating compressor-yr

7.75 ± 39% MMscf CH_4/centrifugal compressor-yr
= 148 tonne CH_4/centrifugal compressor-yr

These emission factors are a summary per average compressor, and include individual sources such as seal leakage, starter line leakage, compressor PRV leakage, certain fugitive components on the compressors (such as cylinder valve covers and fuel valves) and blowdown open-ended-line leakage. The overall average component emission factors are based on the fraction of time associated with each operating mode for reciprocating and centrifugal compressors in gas processing service. The operating modes are shown in Table 1-3.

Table 1-3. Operating Modes of Compressors in Gas Processing Service
(GRI and EPA, 1996)

Operating Mode	Percent of Time Associated with Operating Mode	
	Reciprocating Compressor	Centrifugal Compressor
Pressurized	89.7%	43.6%
Depressurized	10.3%	56.4%

Of the total CH_4 emissions from natural gas operations determined from the GRI/EPA study, gas processing compressor fugitive emissions contributed 5.32% (± 95.1%) for reciprocating compressors and 1.79% (± 91.4%) for centrifugal compressors (61% of CH_4 emissions from gas processing activities).

1.3.3 Compressor Seals

This section addresses more detailed emission source information from EPA's Natural Gas STAR program and from further studies conducted on compressor seals since the GRI/EPA study. A 2006 California Energy Commission (CEC, 2006) document reviewed the API *Compendium* (American Petroleum Institute, 2004) emission factors and commented that centrifugal and reciprocating seals have different emission characteristics and should not be combined in one emission factor. Further, the CEC document noted that centrifugal compressor seals can be classified as either wet or dry technologies. The wet seals use oil to form a barrier to prevent leakage from the compressor seal. The circulating oil is stripped of gas that it absorbs at the high-pressure seal face and vents the gas to the atmosphere. Therefore, wet seals have emissions both from fugitive leakage at the seal face as well as the vented emissions from the circulating oil. The CEC paper indicated that the wet seals were more commonly used when the 1996 GRI/EPA study was developed, which is the basis of the *Compendium* emission factors.

Dry seals have much lower emissions than wet seals since the barrier fluid is high pressure gas, which does not involve venting from stripping oil, and the seal design is different, resulting in much lower seal leakage. An EPA Natural Gas STAR Lessons Learned paper on replacing wet seals with dry seals states that dry gas seals substantially reduce methane emissions (EPA, 2006). The main difference in the emissions from wet and dry seals is the vented emissions from the recirculation oil associated with wet seals.

Based on guidance in the CEC paper, the original emission factors from the fugitives report of the 1996 GRI/EPA natural gas CH_4 emissions study were reviewed. The individual seal emission factors from this study were never presented in the GRI/EPA study, as compressor equipment level emission factors were presented instead. Additionally, the Gas STAR reports were reviewed for compressor seal emissions information. The CEC document notes that the authors had discussions with individuals associated with the original GRI/EPA measurements, who indicated that measurements were made of the seal gas leakage for the fugitives estimate, while the seal oil degassing emissions were captured in the station venting measurements. The station venting raw data from the 1996 GRI/EPA study were reviewed to see if they include specific seal oil vented emissions, but unfortunately the available data were not disaggregated to that level of detail.

The CEC document recommended reviewing the 1996 GRI/EPA data for separate reciprocating and centrifugal emission factors, as well as the Gas STAR reports. The CEC document also recommended reviewing a study by the Wuppertal Institute for measurements on the Russian Gazprom transmission system for wet seal measurement data. Unfortunately, this report has not been located. However, compressor seal leak data from the 1996 GRI/EPA fugitive report and the Natural Gas STAR reports have been reviewed and summarized in Table 1-4.

As shown in Table 1-4, there are several potential compressor seal emission factors. The only emission factor found that is believed to include both the wet seal vented and fugitive emissions is the last entry taken from Natural Gas STAR (the other entries are probably fugitive emissions from the seal face). The emission factors shown in Table 1-4 were taken from a variety of sources and provided in different units (e.g., metric tonnes, as total gas, as CH_4); but are shown in Table 1-4 on the same basis (scf gas/seal-hour) for comparison purposes. As observed in Table 1-4, there is a wide range of variability in the reported compressor seal emission factors for both hourly and annual emissions.

Table 1-4. Comparison of Compressor Seal Emission Factors

Seal Type	Emission Factor (scf CH_4/seal-yr)	Emission Factor (scf gas/seal-yr)	Emission Factor (scf gas/seal-hr)	Default CH_4 content (mole %)	Source	Notes
Production						
Unspecified	2,370	3,008	0.343	78.8%	Vol. 8, Table 4-8, 1996 GRI/EPA CH_4 study	Based on western U.S. onshore; converted to hourly basis assuming 8760 hrs/yr
Unspecified*			42.2	Not given	1992 Picard study, in Table B-17 of the Feb. 2004 API *Compendium*	Converted from kg/hr-component using a natural gas density of 1 lb/23.8 ft^3 from Table 3-5 of the Feb. 2004 API *Compendium*.
Processing						
Reciprocating	450,000	517,241	65.8	87.0%	Vol. 8, Table 4-12, 1996 GRI/EPA CH_4 study	Converted annual to hourly accounting for 89.7% of the year pressurized
Centrifugal	228,000	262,069	68.6	87.0%		Converted annual to hourly accounting for 43.6% of the year pressurized
Transmission						
Reciprocating	396,000	423,983	61.2	93.4%	Vol. 8, Table 4-15, 1996 GRI/EPA CH_4 study	Converted annual to hourly accounting for 79.1% of the year pressurized
Centrifugal	165,000	176,660	83.3	93.4%		Converted annual to hourly accounting for 24.2% of the year pressurized
Recip. - rod packing - running		865,000	98.7	Not given	Indaco study, provided in Gas STAR Lessons Learned, directed inspection at comp. stns.	Converted annual to hourly assuming 8760 hrs/yr
Recip. - rod packing - idle		1,266,000	144.5	Not given		
Centrifugal - Dry		62,700	7.16	Not given	Indaco study, provided in Gas STAR Lessons Learned, directed inspection at comp. stns.	Converted annual to hourly assuming 8760 hrs/yr
Centrifugal - Wet		278,000	31.7	Not given		
Reciprocating*			34.7	Not given	1992 Picard study, in Table B-16 of the Feb. 2004 API *Compendium*	Original EFs were in units of kg THC/hr-component and converted to scf assuming a natural gas density of 1 lb/23.8 ft^3 from Table 3-5 of the Feb. 2004 API *Compendium*.
Centrifugal*			42.7	Not given		
Storage						
Reciprocating	300,000	321,199	54.3	93.4%	Vol. 8, Table 4-22, 1996 GRI/EPA CH_4 study	Converted annual to hourly accounting for 67.5% of the year pressurized
Centrifugal	126,000	134,904	68.7	93.4%		Converted annual to hourly accounting for 22.4% of the year pressurized

Table 1-4. Comparison of Compressor Seal Emission Factors, continued

Seal Type	Emission Factor (scf CH_4/seal-yr)	Emission Factor (scf gas/seal-yr)	Emission Factor (scf gas/seal-hr)	Default CH_4 content (mole %)	Source	Notes
Unspecified Gas Industry						
Centrifugal - Dry**	up to 3,154,000	up to 3,376,000	up to 385	Not given; assume 93.4%	EPA Gas STAR Lessons Learned, replacing wet seals with dry seals for centrifugal comp.	Converted scf/min to hourly and annual assuming continuous operation; emission factor provided in terms of CH_4 emissions; converted to total gas emissions assuming 93.4 mole % CH_4 in the gas.
Centrifugal - Dry**	262,800 - 1,576,800	281,370 - 1,688,200	32.1 - 192.7			
Centrifugal - Wet **(includes vented)**	21,024,000 - 105,120,000	22,510,000 - 112,548,000	2570 - 12,850			

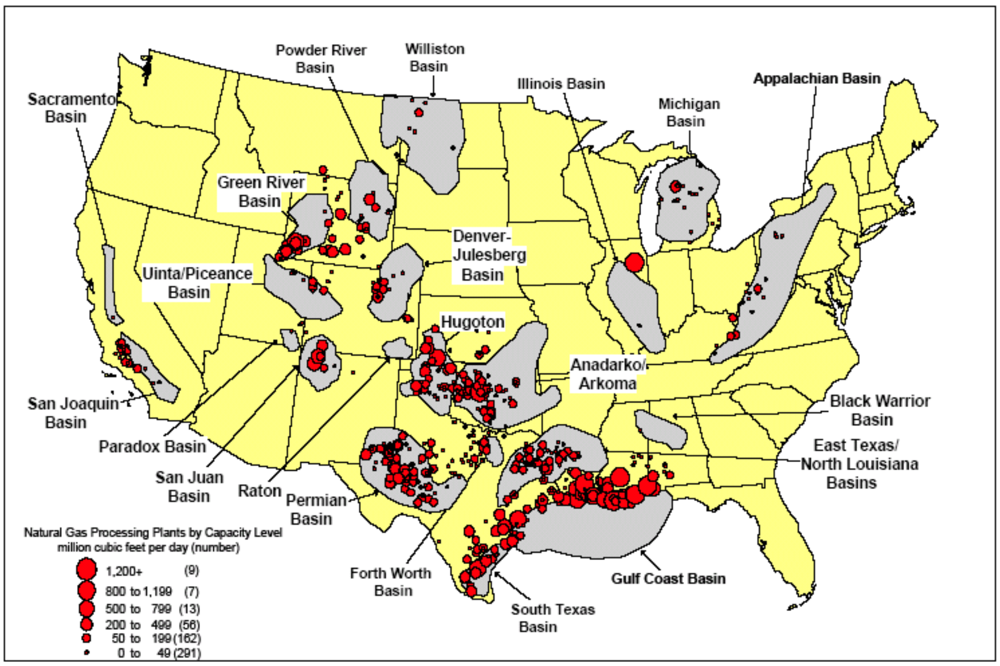
*Emission factors already presented in the API *Compendium*.
** The EPA Gas STAR paper presents two sets of emissions data for dry centrifugal seals within the same paper.

2.0 Measurement Campaigns

This section provides details on the test sites and measurements collected during this study.

2.1 Selection of Test Sites

Figures 2-1 and 2-2 show the locations of natural gas processing plants and interstate pipeline compressor stations operating in the lower 48 states, respectively. About one-half the total number of gas plants are in Texas, Louisiana, and Oklahoma, while a large fraction of the rest are in Wyoming, Colorado, and New Mexico. Interstate pipeline compressor stations are more dispersed.



Note: Eight Alaska plants not displayed, but count is reflected in the legend.
Source: Energy Information Administration, Gas Transportation Information System, Natural Gas Processing Plant Database.

Figure 2-1. Concentrations of Natural Gas Processing Plants, 2004

Voluntary partnerships with gas plant and pipeline operating companies were relied on for site access. Access to natural gas processing plants and transmission compressor stations was requested via emails sent on behalf of the project team by the AGA, API, GPA, and INGAA to their respective members. Companies choosing to participate in the study were then asked to provide a list of candidate test sites that were representative of their U.S. operations. Test sites were selected from the pool of candidates to represent a mix of comparatively older and newer facilities and different geographic regions and pipelines. Logistical and budgetary issues were considered by selecting sites with relatively large numbers of reciprocating and/or centrifugal compressors and comparatively easy access to emissions sources. Other practical issues such as distances between sites were also considered (to control travel expenses). Incentives to participate in this study include anonymity, and site-specific emission factors. The pool of test sites ideally included:

- Reciprocating and centrifugal compressors;
- Construction dates before and after 1996 (the year the GRI/EPA study was published);
- Wet and dry centrifugal compressor seals;
- Compressors in operating, standby, and idle modes;
- Accessible open ended blowdown and starter lines;
- Accessible compressor seal vents;
- A mix of compressor manufacturers, models, sizes, and ages;
- Different approaches to leak detection and repair; and
- Natural Gas STAR Partners and non-partners.

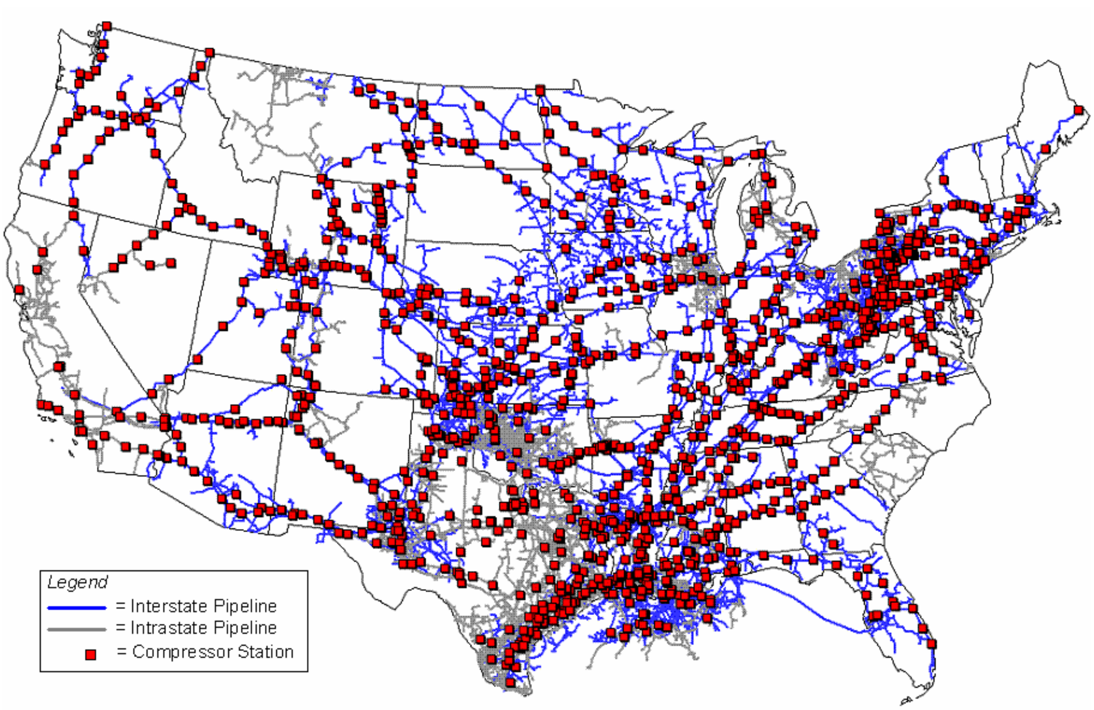


Figure 2-2. Natural Gas Pipeline Compressor Stations, 2008
(Source: Energy Information Administration, Office of Oil & Gas, Natural Gas Division, Natural Gas Transportation Information System.)

A total of three companies granted access to their compressor sampling sites and signed access agreements with the University of Texas. Measurements were conducted during three separate campaigns during 2009 – 2011. Measurements at the compressor stations included the following:

- Station fugitive screening by FLIR camera (non-quantitative);
- Fugitive measurement on identified leakers by High Volume Sampler device; and
- Reciprocating and centrifugal compressor vent measurements by alternate methods (pitot tube anemometer or calibrated bag).

Sampling at the first group of sites in East Texas occurred for a week in November, 2009. A second week of sampling occurred in February, 2010, at a group of sites in West Texas. A third week of sampling occurred in May, 2011, at a group of sites in New Mexico. The strategy in conducting the sampling was to collect as much data as possible at the sites, using multiple instruments.. Measurements included compressor related fugitive components (flanges, valves, OELs, PRVs), as well as blowdown vent lines and compressor seal and rod packing emissions.

2.2 Site Descriptions

Measurements were made at a total of eleven sites which were constructed between the 1950s and 2000s. For comparison, the 1996 GRI/EPA compressor emission factors were based on measurements at 15 compressor stations. Samples were collected from 66 reciprocating compressors and 18 centrifugal compressors, with a total of 48 reciprocating compressors at transmission compressor stations. A list of the sites surveyed is provided in Table 2-1.

Table 2-1. Description of Sites Surveyed

Site	Survey Date	Description	Measured Equipment	Year Built
Site 1	11/2009, 5/2011	Transmission Compressor Station	6 Reciprocating Compressors	1965
Site 2	11/2009, 5/2011	Transmission Compressor Station	3 Centrifugal Compressors	1982
Site 3	11/2009, 5/2011	Transmission Compressor Station	5 Reciprocating Compressors	1992-2009
Site 4	2/2010	Transmission Compressor Station	15 Reciprocating Compressors	1948
Site 5	2/2010	Transmission Compressor Station	5 Reciprocating Compressors	1948
Site 6	5/2011	Gathering/Boosting compressors	13 Reciprocating Compressors	1992
Site 7	5/2011	Gathering/Boosting compressors	6 Reciprocating Compressors	1993
Site 8	5/2011	Gathering/Boosting compressors	6 Reciprocating Compressors	1992
Site 9	5/2011	Gas Processing Plant	2 Centrifugal Compressors	1993
Site 10	5/2011	Gathering/Boosting compressors	4 Centrifugal Compressors	1971
Site 11	5/2011	Gas Processing Plant	6 Centrifugal Compressors	1950

Each of the volunteer companies that provided sites in Table 2-1 is a Participant in the EPA's Natural Gas STAR program, however, that was not a requirement for site selection. It is unknown whether the visited sites made any changes due to Natural Gas Star recommended best practices.

2.3 Field Measurement Methods

Measurements of the compressor-related “vent lines” was the primary focus of the field measurement visits, since these sources were the largest single emitters in the previous studies. The “vent lines” were often elevated stacks, open to the atmosphere. The compressor-related “vent lines” that were measured were 1) the combined rod packing vent lines on reciprocating compressors, 2) the wet seal vent line on centrifugal compressors with wet seals, and 3) the compressor open-ended line (OEL) leakage through the compressor blowdown vent line. The reciprocating compressor rod packing vent lines were most often combined into a single elevated vent for each compressor (though some smaller gathering compressors did have individual, non-elevated vents for each cylinder). The compressor Blowdown (BD) vent line was usually a direct line from each compressor, but at many sites the BD vent lines were joined into a common elevated station vent stack that also had other sources routed to the same stack. The actual blowdown events were not measured; instead the amount of continuous leakage through the blowdown line was measured.

In addition to the compressor vents, fugitive screening and fugitive measurements of ordinary leaking components such as flanges, valves, OELs, PRVs were conducted throughout the site at five of the eleven sites. Not all eleven sites were measured for ordinary fugitives since the compressor vents were the main focus, and because the total site fugitive screening is an expensive measurement approach.

Details of the sampling conducted at each host site are provided in Table 2-2. Columns in the table show which vents and components were measured. A summary of the sampling methods are provided in the remainder of this section. Details of the sampling procedures are available in the project’s Quality Assurance Project Plans, provided in as an addendum to this report..

Table 2-2. Site-Specific Sources Sampled

Site	Equipment Type	HP	Status	Rod Packing		Wet Seal Degas	Compressor OEL leak through BD Line	Lube Oil Tank	Site		
				Rod Packing Combined Vents	Individual Rod Packing Seal Leaks				Discharge PRV	IR Screening	Component Leaks
	Recip 1	2,650	Idle but pressurized	M			M		NM		
	Recip 2	2,650	Idle but pressurized	M			M		NM		
	Recip 3	2,650	Idle but pressurized	EI	N/A		M		NM		
Site 1	Recip 4	4,200	Idle but pressurized	EI		N/A	M	N/A	NM	M	M
	Recip 5	8,200	Idle, Depressurized, open	EI			M		NM		
	Debrine piping	N/A	N/A	N/A	N/A		M		NM		
	Recip 1	2,800	Idle but pressurized		M,NE		M,NE		NM		
	Recip 2	2,800	Idle but pressurized		M,NE		M,NE		NM		
	Recip 3	2,800	Idle but pressurized	N/A	M		M,NE		NM		
	Recip 4	2,800	Idle but pressurized		M		M,NE		NM		
Site 2	Recip 5	2,800	Idle but pressurized		M	N/A	M,NE	N/A	NM	M	M
	Recip 6	2,800	Idle but pressurized		EI		M,NE		NM		
	Station BD Vent #1 - Yard Piping	N/A	--				M		NM		
	Station BD Vent #2 - Idle Line piping	N/A	--	N/A	N/A		NM		NM		
	Station BD Vent #3 - Yard Piping	N/A	--				M		NM		
	Centrif 1	4,800	Idle, depressurized			M,NE	M		NM		
Site 3	Centrif 2	4,800	Running	N/A	N/A	M	M	N/A	NM	M	M
	Centrif 3	4,680	Running			M	M		NM		

M = Measured
NM = Not Measured
N/A = Not Applicable or Not Present
EI = Inaccessible
M,NE = Measured, No Emissions

Table 2-2. Site-Specific Sources Sampled, continued

Site	Equipment Type	HP	Status	Rod Packing		Wet Seal Degas	Compressor OEL leak through BD Line	Lube Oil Tank	Site		
				Rod Packing Combined Vents	Individual Rod Packing Seal Leaks				Discharge PRV	IR Screening	Component Leaks
Site 4	Recip 1	1,235	Idle, depressured	NM	N/A	N/A	M	N/A	M	M	M
	Recip 2	1,235	Running	M			M		M		
	Recip 3	1,235	Idle, depressured	NM			M		M		
	Recip 4	1,235	Running	M			M		M		
	Recip 5	1,235	Idle, depressured	NM			M		M		
	Recip 6	1,235	Running	M			M		M		
	Recip 7	1,235	Idle, depressured	NM			M		M		
	Recip 8	1,235	Running	M			M		M		
	Recip 9	1,235	Idle, depressured	NM			M		M		
	Recip 10	1,235	Idle, depressured	NM			M		M		
	Recip 11	1,800	Idle, depressured	NM			M		M		
	Recip 12	1,235	Idle, depressured	NM			M		M		
	Recip 13	3,500	Idle, depressured	NM			M		M		
	Recip 14	3,500	Idle, depressured	NM			M		M		
	Recip 15	1,800	Idle, depressured	NM			M		M		
Site 5	Recip 1	1,002	Running	NM	N/A	N/A	NE	N/A	NE	M	M
	Recip 2	1,002	Idle, depressured	NM			M		M		
	Recip 3	1,002	Idle, depressured	NM			M		M		
	Recip 4	1,002	Running	NM			NE		NE		
	Recip 5	1,002	Idle, depressured	NM			M		M		
	Recip 6	2,278	Idle, depressured	M			NM		NM		
	Recip 7	2,278	Idle, depressured	M			NM		NM		

M = Measured
NM = Not Measured
N/A = Not Applicable or Not Present
EI = Inaccessible
M,NE = Measured, No Emissions

Table 2-2. Site-Specific Sources Sampled, continued

Site	Equipment Type	HP	Status	Rod Packing		Wet Seal Degas	Compressor OEL leak through BD Line	Lube Oil Tank	Site		
				Rod Packing Combined Vents	Individual Rod Packing Seal Leaks				Discharge PRV	IR Screening	Component Leaks
	Recip 1		Running		M		M,NE	M	M,NE		
	Recip 2		Running		M,NE		M,NE	M	M,NE		
	Recip 3		Running		M		M,NE	M	NM		
	Recip 4		Running		M		M,NE	M	M,NE		
	Recip 5		Running		M		M,NE	M	M		
	Recip 6		Running		NM		M	NM	M,NE		
Site 6	Recip 7		Idle, Depressured	N/A	NM	N/A	M,NE	NM	M,NE	NM	NM
	Recip 8		Idle, Depressured		NM		M,NE	NM	M		
	Recip 9		Running		M		M,NE	M	M		
	Recip 10		Idle, Depressured		NM		M,NE	NM	NM		
	Recip 11		Idle, Depressured		NM		M,NE	NM	M,NE		
	Recip 12		Running		M		M,NE	M	M,NE		
	Recip 13		Idle, Depressured		NM		M,NE	NM	NM		
	Recip 1		Running		M		M,NE	M,NE	M		
	Recip 2		Running		M		M,NE	M,NE	M,NE		
Site 7	Recip 3		Running	N/A	M	N/A	M,NE	M,NE	M,NE	NM	NM
	Recip 4		Idle, Depressured		NM		M,NE	M,NE	M,NE		
	Recip 5		Idle, Depressured		NM		M,NE	M,NE	M,NE		
	Recip 6		Running		M		M,NE	M,NE	M,NE		
	Recip 1		Idle, depressured	NM			M,NE	NM	M,NE		
	Recip 2		Running	M			M,NE	M,NE	NM		
	Recip 3		Running	M			M,NE	M,NE	M,NE		
Site 8	Recip 4		Running	M	N/A	N/A	M,NE	M,NE	M,NE	NM	NM
	Recip 5		Idle, Depressured	NM			NM	NM	NM		
	Recip 6		Idle, Disassembled	NM			M,NE	NM	NM		
	Recip 7		Running	M			M,NE	M,NE	M,NE		

M = Measured
NM = Not Measured
N/A = Not Applicable or Not Present
EI = Inaccessible
M,NE = Measured, No Emissions

Table 2-2. Site-Specific Sources Sampled, continued

Site	Equipment Type	HP	Status	Rod Packing		Wet Seal Degas	Compressor OEL leak through BD Line	Lube Oil Tank	Site		
				Rod Packing Combined Vents	Individual Rod Packing Seal Leaks				Discharge PRV	IR Screening	Component Leaks
Site 9	Centrif 1		Running	N/A	N/A	M	M,NE	N/A	NM	NM	NM
	Centrif 2		Running			M	M		NM		
Site 10	Centrif 1		Running	N/A	N/A	M	M	N/A	M	NM	NM
	Centrif 2		Idle, Depressured			NM	M		M		
	Centrif 3		Running			M	M		M		
	Centrif 4		Running			M	M		M		
Site 11	Centrif 1		Running	N/A	N/A	M	M	N/A	NM	NM	NM
	Centrif 2		Idle, Depressured			NM	M		NM		
	Centrif 3		Running			M	M		NM		
	Centrif 4		Running			M	M		NM		
	Centrif 5		Running			M	M		NM		
	Centrif 6		Running			M	M		NM		

M = Measured
NM = Not Measured
N/A = Not Applicable or Not Present
EI = Inaccessible
M,NE = Measured, No Emissions

2.3.1 Equipment Component Counts and Component Leaks

At five stations fugitive leak sources associated with each compressor were classified (i.e., connector, valve, etc.) and counted. First, a FLIR infrared camera was used to locate (but not quantify) any potential leaking components. A trained team from the company that owned the FLIR was used to make those measurements. Once the FLIR camera team located a leaking component (usually only a few sources per station), then a quantification was performed using the high volume (Hi-Flow) sampler. The high volume sampler operates by pulling in a relatively large volume of air (up to 8 cfm), and determining the CH_4 concentration in the air. Where possible, packing seal vents were selected randomly, disconnected from the common vent, and measured with the Hi-Flow. A photograph of the FLIR camera and Hi-Flow Sampler in use is shown in Figure 2-3.

Figure 2-3. FLIR Camera (right) and Hi-Flow Sampler (left)

While this approach was used early in the first few stations, it became clear that, as in the past GRI/EPA study, only the few very large leaks on the compressor seals and on the compressor blowdown OELs were important contributors to the total emissions.

2.3.1.1 High Volume Sampler

The high volume (Hi-Flow) sampler is portable, intrinsically safe, battery-powered instrument designed to determine the rate of gas leakage around various pipe fittings, valve packings, and compressor seals found in natural gas transmission, storage, and processing facilities. This instrument was used to measure leak rates for fugitive components that were identified as leaking by an initial IR camera evaluation of the site. A component’s leak rate is measured by sampling at a high flow rate so as to capture all the gas leaking from the component along with a certain amount of surrounding air. By accurately measuring the flow rate of the sampling stream and the natural gas concentration within that stream, the gas leak rate can be calculated using Equation 1. The instrument automatically compensates for the different specific gravity values of air and natural gas, thus assuring accurate flow rate calculations.

$$\text{Leak} = \text{Flow x (Gas sample – Gas background) x } 10^{-2} \qquad \text{Equation 1}$$

Where,

Leak	= rate of gas leakage from source (cfm);
Flow	= sample flow rate (cfm);
Gas sample	= concentration of gas from leak source (%); and
Gas background	= background gas concentration (%).

2.3.2 Open-Ended Lines

The emission rates from OELs and vents were determined by measuring the velocity profile across the vent line and the flow area at that point. Measurements on these lines were made using an enclosed rotary vane anemometer, or a hot-wire anemometer probe. For measurements made at a vent tip, flow velocities were measured with an encased rotary vane anemometer (Omega, model number HHF710). Rod packing tubing vents were measured using a low-flow slim probe hot wire anemometer (Omega, HHF42). The anemometer was enclosed in a fixed plastic pipe of approximately 3" diameter. The process vent line was sealed to the anemometer pipe, using a variety of simple seals such as gasket material and duct tape. The plastic pipe of a fixed size meant that only the anemometer readout (velocity) was needed, rather than the exact size of the process vent pipe. With the velocity and diameter, the volume released per unit time was calculated.

In ideal cases, there was one blowdown line per vent. In a few cases, multiple compressors were routed to a single co-mingled vent line, with no access to individual compressor vent lines upstream. These latter cases made it impossible to produce average compressor measurements for the site, especially where compressors in different modes (idle & depressurized and operating) were connected to one combined vent line. Photos of sampling a blowdown vent using a hot wire anemometer are shown in Figure 2-4 and 2-5.

Also, in one case the top of the combined vent was inaccessible, so a hot wire anemometer was inserted through a port (an open 1" diameter bleed valve) to make the vent velocity measurement.

When measuring flows from vents, a distinction is made between continuous fugitive leak emissions and the short duration discharge of de-pressured equipment, which is often called a blowdown. Blowdown quantities from the equipment is not the topic of this report, so those intermittent discharges were ignored. However, continuous leakage emissions that flow through the blowdown vent line when it is idle were included as fugitive emissions.

Blowdown emissions from continuous vent systems and intermittent vent systems during venting events are defined as "venting" emissions. For example, blowdown valves are opened to depressurize the system when a compressor is being shut down. The gas that is intentionally discharged during the blowdown is considered vented – not fugitive – emissions, and was not measured as part of this study. When a blowdown valve is closed, any gas leakage through the valve and out the vent stack was measured as fugitive emissions.

Additionally, some locations had lube oil tanks with separate elevated vents. If this configuration was present at a facility, the anemometer was used to measure emissions from the lube oil tank vents. Lube oil vents may include fuel/exhaust from the engine driver side of the compressor, unless there are separate lubrication systems for the engine side and the compression side of a compressor.

Figure 2-4. Measurement of Compressor Blowdown Vent Line Leakage with Encased Rotary Vane Anemometer

Figure 2-5. Sampling a Blowdown Vent with Hot Wire Anemometer

2.3.3 VPAC Measurements

In addition to the vent rate measurement equipment listed above, a “through-valve acoustic leak detection device” was utilized at six sites (four gathering/boosting compressor stations and two gas processing plants). Originally designed as a valve loss control system for flare and steam valves, the VPAC device uses a leak quantification algorithm to quantify a leak rate of valves. A photo of the VPAC in use is shown in Figure 2-6. A representative of the acoustic device manufacturer attended the site visits and conducted the VPAC tests. Dual measurements were taken where possible with both the acoustic device and the direct flow measurements to compare readings from the two devices. The VPAC measurements were reported to this project in a single-blind fashion. That is, the VPAC results were reported without knowledge of the results of the other direct measurements.

Figure 2-6. Through-Valve Acoustic Leak Detection (VPAC)

2.3.4 Compressor Seals

Measurements on compressor seals depended on the type of compressor. For reciprocating compressors, the following techniques were employed:

- Where rod packing vent lines were piped together (multiple cylinders joined into a single vent line per compressor), the enclosed rotary vane anemometer was used to make the measurements at the top of the rod packing vent line. In those cases, one single measurement per compressor was made. An example is shown in Figure 2-7.

- Where rod packing vent lines were individually vented to the atmosphere at the distance piece, each distance piece vent was measured with a hand-held hot wire anemometer. An example of this sampling is shown in Figure 2-8.

Figure 2-7. Sampling a Rod Packing Vent Stack with Enclosed Rotary Vane Anemometer

Figure 2-8. Sampling a Rod Packing Vent with Hand-held Hot Wire Anemometer

For centrifugal compressors with wet seals, measurements were made of wet seal degassing at the fill port to the seal oil sump. Each sump had a dedicated vent line, but in every case on this project, the tip of that vent line was placed above the turbine driver exhaust stack, preventing any safe access. The dedicated vent line had no valves and therefore could not be blocked/closed. For these measurements, the seal oil fill cap into the sump was opened, and it was assumed that this opening was now the path of least resistance, since the dedicated vent lines were 20-50 feet in length from the sump. Calibrated plastic bags of known internal volume were used to measure the vent rate, by timing how long each sump took to fill the bag. A set of three repeat bag measurements were made for each sump. In one case, there was no access to the fill port, and measurements were made using the enclosed anemometer directly off the top of the sump knock-out pot. This measurement technique is shown in Figure 2-9.

Figure 2-9. Centrifugal Compressor Seal Oil Gas Measurement Using Calibrated Bag Technique

On the wet seal data for centrifugal compressors, this study has found, after the fact, that there may be several technical issues surrounding a proper measurement from a wet seal system. Seal oil systems for centrifugal compressors can be complex, and may require the use of a detailed P&ID (piping and instrumentation diagram) to determine where all the flash locations in a system are. For example, as can be seen in Figure 2-10, a seal oil system may contain a flash drum/pot, where a separate vent line discharges any absorbed gas from the oil circulating to the seal. This is not the same line as the main vent line from the sump, where many companies (and this project) took samples. In addition, some seal oil systems may also have blowers, as shown in Figure 2-10, which would affect calibrated bag measurements from the sump. Many operators are not fully aware of the detailed workings of a particular compressor's seal oil system because it is a self-contained, skid mounted package that is not altered day-to-day by operations personnel. Therefore, this project's measurements of wet seal degassing should be used as a benchmark, but would require further analysis before the measurements could be used to develop new emission factors.

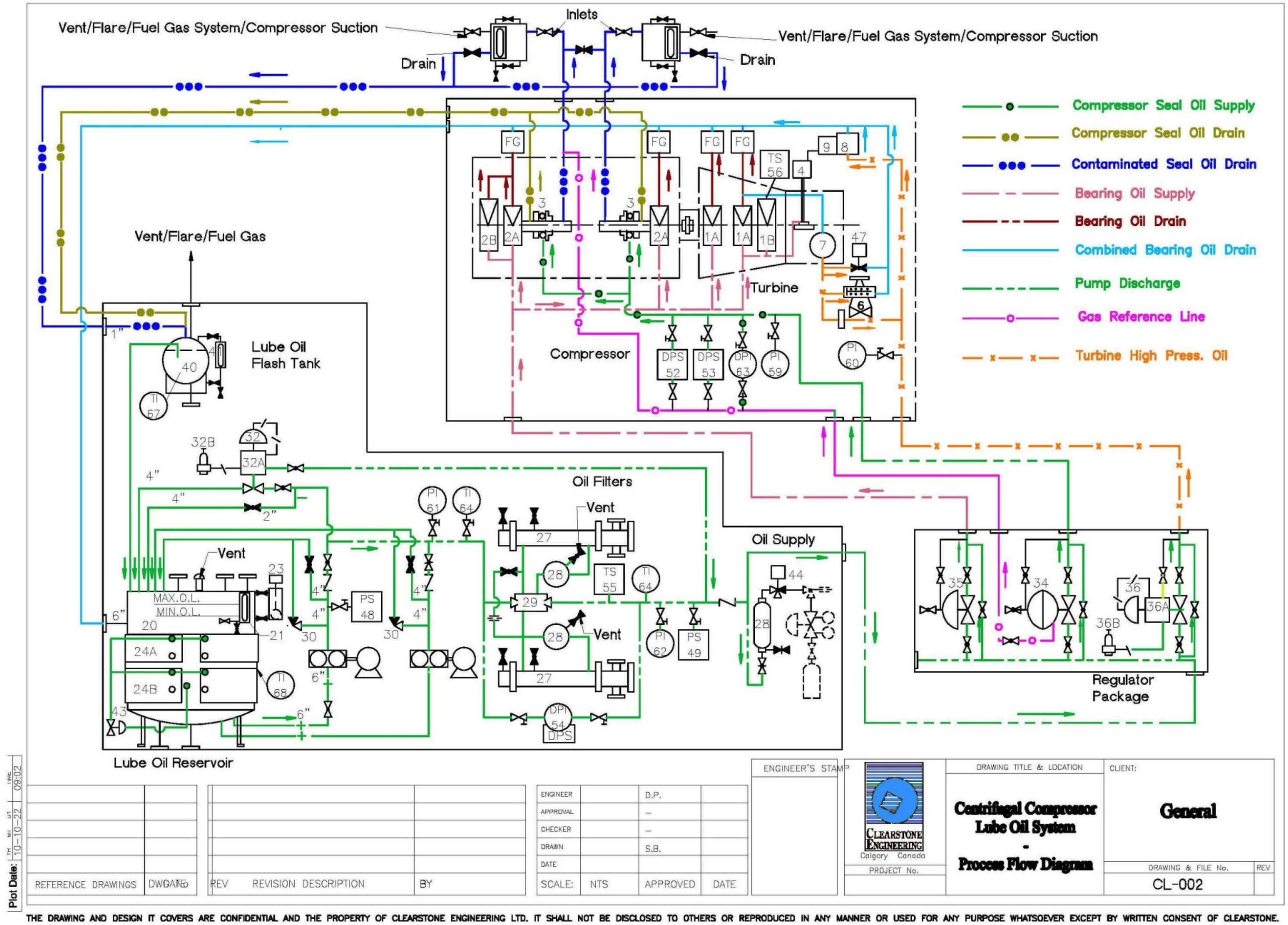


Figure 2-10. Centrifugal Compressor Lube Oil System Process Flow Diagram (Picard, 2011).

2.4 Quality Control

Where total site fugitives were measured, CH_4 background concentrations were measured simultaneous with every leak test and subtracted from the main sample flow CH_4 concentration. This is necessary to prevent background concentrations, which may be elevated by other nearby leaks, from influencing the leak rate determinations for individual components. The Hi-Flow Sampler uses two detectors simultaneously to determine the background and the main sample flow concentration. One detector draws air flow from the main sample hose and the second detector draws air from a separate background probe. The background probe was held near the leak being measured while the sample hose is held at the leak.

To check if the instrument is capturing all the gas that is escaping from the leak source, two measurements were performed at two different flow rates. The first measurement was taken at the highest possible flow rate, followed by a second measurement at a flow rate that is approximately 70–80% of the first. If the two calculated leak rates are within 10% of each other, then it was assumed that all gas has been captured during the test.

Calibration checks of both the background and leak-gas detectors were performed at the beginning and end of every day using a certified 2.5% CH_4 gas standard. The Hi-Flow Sampler has a built in feature to perform these checks.

The high flow sampler was calibrated upon arrival at each test site or whenever a single point check of the calibration is outside the ±10% acceptability range. The calibration check was performed using the vendor-supplied calibration kit with zero air and gas standards of 2.5% and 100% CH_4. The leak-gas and background gas detectors were calibrated at these concentrations using the menu-driven programmed procedure given in the Hi-Flow Sampler operation and maintenance manual.

For the other instruments, such as the anemometers, the instruments were calibrated before and after the tests to assure their accuracy. Readings made with these instruments were corrected for the actual gas composition because in most cases the instruments were calibrated on air and had to be corrected for measuring natural gas.

Results of this measurement project were also cross checked by independent technical review of a scientist and engineer not associated with this project.

3.0 Measurement Results and Analyses

This section presents the results from the field measurement campaigns of this study. Raw measurement data is presented in Appendix B.

3.1 Measurement Results

Component counts were collected for five transmission compressor stations, and are shown as an average per station in Table 3-1.

Table 3-1. Component Count Summary

Component	Average Count per Facility	Standard Deviation
Valves	327	112
Flanges	415	163
Compressor Seals	22	14
PRVs	13	5
OELs	16	22
Connectors	376	209

The overall fugitive emissions from valves, flanges, and other sources are reported as an average over all five sites in Table 3-2 below. As the table shows, the new factors show a lower leak rate from an average component when compared to the GRI/EPA data from the 1990's. While this is from a relatively small sample set compared to the GRI/EPA study, these lower emission factors may be the result of better Leak Detection and Repair (LDAR) practices that have developed since the 1990s' for ordinary fugitives in natural gas systems.

Table 3-2. Fugitive Emissions from Valves and Flanges using Hi-Flow Sampler Compared to Previous Results

Facility Component	Total Number of Components Screened	Component Emission Factor (Mscfy)	1996 GRI/EPA Emission Factor (Mscfy)
Valves	1,634	0.093	0.184
Flanges	1,244	0.051	

As was found in the previous GRI/EPA study, the largest single emission sources at a compressor station are the compressor blowdown (BD) vent lines and the compressor seal vents. These remain the largest sources in the sampling for this project. Sampling results for compressor vents are provided in Tables 3-3, 3-4, and 3-5. It is assumed that transmission compression, gathering/boosting, and gas processing centrifugal compressors emission factors can be grouped together; whereas, transmission compression reciprocating compressors are grouped separately from other reciprocating compressors.

Table 3-3. Sampling Results for Centrifugal Compressors Vents
(Includes transmission compression, gathering/boosting, and gas processing plant measurements)

Scenario	Sample Size	Average CH_4 Emission Factor (Mscfy)	1996 GRI/EPA Emission Factor[1] (Mscfy)
Average BD vent for Run	3	83	9,352
Average BD vent for Idle + Run*	11	1,584	
Wet Seal (Run)	9	8,137	165

*For some sites, the running and idle compressors were routed to vent with blowdown lines and PRVs, therefore individual compressor operating mode emission factors could not be calculated.
[1]Hummel, K.E., Campbell, L.M., and M.R. Harrison (Vol. 8), Table 4-15, 1996 GRI/EPA CH_4 study, adjusted for 24.2% time the compressor is pressurized.

Table 3-4. Sampling Results for Reciprocating Compressors (Transmission Compressors)

Scenario	Sample Size	Average (Mscfy)	1996 GRI/EPA Emission Factor[1] (Mscfy)
Average BD vent for Idle + pressurized	10	1,957	3,683
Average BD + PRV for Run*	6	8,512	
Average BD + PRV vent for Idle + depressurized*	15	15,792	
Average Rod Packing for Idle + pressurized	5	12,236	396
Average Rod Packing for Run	2	29,603	

*Includes PRVs. [1]Vol. 8, Table 4-15, 1996 GRI/EPA CH4 study.
[1]Hummel, K.E., Campbell, L.M., and M.R. Harrison (Vol. 8), Table 4-15, 1996 GRI/EPA CH4 study, adjusted for 79.1% time the compressor is pressurized.

Table 3-5. Sampling Results for Reciprocating Compressors (Gathering/Boosting Compressors)

Scenario	Sample Size	Average (Mscfy)	1996 GRI/EPA Emission Factor (Mscfy)
Average BD vent for Run	16	28	0.215[1]
Average BD vent for Idle + depressurized	8	0	
Average PRV for Run	12	1,097	1.332[2]
Average PRV for Idle + depressurized	6	0	N/A
Average Rod Packing for Run	15	241	9.48[3]

[1]Hummel, K.E., Campbell, L.M., and M.R. Harrison (Vol. 8), Appendix B-4, 1996 GRI/EPA CH_4 study. (Gathering Compressors OEL). GRI/EPA treated all OELs in production identically, and did not separate out the compressor BD line OELs.
[2]Hummel, K.E., Campbell, L.M., and M.R. Harrison (Vol. 8), Appendix B-4, 1996 GRI/EPA CH_4 study (Gathering Compressors PRV).
[3]Hummel, K.E., Campbell, L.M., and M.R. Harrison (Vol. 8), Appendix B-4, 1996 GRI/EPA CH_4 study (Gathering Compressors, Compressor Seal). Assumes four seals per compressor.

3.3 Comparison to Existing Data

The new measurements made for this project on fugitive components produced lower emission factors than the previous GRI/EPA study, as shown in Table 3-1. This may be due to improved LDAR practices for accessible fugitive components that have been implemented by companies in the past two decades. Some of the sites visited were for companies that have participated in Natural Gas STAR. Programs like EPA's Natural Gas STAR and general awareness of GHG emissions may have led to an actual reduction. However, it is premature to make a definitive finding given the limited sample set for this project.

For compressor vents (rod packing vent and blowdown line vents), the results are mixed. As shown in Table 3-3, for centrifugal transmission compressors this project found the average blowdown line emission factors were significantly lower than the GRI/EPA study, but found wet seal degassing vent emissions that were much higher. Both of the new measurements are from a very limited sample set, smaller than the previous sample set of the GRI/EPA study. It should also be noted that it is difficult to compare the simple emission factors from this study with the GRI/EPA emission factors for an average compressor, which were already adjusted for operating time of the compressors.

For the wet seal degassing vents, it is possible that this project over-measured, by capturing some exhaust gas blowthrough from the engine side of the shared seal oil system, or from systems with blowers if the blowers were not identified. Since no gas analysis was performed on the measured volumes, we are unable to rule out that possibility. It is also possible that the volumes were under-measured since the main seal oil vent line could not be blocked during the measurement. Additional tests and investigations are needed to make a definitive determination; however, the experiences from this study can help inform the design of sampling procedures under the GHG reporting rule.

For reciprocating transmission compressors, this project found average blowdown line emission factors that were significantly higher than the GRI/EPA study, and rod packing vent emissions that were also much higher as shown in Table 3-4. Both of the new measurements are from a very limited sample set, smaller than the previous sample set of the GRI/EPA study. While there is not enough data to draw a definitive conclusion, it is clear that the new data set does not indicate that reciprocating compressor vent emission factors have been reduced since the 1990's. This may be valid given the age of many of the reciprocating compressors, which have only aged further since the tests in the 1990's. Technology for seal packing and isolation valve seats has not changed significantly since the GRI/EPA report. Given the data from EPA's Natural Gas STAR and the GRI/EPA study, a company could monitor rod packing emissions more carefully if they so elected, and thus replace rod packing more frequently. The measurements from this project do not seem to show any reductions from those practices, if they exist.

3.4 Comparison of VPAC to Direct Measurement Results

A comparison was made between the direct measurement readings and the VPAC method measurements. A plot of the data along with a linear regression of the data are shown in Figures 3-1 and 3-2. Ideally, it would be expected that a one-to-one relationship would be demonstrated between two comparable measurement methods. Driven by two high values (greater than 7,000 scf/day) measured by the direct measurement approach, a slope of 0.0038 was observed for the complete set of VPAC measurements as a function of direct measurements. If the two direct measurement high flow data points are removed from the data set, a negative correlation (slope) of the two measurement methods is observed, at a slope of -0.0024.

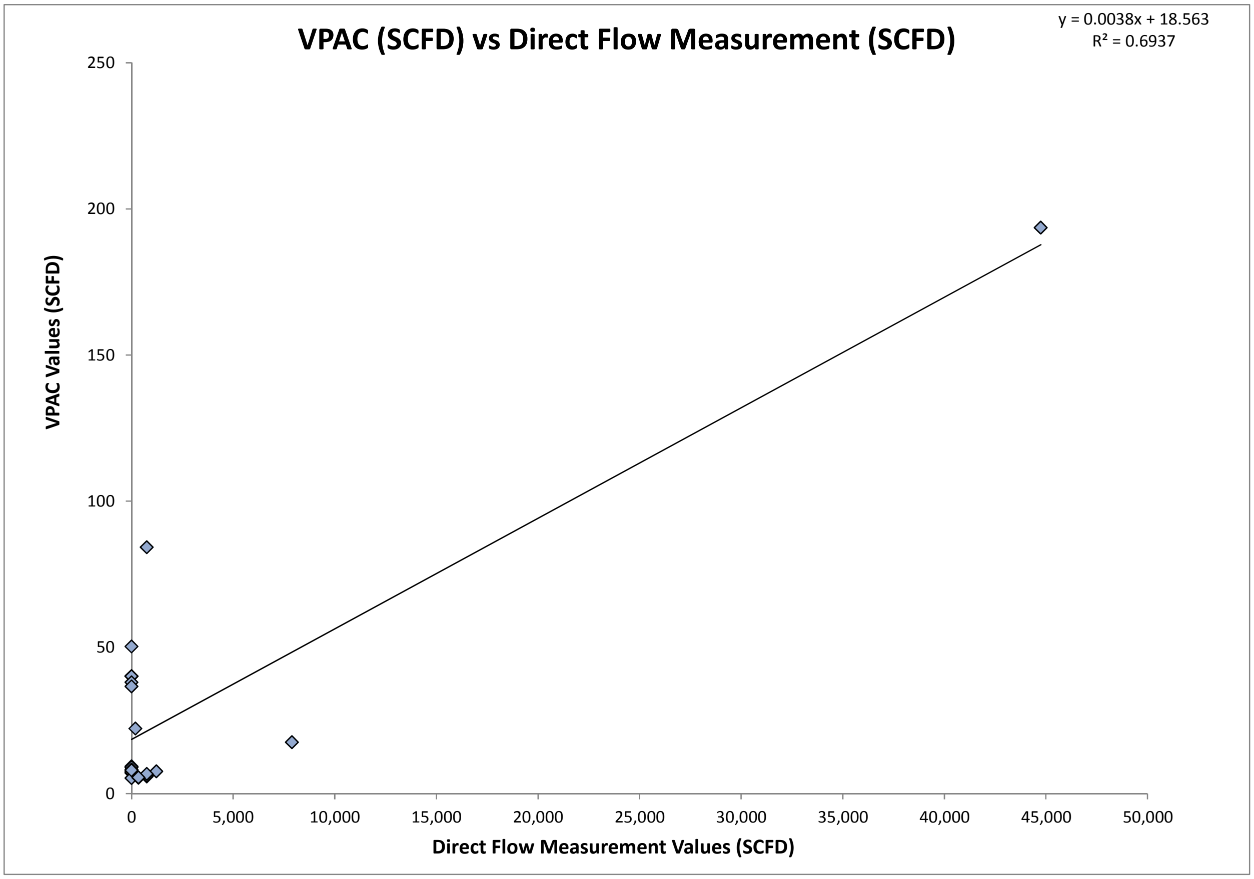


Figure 3-1. VPAC vs. Direct Flow Measurement Method, complete data set
(please note the axes scales)

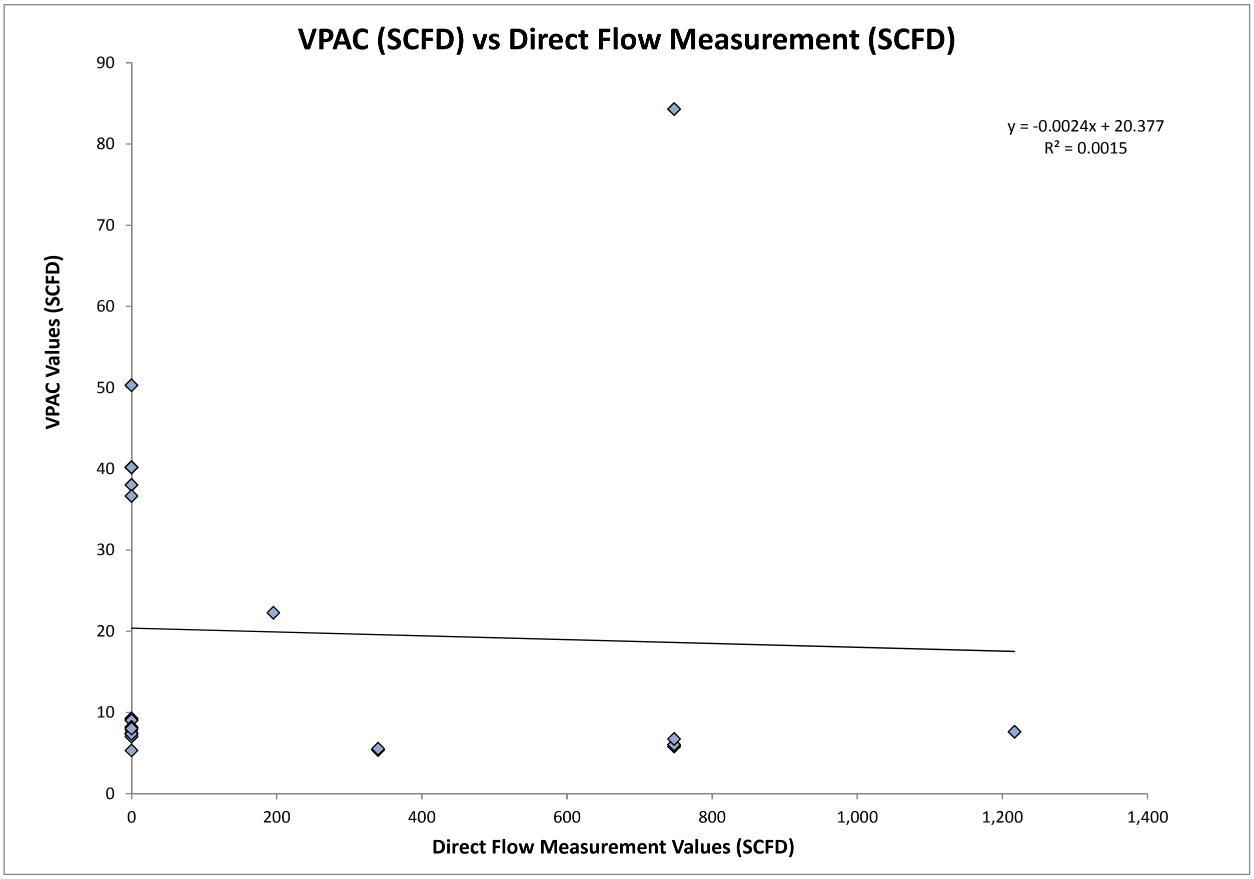


Figure 3-2. VPAC vs. Direct Flow Measurement Method, modified data set for lower flow
(please note the axes scales)

There appears to be no statistically significant correlation between the VPAC and the direct flow measurement methods. Therefore, it does not appear that the VPAC method should be considered as an accurate alternative to direct measurement for the few sources tested in this study at gathering/boosting compressors and gas processing plants.

4.0 Conclusions and Recommendations

The initial impetus of this study was to establish new emission factors that were both statistically superior to the GRI/EPA emission factors, and more relevant than the GRI/EPA factors (by including more recent samples). Some stakeholders in the process expected that the factors might be lower, given improvements in practices.

The data from this report is not as robust as the GRI/EPA data, since fewer sites were sampled. For centrifugal transmission compressors, the measurements of fugitive components and blowdown line vents produced lower emission factors than the previous GRI/EPA study; however, centrifugal wet seal degassing vent emissions were much higher. On the wet seal data for centrifugal compressors, this study has found after the fact, that there may be several technical issues surrounding a proper measurement from a wet seal system; therefore, the emission factors from this report for wet seal degassing should be used only as an evaluative measurement. A useful conclusion from this study may be that future measurement campaigns need to understand the detailed design of each unique sampled compressor seal oil system, understand all the possible degassing locations, and only then determine where to sample the system. Since wet seal gas systems require a more detailed evaluation than was previously anticipated, installation of measurement ports may require a careful review of the P&ID drawings for the seal oil system, finding flash points such as the flash drum pot for measurement. If blowers are used, a sample from the seal oil sump vent may not be representative of the total generation of all flash gas.

For reciprocating transmission compressors, this project found average blowdown line and rod packing vent emission factors that were significantly higher than the GRI/EPA study. While there is not enough data to draw a definitive conclusion, it is clear that the new data set does not indicate that reciprocating compressor vent emission factors have been reduced since the 1990's. These higher results may be due to continued aging of the compressors since the 1996 GRI/EPA study.

There appears to be no statistically significant correlation between the VPAC measurements and the direct flow measurement methods. Therefore, it does not appear that the VPAC method should be considered an accurate alternative to direct measurement for the few sources tested in this study at gathering/boosting compressors and gas processing plants.

Some of the insight from this report might be useful for future measurement campaigns or compressor operators. For example:

- More explicit specifications for location of the wet seal degassing vent measurement (including possible protocols for that measurement);
- Use of calibrated bag measurements for wet seal degassing since the oil mist may adversely affect other measurement instruments;
- Reconsideration of alternate methods to the acoustic through-valve leak device for this service, since the acoustic through-valve device appears non-correlated to direct measurements;
- More explicit specifications for location of ports for individual compressor BD line leakage measurements; and
- Protocols for certain measurement techniques, such as use of inserted anemometers and encased anemometers.

Appendix A – Summary of Document Review

Doc. #	Document or Reference Reviewed	Review Comments
1	American Gas Association. Gas Facts, 2007, A Statistical Record of the Gas Industry, 2006 Data. 01 March 2008.	Provides activity data: miles of plastic pipeline mains
2	American Gas Association. Greenhouse Gas Emission Estimation Methodologies, Procedures, and Guidelines for the Natural Gas Distribution Sector, Draft, Prepared by innovative environmental solutions, inc., April 4, 2008.	All emission factors are derived from the GRI/EPA study
3	American Petroleum Institute. *Fugitive Hydrocarbon Emissions for Oil and Gas Production Operations*, API Publication Number 4589, Prepared by Star Environmental. December 1993.	Provides emission factors, but not for the sources of interest
4	Australian Government Department of Climate Change. Australian Methodology for the Estimation of Greenhouse Gas Emissions and Sinks 2006 Energy (Fugitive Fuel Emissions), National Greenhouse Gas Inventory Committee, Australia, December 2007. http://www.greenhouse.gov.au/inventory/methodology/index.html	References E&P forum for a fugitive emission factor based on volume flared.
5	Australian Government Department of Climate Change. Australian Methodology for the Estimation of Greenhouse Gas Emissions and Sinks 2006 Energy (Stationary Sources), National Greenhouse Gas Inventory Committee, December 2007. http://www.greenhouse.gov.au/inventory/methodology/index.html	Does not address emission sources of interest
6	Australian Government Department of Climate Change. National Greenhouse Accounts (NGA) Factors, Canberra ACT, January 2008.	Does not address emission sources of interest
7	California Air Resources Board. Documentation of California's Greenhouse Gas Inventory (website), April 10, 2008, http://www.arb.ca.gov/cc/inventory/doc/doc_index.php	New data sources reference Gas STAR
8	California Climate Action Registry. Natural Gas Transmission and Distribution Greenhouse Gas Reporting Protocol, Draft, February 2008.	Does not address emission sources of interest
9	California Energy Commission, Evaluation of Oil and Gas Sector Greenhouse Gas Emissions Estimation and Reporting, Final Draft Report FR-05-100, April 2006.	Provides plastic pipeline emission factor comparison derived from GRI/EPA study data
10	California Energy Commission, *Research Roadmap for Greenhouse Gas Inventory Methods*, Prepared by University of California, Berkeley, Lawrence Berkeley National Laboratory, California Energy Commission, Consultant Report CEC-500-2005-097, July 2005. http://www.energy.ca.gov/pier/final_project_reports/CEC-500-2005-097.html	Provides emission factors for production wells, compressor station, plastic pipeline, and distribution services. Cite EIIP and ICF, which are believed to be derived from GRI/EPA study
11	Canadian Association of Petroleum Producers. *A National Inventory of Greenhouse Gas (GHG), Criteria Air Contaminant (CAC) and Hydrogen Sulphide (H2S) Emissions by the Upstream Oil and Gas Industry, Vols. 1-5*, Prepared by Clearstone Engineering Ltd., Calgary, Alberta, Canada, September 2004. http://www.capp.ca/default.asp?V_DOC_ID=763&SubjectID=414802	Does not address emission sources of interest
12	Delucchi, Mark A. A Lifecycle Emissions Model (LEM): Lifecycle Emissions from Transportation Fuels, Motor Vehicles, Transportation Modes, Electricity Use, Heating and Cooking Fuels, and Materials, Appendix E: Methane Emissions from Natural Gas Production, Oil Production, Coal Mining and Other Sources, Institute of Transportation Studies, University of California Davis, UCD-ITS-RR-03-17E, December 2003. http://pubs.its.ucdavis.edu/author_detail.php?id=5	Does not address emission sources of interest
13	Environment Canada Greenhouse Gas Division. Inventory Report: Greenhouse Gas Sources and Sinks in Canada 1990-2005, April 2007.	Does not address emission sources of interest

Appendix A –Summary of Document Review, continued

Doc. #	Document or Reference Reviewed	Review Comments
14	European Environment Agency. Annual European Community Greenhouse Gas Inventory 1990-2005 and Inventory Report 2007, Technical Report No 7/2007, 27 May 2007. http://reports.eea.europa.eu/technical_report_2007_7/en	Does not address emission sources of interest
15	Fernandez, Roger, Robin Petrusak, Donald Robinson, and Duane Zavadil. Cost Effective Methane Emission Reductions for Small and Midsize Natural Gas Producers, Journal of Petroleum Technology, June 2005. http://www.icfi.com/Markets/Environment/doc_files/methane-emissions.pdf	Does not provide emission factors or specific data of interest to the study
16	Intergovernmental Panel on Climate Change. *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 2, Chapter 4: Fugitive Emissions*, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds), IGES, Japan, 2006.	References the API *Compendium* and provides high level national emission factors. Provide combined venting and flaring emission factors associated with well testing and well servicing activities in developed and developing countries.
17	Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme. IPCC Emission Factor Database (EFDB) (website), April 10, 2008. http://www.ipcc-nggip.iges.or.jp/EFDB/find_ef_main.php	Does not address emission sources of interest
18	International Association of Oil and Gas Producers. *Environmental Performance in the E&P Industry 2006 Data*, Report No. 399, October 2007. http://www.ogp.org.uk/pubs/399.pdf	Does not provide emission factors or specific data of interest to the study
19	International Association of Oil and Gas Producers. Flaring & Venting in the Oil & Gas Exploration & Production Industry: An Overview of Purpose, Quantities, Issues, Practices and Trends, Report No. 2.79/288, January 2000. http://www.ogp.org.uk/pubs/288.pdf	Does not provide emission factors or specific data of interest to the study
20	International Petroleum Industry Environmental Conservation Association, International Association of Oil and Gas Producers and American Petroleum Institute. *Petroleum Industry Guidelines for Reporting Greenhouse Gas Emissions*, Prepared by Battelle, December 2003.	Does not provide emission factors or specific data of interest to the study
21	Interstate Natural Gas Association of America. *Activities to Reduce Greenhouse Gas Emissions from Natural Gas*, Prepared by Energy Resources International Inc., Publication F-2000-05, Washington, D.C. 20036, 2000. http://www.ingaa.org/cms/31/3243/3247/3229/277.aspx	Does not address emission sources of interest
22	Interstate Natural Gas Association of America. Greenhouse Gas Emission Estimation Guidelines for Natural Gas Transmission and Storage, Volume 1: GHG Emission Estimation Methodologies and Procedures, Prepared by Innovative Environmental Solutions, Inc., Washington, D.C. 20002, Revision 2, September 28, 2005.	Provides emission factors for specific types of pneumatic devices: actuators or controllers, continuous bleed pneumatics, pneumatic/ hydraulic valve operator, and turbine valve operator. Data derived from GRI/EPA study
23	Interstate Natural Gas Association of America, American Petroleum Institute, and American Gas Association. INGAA/API/AGA Natural Gas Systems GHG Emission Factor Comparison & Improvement Collaborative Project – Status Report: Task 2 - Emission Factor Comparison, Draft Technical Report, 27 November 2005.	References data derived from the GRI/EPA study. Identifies emission estimate approaches that can most benefit from improved methodology and data gaps for natural gas systems

Appendix A –Summary of Document Review, continued

Doc. #	Document or Reference Reviewed	Review Comments
24	Methane to Markets. Methane to Markets Documents, Tools and Resources, April 10, 2008. http://www.methanetomarkets.org/index.htm	Does not provide emission factors or specific data of interest to the study
25	Robinson, D.R., R. Fernandez, and R.K. Kantamaneni. *Methane Emissions Mitigation Options in the Global Oil and Natural Gas Industries*. http://www.epa.gov/gasstar/pdf/ng020.pdf	Does not provide emission factors or specific data of interest to the study
26	United Nations Economic Commission for Europe Convention on Long-range Transboundary Air Pollution Co-operative Programme for Monitoring and Evaluation of the Long-range transmission of Air Pollutants in Europe. *EMEP/CORINAIR Emission Inventory Guidebook - 2007*, Technical Report No 16/2007, December 2007. http://reports.eea.europa.eu/EMEPCORINAIR5/en/page002.html	Provides fugitive component emission factors for oil and gas facilities based on a 1992 Canadian study
27	U.S. Department of Energy, Energy Information Administration Office of Integrated Analysis and Forecasting. *Documentation for Emissions of Greenhouse Gases in the United States 2005*, DOE/EIA-0638 (2005), Washington, D.C. 20585, October 2007.	Does not provide emission factors or specific data of interest to the study
28	U.S. Department of Energy, Energy Information Administration. *Monthly Energy Review*, Washington, D.C., various years. http://www.eia.doe.gov/overview_hd.html	Does not provide emission factors. May provide information of interest to activity data
29	U.S. Department of Energy, Energy Information Administration. *Natural Gas Annual*, Washington, D.C., various years. http://tonto.eia.doe.gov/dnav/ng/ng_pub_publist.asp	Does not provide emission factors. May provide information of interest to activity data
30	U.S. Department of Energy, Energy Information Administration. *Natural Gas Monthly*, Washington, D.C., various years. http://tonto.eia.doe.gov/dnav/ng/ng_pub_publist.asp	Does not provide emission factors. May provide information of interest to activity data
31	U.S. Department of Energy, Energy Information Administration Office of Policy and International Affairs. *Technical Guidelines Voluntary Reporting of Greenhouse Gases (1605(b)) Program, Office of Policy and Internal Affairs, United States Department of Energy*, January 2007.	References emission factors derived from the GRI/EPA study
32	U.S. Department of the Interior, Minerals Management Service Gulf of Mexico OCS Region. *Year 2005 Gulfwide Emission Inventory Study*, OCS Study MMS 2007-067, Prepared by Eastern Research Group, Inc., New Orleans, December 2007. http://www.gomr.mms.gov/PI/PDFImages/ESPIS/4/4276.pdf	*Report only provides summary data. Access to the original database could be valuable*
33	U.S. Department of Transportation, Office of Pipeline Safety. Pipeline Statistics, April 15, 2008. http://ops.dot.gov/stats/stats.htm	Does not provide emission factors. May provide information of interest to activity data
34	U.S. Environmental Protection Agency. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 - 2005*, Washington, D.C. 20460, April 15, 2007. http://www.epa.gov/climatechange/emissions/downloads06/07CR.pdf	Does not provide emission factors or specific data of interest to the study
35	U.S. Environmental Protection Agency. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 - 2006*, Public Review Draft, Washington, D.C. 20460, February 22, 2008. http://www.epa.gov/climatechange/emissions/usinventoryreport.html	Does not provide emission factors or specific data of interest to the study

Appendix A –Summary of Document Review, continued

Doc. #	Document or Reference Reviewed	Review Comments
36	U.S. Environmental Protection Agency. Natural Gas STAR Documents, Tools and Resources. http://www.epa.gov/gasstar/	*Some specific information is presented below*
37	CAPP. CH4 and VOC Emission from the Canadian Upstream Oil and Gas Industry, Volume 1. Organic and Common-Pollutant Emissions by the Canadian Upstream Oil and Gas Industry.	*Provides Canadian emission factors for well servicing operations (by Province/Territory), counts of gas wells (high pressure sour, high pressure sweet, and low pressure sour), fugitive component counts for production wells (high pressure and shallow gas wells), and fugitive component counts and emissions for reciprocating versus centrifugal compressors. Reports are from the mid-90s. Information is used or cited in the API Compendium.*
38	CAPP. A Detailed Inventory of CH4 and VOC Emission from the Canadian Upstream Oil and Gas Industry, Volume 2. Development of the Inventory. Canadian Petroleum Association (CPA). A Detailed Inventory of CH4 and VOC Emissions from Upstream Oil and Gas Operations in Alberta, Volumes I-III, March 1992.	
39	CPA. A Detailed Inventory of CH4 and VOC Emissions From Upstream Oil and Gas Operations in Alberta. Volume 1. Overview of the Emission Data. Canadian Petroleum Association (CPA). A Detailed Inventory of CH4 and VOC Emissions from Upstream Oil and Gas Operations in Alberta, Volumes I-III, March 1992.	*In addition to information noted above for CAPP study, these reports provide fugitive compressor seal emission factors. Reports are from the mid-90s. Information is used or cited in the API Compendium.*
40	CPA. A Detailed Inventory of CH4 and VOC Emissions From Upstream Oil and Gas Operations in Alberta. Volume 2. Development of the Inventory. Canadian Petroleum Association (CPA). A Detailed Inventory of CH4 and VOC Emissions from Upstream Oil and Gas Operations in Alberta, Volumes I-III, March 1992.	
41	CPA. A Detailed Inventory of CH4 and VOC Emissions From Upstream Oil and Gas Operations in Alberta. Volume 3. Results of the Field Validation Program. Canadian Petroleum Association (CPA). A Detailed Inventory of CH4 and VOC Emissions from Upstream Oil and Gas Operations in Alberta, Volumes I-III, March 1992.	

Appendix B – Data Summary

(A full compilation of the data collected are available in a spreadsheet addendum to this report)

Table B-1. Fugitive Emissions from Valves and Flanges using Hi-Flow Sampler

Hundreds of components were screened using the FLIR camera, most components showed no leaks. The few components that did indicate a leak with the FLIR were measured using the Hi-Flow device and are presented in this table.

Site	Leaking Component	Mscf/yr
Site 1	Valve 1	83.52
	Flange 1	77.95
	Flange 2	11.14
	Flange 3	53.82
	Flange 4	7.42
	Flange 5	22.27
Site 2	Valve 1	53.82
	Valve 2	40.83
	Flange 1	111.35
	Flange 2	118.78
	Flange 3	87.23
	Flange 4	87.23
Site 3	Valve 1	1,033.73
	Valve 2	11.14
	Valve 3	139.19
Site 4	Valve 1	14.72
	Valve 2	331.65
	Valve 3	208.66
	Flange 1	161.88
	Flange 2	38.37
	Flange 3	157.15
	Flange 4	45.73
	Flange 5	19.97
	Flange 6	7.36
Site 5	Valve 1	62.02
	Valve 2	176.60
	Valve 3	259.65
	Flange 1	29.43
	Flange 2	129.82

Table B-2. Centrifugal Compressor Vents (Transmission, Gathering/Boosting, and Gas Processing Plant)

Site	Equipment Name	Run Mode	Wet Seal Degassing		Blowdown Line Leaks	
			SCFD	VPAC Comparison SCFD	SCFD	VPAC Comparison SCFD
Site 3	Centrif 1	Idle, depressurized	0.00	-	129,756.40	-
	Centrif 2	Running	37,028.57	-	0.00	-
	Centrif 3	Running	51,840.00	-	0.00	-
Site 9	Centrif 1	Running	3,021.06	-	0.00	50.28
	Centrif 2	Running	3,756.20	-	195.49	22.24
Site 10	Centrif 1	Running	18,103.71	-	-	-
	Centrif 2	Idle, depressured	0.00	-	-	-
	Centrif 3	Running	60,413.51	-	-	-
	Centrif 4	Running	0.00	-	-	-
	Blow Down #1 - Combined (4 compressors + 2 stations + 2 PRVs)	n/a	-	-	44,745.54	193.54
	Blow Down #2 - Emergency Shutoff Valve	n/a	-	-	7,890.81	17.57
Site 11	Centrif 1	Running	12,713.28	-	747.88	5.78
	Centrif 2	Idle, depressured	0.00	-		84.28
	Centrif 3	Running	14,645.70	-		6.04
	Centrif 4	Running	35,698.89	-		6.72
	Centrif 5	Running	22,782.20	-	339.95	5.36
	Centrif 6	Running	29,494.81	-		5.52

Table B-3. Reciprocating Compressor Vents (Transmission Compressors)

Site	Equipment Name	Run Mode	Blowdown Line Leaks	Rod Packing Vent
			SCFD	SCFD
Site 1	Recip 1	Idle, pressurized	13,404.59	47,934.80
	Recip 2	Idle, pressurized	13,404.59	57,157.16
	Recip 3	Idle, pressurized	13,404.59	-
	Recip 4	Idle, pressurized	13,404.59	-
	Recip 5	Idle, depressurized, open	4,825.65	-
Site 2	Recip 1	Idle, pressurized	0.00	0.00
	Recip 2	Idle, pressurized	0.00	0.00
	Recip 3	Idle, pressurized	0.00	18,766.42
	Recip 4	Idle, pressurized	0.00	35,709.82
	Recip 5	Idle, pressurized	0.00	8,042.75
	Recip 6	Idle, pressurized	0.00	-
	Station BD Vent #1 - Yard Piping	n/a	10,187.49	-
	Station BD Vent #2 - Idle Line piping	n/a	-	-
	Station BD Vent #3 - Yard Piping	n/a	9,115.12	-
Site 4	Recip 1	Idle, depressured	29,021.41	-
	Recip 2	Running	27,984.93	-
	Recip 3	Idle, depressured	35,758.52	11,401.27
	Recip 4	Running	26,948.45	-
	Recip 5	Idle, depressured	67,371.13	10,364.79
	Recip 6	Running	32,130.84	-
	Recip 7	Idle, depressured	77,735.91	8,291.83
	Recip 8	Running	52,860.42	-
	Recip 9	Idle, depressured	150,289.43	26,948.45
	Recip 10	Idle, depressured	15,547.18	
	Recip 11	Idle, depressured	33,167.32	-
	Recip 12	Idle, depressured	18,656.62	-
	Recip 13	Idle, depressured	34,203.80	-
	Recip 14	Idle, depressured	25,911.97	-
	Recip 15	Idle, depressured	21,766.06	-

Table B-3. Reciprocating Compressor Vents (Transmission Compressors), continued

Site	Equipment Name	Run Mode	Blowdown Line Leaks	Rod Packing Vent
			SCFD	SCFD
Site 5	Recip 1	Running	0.00	NM
	Recip 2	Idle, depressured	17,620.14	NM
	Recip 3	Idle, depressured	9,328.31	NM
	Recip 4	Running	0.00	NM
	Recip 5	Idle, depressured	107,793.80	NM
	Recip 6	Idle, depressured	NM	55,969.86
	Recip 7	Idle, depressured	NM	106,239.08

NM = Not Measured

Table B-4. Reciprocating Compressor Vents (Gathering/Boosting Compressors)

Site	Equipment Name	Run Mode	Rod Packing Seal Leaks	Blowdown Line Leaks		Discharge PRV	Lube Oil Tank
			SCFD	SCFD	VPAC Measurement SCFD	SCFD	SCFD
Site 6	Recip 1	Running	387.03	0.00	7.28	-	4,552.70
	Recip 2	Running	0.00	0.00	7.46	0.00	0.00
	Recip 3	Running	91.15	0.00	7.29	0.00	9,202.27
	Recip 4	Running	154.25	0.00	7.02	0.00	37,971.46
	Recip 5	Running	3,187.36	0.00	7.84	17,435.88	25,378.89
	Recip 6	Running	0.00	1,216.83	7.61	0.00	-
	Recip 7	Idle, depressured	0.00	0.00	40.17	0.00	-
	Recip 8	Idle, depressured	0.00	0.00	40.17	0.00	-
	Recip 9	Running	882.03	0.00	40.17	14,723.63	74,586.80
	Recip 10	Idle, depressured	0.00	0.00	40.17	-	-
	Recip 11	Idle, depressured	0.00	0.00	40.17	0.00	-
	Recip 12	Running	112.18	0.00	7.33	0.00	5,811.96
	Recip 13	Idle, depressured	0.00	0.00	40.17	-	-
Site 7	Recip 1	Running	15.44	0.00	9.02	3,914.03	-
	Recip 2	Running	262.40	0.00	9.10	0.00	-
	Recip 3	Running	370.45	0.00	9.27	0.00	-
	Recip 4	Idle, depressured	0.00	0.00	-	0.00	-
	Recip 5	Idle, depressured	0.00	0.00	-	0.00	-
	Recip 6	Running	308.71	0.00	9.03	0.00	-
Site 8	Recip 1	Idle, depressured	0.00	0.00	38.02	0.00	-
	Recip 2	Running	78.33	0.00	5.29	-	0.00
	Recip 3	Running	1,345.65	0.00	8.13	0.00	0.00
	Recip 4	Running	170.65	0.00	8.18	0.00	0.00
	Recip 5	Running	2,544.43	0.00	7.99	0.00	0.00

Appendix C – References

American Petroleum Institute (API). Compendium of Greenhouse Gas Emissions Estimation Methodologies for the Oil and Gas Industry, API, Washington, DC, 2004. Errata, February, 2005. http://www.api.org/ehs/climate/new/upload/2004_COMPENDIUM.pdf http://ghg.api.org/documents/CompendiumErrata205.pdf

California Energy Commission (CEC). *Evaluation of Oil and Gas Sector Greenhouse Gas Emissions Estimation and Reporting*, California Energy Commission, Consultant Report, Final Draft, April 14, 2006.

GRI and EPA. Harrison, M.R., Shires, T.M., Wessels, J.K., Cowgill, R. M. *Methane Emissions from the Natural Gas Industry, Volumes 1 – 15*, Final Report, GRI-94/0257 and EPA-600/R-96-080, Gas Research Institute and US Environmental Protection Agency, June 1996.

Hummel, K.E., Campbell, L.M., and M.R. Harrison. *Methane Emissions from the Natural Gas Industry, Volume 8: Equipment Leaks*, Final Report, GRI-94/0257.25 and EPA-600/R-96-080h, Gas Research Institute and US Environmental Protection Agency, June 1996. (Part of the GRI/EPA methane emissions inventory project.) www.gastechnology.org

Picard, Dave. *Centrifugal Wet Seal Schematic*. Clearstone Engineering, LTD. E-mail to the authors. 15 August 2011.

Rolls Royce. *Centrifugal compressors: Pipeline and barrel compressors for the energy industry*. 2010. http://www.rolls-royce.com/Images/EC201(rev)_tcm92-22934.pdf

U.S. Environmental Protection Agency (EPA). Lessons Learned from Natural Gas STAR Partners. *Replacing Wet Seals with Dry Seals in Centrifugal Compressors*, October 2006. http://www.epa.gov/gasstar/documents/ll_wetseals.pdf

U.S. Environmental Protection Agency (EPA). Lessons Learned from Natural Gas STAR Partners. *Reducing Methane Emissions from Compressor Rod Packing Systems*, October 2006. http://www.epa.gov/gasstar/documents/ll_rodpack.pdf

U.S. Environmental Protection Agency (EPA). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2009.* April, 2011.