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FINAL PROJECT REPORT

# ESTIMATION OF METHANE EMISSIONS FROM THE CALIFORNIA NATURAL GAS SYSTEM

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# PREFACE

The Energy Research and Development Division of California Energy Commission supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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*Estimation of Methane Emission from the California Natural Gas System* is the final report for the Estimation of Methane Emissions project (contract number 500-09-007) conducted by California State University, Fullerton. The information from this project contributes to Energy Research and Development Division's Energy-Related Environmental Research Program.

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# ABSTRACT

The California Global Warming Solutions Act of 2006 (Assembly Bill 32) established a comprehensive program of regulatory and market mechanisms to achieve real, cost-effective, quantifiable reductions of greenhouse gases. The Public Interest Energy Research Program of the California Energy Commission has been funding climate change research since 2001 to study options available to reduce greenhouse gas emissions in California.

This project produced current, reliable and California-specific methane fugitive emission factors that could be used to establish a more accurate methane emission inventory for the California natural gas industry. The results from this project could be used to support regulatory programs to achieve effective and efficient methane emission reductions from California's natural gas system to consequently minimize adverse environmental impacts from these emission sources.

The research team surveyed equipment and systems in all five sectors of California natural gas industry: production, processing, storage, transmission and distribution. Equipment and systems surveyed included 172 wellheads, 131 separators, 17 dehydrators, 145 piping segments, 66 compressors (51 reciprocating, nine centrifugal, and six rotary), 374 pneumatic devices, 19 metering and regulating stations, 34 hatches, two pumps and 12 customer meters. Components screened on the equipment consisted of 10,101 flanges, 10,765 manual valves, 384 open-ended lines, 358 pressure relief valves, 930 regulators, 146 seals, 57,061 threaded connections, 12,274 welded connections and 138 "others." Three types of component-level emission factors (average, screening ranges and correlation) were developed using the data generated from field activities during this study. These component-level emission factors were then used to develop equipment-level average emission factors when appropriate.

**Keywords:** California Energy Commission, methane, natural gas industry, fugitive emission, greenhouse gases, climate change, emission factors, AB32, Public Interest Energy Research

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# EXECUTIVE SUMMARY

## Introduction

The California Global Warming Solutions Act of 2006 (Assembly Bill 32) established the world's first comprehensive program of regulatory and market mechanisms to achieve real, cost-effective, quantifiable reductions of greenhouse gases (GHGs). GHGs are known to contribute to climate change. Changes in climate will affect every aspect of the California economy and its natural ecosystems.

Energy generation and consumption is the main contributor to GHG emissions in the state. The Public Interest Energy Research (PIER) Program of the California Energy Commission has been funding climate change research since 2001 to address the environmental implications (i.e., climate change impacts) of the energy system and to study options available to reduce GHG emissions in California. Assembly Bill 32 delegated the California Air Resources Board (ARB) as the agency responsible for monitoring and regulating many GHG emission sources to reduce California GHG emissions to 1990 levels by 2020. Mandatory caps would begin in 2012 for significant sources and ratchet down to meet the 2020 goals. ARB began to measure the GHG emissions of the industries that, it determined, were significant sources of GHG emissions in preparation for the mandatory caps taking effect. Reductions of methane emissions from the natural gas system will reduce environmental impacts and contribute significantly to the development of the policies and regulations needed to implement the Scoping Plan adopted by ARB on December 11, 2008.

## Project Purpose

This project developed current, reliable, and California-specific fugitive methane emission factors that could be used to establish a more accurate methane emission inventory for the California natural gas system. The project tested as many systems and components in as many facilities as possible to obtain a representative sample of all five sectors of the California natural gas industry: production, processing, storage, transmission and distribution.

This project was intended to "advance energy science or technologies of value to California citizens…" (Public Resources Code 25620(c)), and is part of a "full range of research, development, and demonstration activities that…are not adequately provided for by competitive and regulated markets" (Public Resources Code 25620.1(a)). This project also supported California's goal to implement all strategies identified by the Climate Action Team as necessary to meet the Governor's GHG emissions reduction goals.

## Project Results

The technical plan was produced in coordination with the ARB, so the field test protocols were developed mainly based on the ARB test protocol, "*Draft Test Protocol – Detection and*

*Quantification of Fugitive and Vented Methane, Carbon Dioxide, and Volatile Organic Compounds from Crude Oil and Natural Gas Facilities*." This field test quantified concentrations and flow rates from emission sources using a series of measurements that required using a combination of instruments.

Site surveying for fugitive methane emissions was a difficult operation. Facilities were concerned about the safety of visitors and tended to be busy with their routine operations. Some areas of a facility were deemed unsafe for the research team to survey and access was not granted. A total of 25 facilities were surveyed during 27 visits. Twenty-four of those visits (including two return visits) were scheduled at least one week in advance. Surprise visits were conducted at three facilities. It is plausible that the data from the scheduled visits had a bias created by the site personnel pre-screening the site for leaks and fixing any that were found prior to the research team's arrival and survey.

The first scheduled site survey was performed on October 22, 2009 as part of the preliminary phase of this project. The final scheduled site survey was performed on March 29, 2011. Surprise visits were conducted between May 24 and May 26, 2011 with the assistance of the San Joaquin Valley Air Pollution Control District.

Access to California natural gas industry facilities was required to conduct this project. This access was facilitated through introductions of the research team to the industry personnel by the ARB. The following companies allowed the team access to their facilities: Aera Energy; Breitburn Energy; Chevron Corporation; City of Palo Alto Utilities Department; Exxon Mobil Corporation; Inergy L.P.; Occidental Petroleum Corporation; Pacific Gas and Electric Company; Rosetta Resources Inc.; San Diego Gas & Electric; Southern California Gas Company; Seneca Resources Corporation; The Termo Company; and Venoco Inc. Some of these companies allowed access to multiple facilities. Aera Energy, Chevron Corporation, Inergy L.P., and San Diego Gas & Electric allowed access to two of their facilities. Pacific Gas and Electric Company and Southern California Gas Company allowed access to four of their facilities.

The research team surveyed equipment and systems in all five sectors of the California gas industry: production, processing, storage, transmission and distribution. Equipment/systems surveyed included 172 wellheads, 131 separators, 17 dehydrators, 145 piping sectors, 66 compressors (51 reciprocating, nine centrifugal and six rotary), 374 pneumatic devices, 19 metering and regulating stations, 34 hatches, two pumps and 12 customer meters. Components screened on the equipment consisted of 10,101 flanges, 10,765 manual valves, 384 open-ended lines, 358 pressure relief valves, 930 regulators, 146 seals, 57,061 threaded connections, 12,274 welded connections and 138 "others." Three types of component-level emission factors (average, screening ranges, correlation) were developed using the data generated from field activities of this study. These component-level emission factors were then used to develop equipment-level average emission factors when appropriate. The equipment components were categorized into nine groups based on ARB's Draft Test Protocol: flanges, manual valves, open-ended lines, "others," pressure relief valves, regulators, seals, threaded connections and welded connections.

For a given screening value range, the measured leak rates spanned several orders of magnitude. The recorded leak rates ranged from below detection limit (<0.01 cfm) to 8.85 cubic feet per minute (cfm) and the screening values ranged from 100 to ≥50,000 parts per million by volume (ppmV). Many of the leaking components had high screening values, but their leak rates were below the detection limit of the flow rate device, even at ≥50,000 ppmV. This implies a poor correlation between the leak rates and the screening values.

All the component leakage rate histograms appeared to have the same trend. The majority of leakage rates were within the range of 0 to 0.02 cfm. For emission rates greater than 0.02 cfm, the frequency at which the leakages occurred decreased as the emission rate increased.

Pegged emission factors for screening values of ≥10,000 ppmV and for ≥50,000 ppmV were derived. For each component type, the values of two pegged emission factors are relatively similar. The pegged emission factors for seals and open-ended lines are larger than those of flanges, manual valves, and threaded connections. The emission factors with a pegged value of 10,000 ppmV are either smaller than, comparable to, or larger than the corresponding ones in the 1996 EPA/GRI study.

The correlation equations between the leak rates and screening values were also derived for leaking components. In general, the correlations are relatively poor due to the wide ranges of leakage rates found for each type of component. The correlation equations derived in this study are different from the EPA/GRI or CAPCOA correlation equations. The differences may be partly attributed to the poor correlation between the leak rates and the screening values in this study and the relatively large minimum detection limit of the High-Flow samplers. It should also be noted that the correlation equations in this study only used data from the natural gas industry and those of the 1996 EPA/GRI and the 1999 CAPCOA studies came from a variety of operations and services.

Component-level average emission factors for different component types were also derived. The emission factors are either smaller than, comparable to, or larger than the corresponding ones in the 1996 EPA/GRI study.

## Project Benefits

The results from this project could be used to support regulatory programs to achieve effective and efficient methane emission reductions from California's natural gas system and to minimize adverse environmental impacts from these emission sources.

# CHAPTER 1: Introduction

## 1.1 Project Background

The California Global Warming Solutions Act of 2006 (AB32) established a comprehensive program, the first in the world, of regulatory and market mechanisms to achieve real, cost-effective, quantifiable reductions of greenhouse gases (GHGs). GHGs are considered related to climate change. Changes in climate will affect every aspect of the California economy and its natural ecosystems.

Energy generation and consumption is the main contributor to GHG emissions in the state. The Public Interest Energy Research (PIER) Program of California Energy Commission (Energy Commission) has been funding climate change research since 2001 to address the environmental implications (i.e., climate change impacts) of the energy system and to study options available to reduce GHG emissions in California. AB32 delegated the Air Resources Board (ARB) as the agency responsible for monitoring and regulating many GHG emission sources to reduce state GHG emissions to 1990 levels by 2020. Mandatory caps would begin in 2012 for significant sources and ratchet down to meet the 2020 goals. In the interim, ARB began to measure the GHG emissions of the industries that, it determined, were significant sources of GHG emissions in preparation for the mandatory caps taking effect.

Natural gas is one of the primary sources of energy in California. Methane ($CH_4$) is the main component of natural gas and it is one of the dominant GHGs. The California natural gas system is comprised of oil and gas facilities that extract and process natural gas and the pipeline systems that deliver gas to customers. These operations are potential sources of methane emissions. Reductions of methane emissions from the natural gas system would decrease environmental impacts. A recent PIER study suggested that methane emissions from the natural gas system can be controlled at a net benefit or at relatively low costs (Choate *et al*., 2005). The Climate Action Team and ARB have embraced this finding, and the ARB developed regulations to control these emissions according to their Scoping Plan, adopted on December 11, 2008. However, fugitive methane emission estimates from this source category could be highly unreliable.

There has been a growing need to understand emissions of methane from the natural gas system over the past decade. These emissions are often estimated by using emission factors (EFs) coupled with activity factors; and the 2009 American Petroleum Institute (API) Compendium of Greenhouse Gas Emission Estimation Methodologies for the Oil and Gas Industry is commonly used (API, 2009). The document is relatively new; however, the methodologies contained in it were mainly obtained from a 1996 study (EPA/GRI, 1996). Therefore, the EFs are at least 15 years old. In addition to being outdated, many of these EFs may not be applicable to California due to regional differences in environmental requirements. For some of the sources, there are no published EFs. Consequently, having current and reliable

EFs, that are specific to California, is a key component for developing a more accurate methane emission inventory for California natural gas system.

To establish more current, reliable, and California-specific fugitive EFs for the California natural gas system, the ARB and the Energy Commission have worked together since 2009 to develop a test program and hire a research group/contractor to perform in-field methane emission source testing. The results would be used to support regulatory programs and to develop a GHG emissions inventory that is specific to California. The Energy Commission's PIER Program provided project management and technical expertise as well as the funds needed for this work, while the ARB provided technical expertise and overall coordination with other efforts. To hire the research contractor, an informal request for proposal (RFP) was issued jointly by and ARB in mid-January of 2009. A research team from the Department of Civil and Environmental Engineering, California State University, Fullerton (CSUF) was chosen as one of the four candidates for a final proposal submission. A formal RFP was issued on February 4, 2009. After the Energy Commissionand ARB reviewed the submitted proposals, the CSUF team was selected as the research team for a 2-year project, titled *Estimation of Methane Emissions from the California Natural Gas System*. The project started on 08/31/2009 and ended on 02/29/2012 (with a six-month no-cost extension).

## 1.2 Methane as a GHG

Greenhouse gases trap the sun's heat close to the earth's surface. GHGs in the earth's atmosphere consist of water vapor, carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), and others. All GHGs absorb infrared radiation or heat from the sun and re-emit it into the atmosphere, which causes the earth's surface to get warmer. Global Warming Potential (GWP) is an index established to compare different GHGs for a common reporting purpose. The absorptive capacity determines the GWP of the GHGs (INGAA, 2000; INGAA, 2005).

Global anthropogenic contributions of methane are significantly larger than natural sources (INGAA, 2000). While combustion of natural gas releases less carbon dioxide than coal or oil, the natural gas is primarily composed of methane, which has a high GWP about 21 to 25 times the GWP of carbon dioxide (EPA, 2006; IPCC, 1997; IPCC, 2001). The "2007 Oil and Gas Industry Survey Results, Draft Report" published by the ARB utilized the carbon dioxide equivalent of 21 for methane (ARB, 2011).

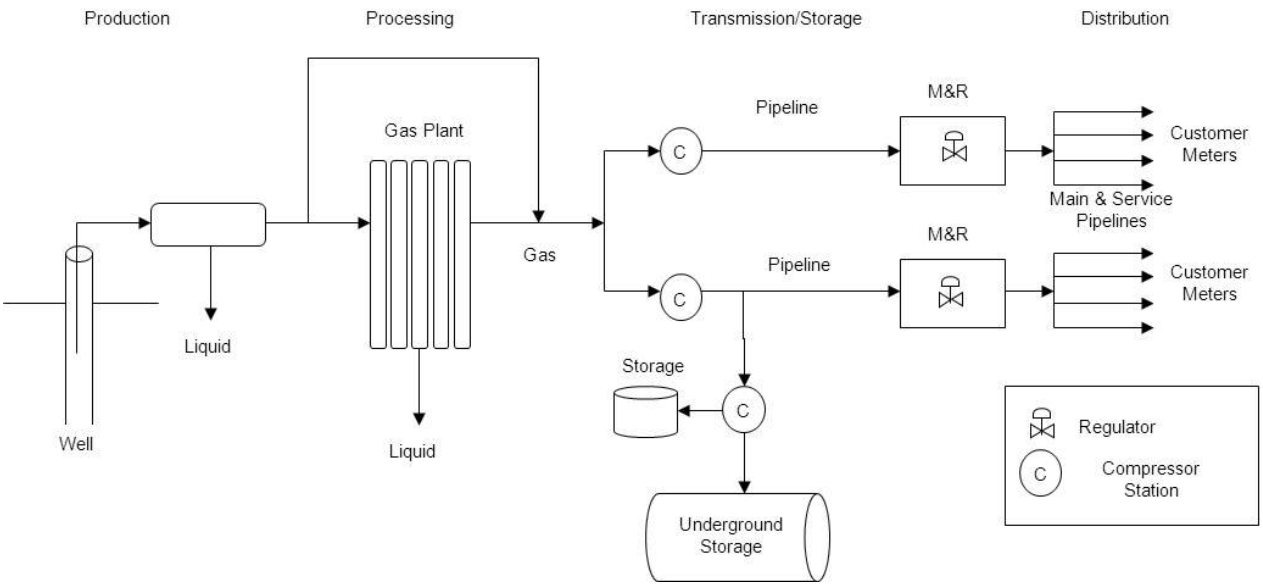
According to the United States Environmental Protection Agency's (USEPA) official estimate, around three trillion cubic feet of methane is released into the atmosphere yearly. As the world's largest gas producer, Russia has the highest estimated annual methane emission of 427 billion cubic feet. The U.S. ranks second with a total of 346 billion cubic feet per year. In addition, scientists and industry officials caution that the real figure is much larger than these estimates (Revkin & Krauss, 2009).

## 1.3 The Natural Gas Industry

Methane is the principal constituent of natural gas and it represents about 95 percent of the mixture (EIA, 2008; EIA, 2009). Methane emissions from the oil and natural gas systems contribute 1.7 percent of the total GHG emissions from the United States in 1998. Methane emissions from natural gas systems are five times larger than those from oil systems (EIIP, 1999). The United States was the world's second largest producer and consumer of natural gas in 2005. In 2000, the United States expelled approximately 120 million-metric tons of carbon-dioxide equivalent of methane (Tingley & Fernandez, 2003) with almost 18 percent of these emissions coming from the natural gas fuel cycle (EPA, 2008).

Natural gas is produced from wells, then processed, compressed, and distributed for use (Figure 1.3.1). The industry, therefore, is generally split into these sectors: production, processing, transmission, storage, and distribution. Methane can be released from all these operations. Emissions from natural gas production accounted for approximately 66 percent of $CH_4$ emissions from the natural gas industry in 2006. Processing facilities accounted for about 6 percent of $CH_4$ emissions and those from the natural gas transmission and storage sector accounted for approximately 17 percent of $CH_4$ emissions from the natural gas industry. Natural gas distribution sector emissions, which accounted for approximately 10 percent of $CH_4$ emissions from the natural gas industry, mainly from equipment leaks from gate stations and pipelines (EPA, 2010; EPA, 2011). The principal sources of $CH_4$ emissions in the natural gas industry are unintentional equipment or pipeline leaks (Camuzeaux, 2011; Robinson *et al.*, 2004).

**Figure 1.3.1: Natural Gas Industry Diagram**




Natural gas production begins with withdrawal of raw gas from underground formations. Wells are used to bring the raw gas to the surface via holes drilled through the underground formations. After reaching the surface, raw gas is treated and passed along for processing. In the production sector, emissions can be found in wells and subsurface equipment. Most emissions from production arise from pneumatic devices (37 percent) followed by fugitive

emissions (21 percent). Although the total amount of fugitive emissions is large, the average leak rate is small because of the large number of valves, connectors, and other pipe fittings on equipment at production sites (EPA, 1996).

The processing of natural gas involves removing liquids and other constituents from the raw gas drawn from underground formations. Natural gas is cleaned and separated to remove secondary byproducts and heavy hydrocarbons. The resulting "pipeline quality" gas is then compressed and injected into the transmission pipelines. Processing of natural gas is a key source of methane emissions since most equipment used is associated with equipment leaks. Fugitive emissions account for the majority of the methane emissions (EPA, 1996).

Transmission of natural gas from production and processing facilities to distribution pipelines is achieved with the use of high pressure, large diameter pipelines. Compressor stations are necessary to move the natural gas throughout the U.S. transmission pipeline system. Typically a compressor station contains large reciprocating and/or centrifugal compressors. Some compressor stations also have metering and regulating (M&R) stations which exchange gas with other transmission companies. Methane emissions from the transmission sector were mainly from compressor stations which accounted for more than two-thirds of total methane emissions in this sector (INGAA, 2000).

Natural gas is stored to compensate for times of high and low demand. The storage facilities are typically within short range of consumption centers to eliminate the need of large transmission pipelines. There are two forms of storage, above ground as liquefied natural gas (LNG) or as a gas below ground. The most common form of storage is below ground in the form of spent gas production fields, aquifers or salt caverns (EPA, 1996). Most storage facilities utilize a compressor station and dehydrators which subsequently are the primary contributors to emissions in storage facilities.

The distribution sector is responsible for delivering the "pipeline quality" natural gas that has been produced. The high pressure pipeline gas must first pass through a "city gate" station in order to reduce and regulate pressure. Ultimately the gas is distributed through pipelines to reach either an M&R station or customer meter. The majority of methane emissions were from underground pipeline leaks and M&R stations (EPA, 1996).

## 1.4 Sources of Methane Emissions in the Natural Gas Industry

Sources of methane emissions in the natural gas industry can be separated into the following types: combustion emissions, vented emissions, fugitive emissions, and other (non-routine) emissions. The following descriptions on emission sources were basically taken from a report of Interstate Natural Gas Association of America (INGAA, 2005).

GHGs from combustion emissions contain carbon dioxide from complete oxidation of organic compounds and methane from incomplete combustion. Combustion emission sources include internal combustion (IC) engines, gas turbine generators, dehydrator reboilers, facility boilers or process heaters, flares, and company fleet vehicles.

Vented emissions are released to the atmosphere by design from equipment such as pneumatic devices and compressors. According to the 1996 EPA/GRI study (EPA, 1996), 28.3 percent of the total methane emissions for the transmission and storage sector are vented emissions. Vented emissions sources include: dehydrator vents, compressor vents, pneumatic devices (isolation valves and control loops), purge or blow-down venting from routine operations or upsets, compressor station venting, storage facility venting, M&R station venting, pigging and inspection, "pull backs" or venting associated with water removal.

Fugitive emissions are unintentional releases due to leaks from closed surfaces and connections. Sources of fugitive emissions are based upon primary equipment that includes subcomponents, such as piping and associated components, compressors, M&R stations, interconnects, farm taps, receipt/sales meter stations, border meter stations, gate stations, storage well components, and organic liquids storage tanks.

Non-routine emissions include releases due to equipment blow-down venting, other emissions (e.g., business travel, employee commuting, outsourced activities), non-routine maintenance activities, anaerobic water treatment, landfills and remediation.

This project focused on fugitive methane emissions from the California gas industry.

## 1.5 The Natural Gas Industry of California

ARB's 2007 Oil and Gas Industry Survey requested general information from companies about their facilities in California. This information included the facility business type, production, and counts of equipment and components. California emissions were calculated based on the data collected from the companies as well as other sources (ARB, 2011). In 2007, the reported California statewide methane emissions for the oil and natural gas industry were 10,836 metric tons/yr from combustion emissions, 24,880 metric tons/yr from vented emissions, and 73,551 metric tons/yr from fugitive emissions. The fugitive emissions accounted for 67 percent of the methane emissions from California.

The report also listed the facilities in California by primary business type. There are 703 onshore natural gas production facilities, 17 natural gas processing facilities, and 10 natural gas storage facilities in California. Overall methane emissions in 2007 by primary business type were 117,835 metric tons/yr from production facilities, 5,102 metric tons/yr from processing facilities, and 276,484 metric tons/year from storage facilities in California. These three facility types accounted for 70 percent of total methane emissions in California in 2007.

The report also stated the fugitive methane emissions by primary business type. Fugitive methane emissions from onshore natural gas production was 10,022 metric tons/yr while natural gas processing fugitive emissions were 10,605 metric tons/yr and natural gas storage fugitive emissions were 8,380 metric tons/yr in 2007. These three primary business types accounted for 39 percent of the fugitive methane emissions in California in 2007. Fugitive emissions by source type were also stated in that draft report: 11,336 metric tons/yr from dehydrators, 2,032 metric tons/yr from wellheads, and 170 metric tons/yr from separators.

Facility, equipment, and component counts published in that draft report could be used in conjunction with EFs from this study to estimate fugitive methane emissions from some types of the components and equipment of the California natural gas industry.

## 1.6 Existing Fugitive Methane Emission Factor Values in Literature

A literature review was conducted to find the existing fugitive methane EFs for the natural gas industry. Most of the emission inventory reports used EFs coupled with activity factors; and the 2009 American Petroleum Institute (API) Compendium of Greenhouse Gas Emission Estimation Methodologies for the Oil and Gas Industry is commonly used (API, 2009). The EFs contained in it were obtained from a report published in 1996 by the Gas Research Institute (GRI) and USEPA (EPA/GRI 1996). While other EFs and estimates have been published (Chambers *et al*., 2006; CEPEI, 2007; Vorgang *et al*., 2009; Marcogaz-EuroGas, 2011), the 1996 EPA/GRI study remains the cornerstone for U.S. natural gas industry methane emission quantification, even the purpose of the study was identification of sources and quantification of national methane emissions and the data were not intended to be used to develop default EFs or industry averages for the natural gas industry (AGA, 2008). This study used the EFs reported in the 1996 EPA/GRI study as benchmarks for comparison. It should also be noted that California Air Pollution Control Officers Association (CAPCOA) and ARB in 1999 revised some of the EFs reported by EPA (CAPCOA, 1999). The relevant EFs from CAPCPA were also used for comparison in Chapter 5 of this report.

# CHAPTER 2:
# Project Objectives and Approaches

## 2.1 Objectives of this Project

Climate changes will affect every aspect of the California economy and its natural ecosystems. The Public Interest Energy Research (PIER) Program of California Energy Commission has been funding climate change research since 2001 to address the environmental implications (i.e., climate change impacts) of the energy system and to study options available to reduce GHG emissions in California. Reductions of methane emissions from the natural gas system would reduce environmental impacts and contribute significantly to the development of the policies and regulations needed to implement the Scoping Plan adopted by the Air Resources Board (ARB) on December 11, 2008.

The primary goal of this study was to produce California-specific fugitive emission factors (EFs) in support of AB32. Quantitative measurements of fugitive emissions were collected and analyzed to produce accurate fugitive EFs for individual systems, as well as components. The fugitive EFs can then be used in conjunction with activity factors collected by the ARB to produce emissions estimates for the individual systems as well as the industry sectors throughout California.

This project "[will] advance energy science or technologies of value to California citizens…" (Public Resources Code 25620(c)), and is part of a "full range of research, development, and demonstration activities that … are not adequately provided for by competitive and regulated markets (Public Resources Code 25620.1(a))"; and supports California's goal to implement all strategies identified by the Climate Action Team as needed to meet the Governor's GHG emission reduction goals.

The overall objective of this project was to develop current, reliable, and California-specific EFs, which can then be used to establish a more accurate methane emission inventory for the California natural gas system. The results from this project would be used to support regulatory programs to achieve effective and efficient methane emission reductions from California's natural gas system, and, consequently, minimize adverse environmental impacts from these emission sources.

## 2.2 Approaches of This Project

This project was broken down into two primary phases. Quantitative data were collected from field activities at various natural gas facilities across California. The field data were then processed for quality assurance and analyzed to produce various fugitive methane EFs.

### 2.2.1 Major Tasks Related to Field Activities

For field activities, the major tasks included the following:

1. Provided assistance to ARB in finalizing the test protocol and the test program.

2. Assembled fugitive emission field survey teams.
3. Conducted fugitive emission field surveys.

The project surveyed as many systems and components in as many facilities as possible to obtain a representative sample of all five sectors of the California natural gas industry: production, processing, storage, transmission, and distribution. In addition to types of sectors, sample data were collected from various point sources and systems, including wellheads, separators, dehydrators, piping segments, compressors, pneumatic devices, metering and regulating stations, hatches, pumps, and customer meters. The emission rates from different point sources and systems may vary depending on factors such as age, size, type, and operating conditions. The project also surveyed a group of facilities with a good representation of the industry geographically. With all these parameters affecting the EFs, the research program was carefully designed.

In addition to selection of sites to be surveyed, a sampling protocol was also developed. In this project, the research team

- Reviewed the draft test plan and protocol prepared by ARB and suggested changes or modifications.
- Worked with the ARB to develop a Testing Plan of what specific sources and sites to be surveyed. The sources surveyed were selected with the goal of improving the overall GHG emissions inventory.
- Identified the instruments needed for surveying the different sources and included the information in the Testing Plan.

The project required a significant number of field activities to be conducted in a relatively short timeframe. The field survey teams were mainly composed of CSUF students from the Civil and Environmental Engineering Department. The students received sufficient training in the operation of the methane-measuring instruments and of equal importance, in health and safety. The field surveys were conducted in two phases: the early-stage sampling phase and the intensive sampling phase. The early-stage sampling phase was conducted in the beginning of the project to generate a revised sampling plan, which was then put into effect for the rest of the project.

### 2.2.2 Major Tasks Related to Data Analysis

The data analysis team analyzed the data that were gathered by the field teams. All the data went through a quality assurance process to verify there were no errors during field documentation. The data were then entered into a database to facilitate the development of fugitive methane EFs.

# CHAPTER 3:
# Technical Plan Development

## 3.1 Field Test Protocols

The field test protocols were developed mainly based upon the California Air Resources Board (ARB) test protocol, titled *Draft Test Protocol – Detection and Quantification of Fugitive and Vented Methane, Carbon Dioxide, and Volatile Organic Compounds from Crude Oil and Natural Gas Facilities* (ARB, 2009; ARB, 2010). This protocol stated the purpose of a field test was to quantify concentrations and flow rates from emission sources. Emission sources were found using a series of measurements that required the utilization of a combination of instruments. The first instrument was a broad-area screening device that would determine the general location of an emission source. The second instrument would identify the specific location of the emission source. The third instrument would quantify the flow rate from that specific location.

To effectively manage the time available at a facility, a team of at least three members was typically used. One team member used either an infrared camera or remote methane detection device to generally locate the plume of the methane emissions. Another team member used a detection/monitoring device to locate the exact orifice from which the gas was being emitted. That team member then used either a bagging technique or a flow rate device to quantify the flow rate at which the orifice was emitting methane. Meanwhile, the third team member counted the components surveyed in each system and recorded the data. The collected data were then combined together off site for subsequent data analysis.

Various data sheets were developed to effectively record all the data acquired from the sites. The most important sheets used include a site description sheet, a leak detection sheet, and a component counting sheet. The site description sheet would have a description of the site as well as a drawing of the facility layout with the various systems surveyed drawn and labeled on it. Facilities were separated into multiple sections to aid in the organization of the data collection. The leak detection sheet would be created for each of the systems surveyed and each leak would be recorded with the time, location, leak concentration, methane flow rate and other information. If a system did not have any leaks, the leak detection sheet would be left empty to keep an accurate count of the systems surveyed. The component count sheet contained the counts of the various components of each system that was surveyed.

Quality assurance is important for the success of such a project as incorrect data would result in flawed EFs. The site survey was conducted after the field team calibrated the instrument to the manufacturer's standards. To ensure accurate data were recorded, each reading was verified by two field team members (one sampling the leak and the other recording the data). The flow rate for each emitting orifice was verified using the flow rate device twice, once at a high volume flow rate and again at a low volume flow rate. The measurement was only accepted if both readings fell within 10 percent of each other. Once the survey was completed for the day, the team verified the calibration on the devices again. If any of the devices were found to be out of calibration, the data for that device would be regarded as inaccurate and would therefore be

deemed irrelevant to the project. The event of data being deemed irrelevant due to an error in calibration at the end of the day never occurred over the course of this project.

The field test protocols were developed with ARB at the start of the project to ensure consistent and accurate data for measuring methane emissions from fugitive sources. The ARB's Draft Test Protocol document states the important term definitions that were applied to the testing and the data sheet protocol. For the purpose of this project, the report adhered to the definitions in the ARB's Draft Test Protocol. Relevant definitions from the 2010 Draft Test Protocol are quoted below (ARB, 2010):

*Anti-Static Bag:* refers to a bag made of anti-static material used for isolating a fugitive or vented leak source, and which does not pose a threat of creating an explosive environment or condition.

*Bagging:* refers to the isolation of a specific component or location to determine a fugitive or vented gaseous flow rate.

*Calibrated Anti-Static Bag:* refers to an anti-static bag calibrated to a specific volume and used to estimate flow rate.

*Detection Device:* refers to a device used to identify a specific fugitive or vented leak source.

*Detection Concentration:* refers to methane concentration as observed by a screening or detection device measured in parts per million calibrated as methane.

*Flange:* refers to a projecting rim on a pipe or object used to attach another flanged component with bolts.

*Flow Rate Device:* refers to a device used to measure flow rates (0 to 8 standard cubic feet per minute) from a fugitive or vented leak source.

*Fugitive:* refers to the un-intentional release of gas from processes or equipment such as valves, flanges or fittings to ambient air.

*Hatch:* refers to any access door or cover that can be manually opened in order to access a tank or vessel.

*Manual Valve:* refers to a hand-operated device used to regulate the flow of gas or fluid. The term manual valve refers to the stem protruding out of the valve packing. Flanges or threaded connections used to attach the valve should be counted in their respective categories. Record valves with one side that is open to atmosphere as Open-Ended Lines.

*Mode:* refers to the operational state when tested. When identifying mode, use the term Standby to describe a compressor that is not running but ready to operate or run.

*Open-Ended Line:* refers to any line that is open to atmosphere including pipes or the open end of a valve.

*Other:* refers to components that are not described by any of the other definitions contained in [ARB's] protocol.

*Pneumatic Actuator (gas):* refers to a natural gas powered device used to control a pneumatic valve used to control the flow of liquids or gases.

*Pneumatic Valve:* refers to a valve controlled by a pneumatic actuator to control the flow of liquids or gases. A pneumatic valve does not include the flanges or threaded connections used to install the device.

*Pressure Relief Valve:* refers to a device that is used to prevent the over-pressurization of a piping system, vessel, or other system. This term refers to the area where pressure is allowed to exit. The valve does not include a flange or a threaded connection used to attach the device.

*Regulator:* refers to a device used to reduce the pressure of natural gas within a natural gas system.

*Screening Device:* refers to a device used to screen a wide area and detect the presence of fugitive or vented methane.

*Seal:* refers to any mechanism used to contain liquid or gas within a line or vessel. The term seal is intended to include those sealing mechanisms that are not described by other definitions contained in the ARB's Draft Test Protocol.

*Threaded Connection:* refers to any juncture of two or more components that uses threading to secure the components together. Threaded connections include all connections regardless of size or use.

*Venting:* refers to the intentional release of gas from equipment or operation processes to ambient air.

*Welded Connection:* refers to any junction of two or more components that uses welding or soldering to secure the components together.

## 3.2 Instruments Required

EPA Reference Method 21 outlined the procedures and equipment types required for the screening and quantification of VOC leaks. The Draft Test Protocol released by the ARB in November 2009 and December 2010 outlined further requirements (ARB, 2009; ARB 2010). As the purpose of this project was to produce California-specific EFs, and the technical plan was produced in coordination with the ARB, this project followed the guidelines outlined in the ARB's Draft Test Protocol.

According to the ARB's Draft Test Protocol, fugitive methane leaks are to be located and quantified using three types of instruments. The first instrument is a screening device used to locate the presence of fugitive methane from a distance. When a leak is detected, a detection device is then to be used to locate the specific fugitive leak source. To quantify the fugitive flow rate from the source, either a bagging procedure or a third device is to be used. All the instruments used to detect and quantify fugitive emissions in any explosive environment must be intrinsically safe. If an area is deemed as an explosive environment by facility personnel, only intrinsically safe instrument is to be used in those areas. The minimum detection limit for

detection devices is to be at least 100 ppmV, with a range of at least 100 to 10,000 ppmV. For the flow rate quantification device, the minimum detection limit is to be at least 0.5 standard cubic foot per minute (scfm) with a range of 0.5 to 8.0 scfm. All of the equipment must be calibrated according to manufacturer standards.

## 3.3 Classification of the Industry Sectors

Natural gas is produced from wells, then processed, compressed, and distributed for use. For the purposes of this study, the natural gas industry was split into the following sectors: production, processing, transmission, storage, and distribution.

The production sector includes the oil and gas wells and the equipment used to produce the natural gas, such as wellheads, separators, dehydrators, compressors, pneumatic devices, and pipelines. The processing sector recovers liquids from the gas stream while maintaining the quality. The processing sector equipment includes dehydrators, compressors, pneumatic devices, and pipelines.

The transmission sector moves the natural gas from gas plants and field production to the local distribution companies. This sector equipment includes compressors, pipelines, meters and pressure regulators, and pneumatic devices.

The storage sector has above- and below-ground storage facilities that store gas for both off-peak and high-demand periods (Kirchgessner *et al*., 1997). At above-ground facilities, gas is liquefied by supercooling and stored in liquid phase in insulated tanks. On the other hand, below-ground facilities store the gas in vapor phase. Below-ground facilities are the predominant type of storage facilities (EPA, 1996). The storage sector equipment includes wellheads, compressors, dehydrators, pneumatic devices, and pipelines.

The distribution sector equipment first receives high pressure gas from transmission pipelines, reduces the pressure, and distributes the gas to the consumers (Kirchgessner *et al*., 1997). This sector includes pipelines, meters and pressure regulators, pneumatic devices, and customer meters.

## 3.4 Classification of the Equipment Systems

The equipment types surveyed over the course of this project were:

- Wellheads
- Separators
- Dehydrators
- Piping Segments
- Compressors
- Pneumatic Devices
- Metering & Regulating Stations
- Hatches

- Pumps
- Customer Meters

A wellhead is the uppermost part of a natural gas well located at production or storage facilities. They typically consist of many flanges, valves, connections and a few other components. All accessible portions of a wellhead were screened from the ground up.

A separator is an equipment used to split natural gas from the condensate, oil, and water. Many separators are very large and therefore some sections are inaccessible without the use of a manlift. All accessible components of each separator were screened, including valves which might be used to test the condensate.

A dehydrator refers to a unit used to remove water from natural gas. A dehydrator is typically composed of a contactor and a reboiler. These devices have two or more large tanks which process the natural gas. Dehydrator surveys included the screening of all components and seals of the dehydrator accessible and deemed as part of the dehydrator up to the mainline from which the gas is supplied.

A piping segment is any piping between two systems. It transmits the gas from one system to another. Most piping segments surveyed were between two systems that were easily accessed.

Compressors are commonly used throughout the natural gas industry to pressurize gas. Each compressor is classified according to the mechanism it utilizes to compress the natural gas. A reciprocating compressor refers to a compressor which uses pistons to compress and pressurize the natural gas and then discharge it. A centrifugal compressor compresses gas by accelerating the particles using a turbine and then converts this velocity into compression. A rotary compressor uses a rotating pair of screws which compress the gas as it flows through them. These compressors typically use natural gas as the fuel source. They vary in sizes and can be very large complex systems.

A pneumatic device is controlled by pressurized gas which can be air or natural gas. These devices are used to regulate the flow of natural gas through components on systems. A pneumatic actuator here refers to a natural gas powered device used to control a pneumatic valve. A pneumatic valve refers to a valve controlled by a pneumatic actuator to control the flow of liquids or gases. A pneumatic valve does not include flanges or threaded connections used to install the device. These devices were screened completely from the mainline they control to all components and seals located on the device.

Metering and regulating (M&R) stations are typically designed to provide a constant output from the facility with constant pressure and other characteristics to the downstream facility. M&R stations are usually composed of many piping components without much complex equipment and therefore the systems were screened entirely, excluding any compressed air systems that control flow.

A hatch refers to any access door or cover that can be manually opened to access a tank or vessel. Each hatch was surveyed around the door seal and any other components if they existed.

A pump is used to deliver fluid to a system. These can be electric or gas driven and may have pistons and/or diaphragms.

A customer meter records the flow and other characteristics of the gas that passes through it. These meters are typically installed at the beginning and the end of the stream ownerships to monitor the flow of gas. Some of these meters are located near households. The meters were screened on all natural gas components up to the mainline which it is sampling.

## 3.5 Classification of the Equipment Components

There are nine types of equipment components considered in this study. The following is a brief description of each type of components found on the equipment.

A flange is a connective device which is typically used to connect two pipes together. A flange is attached to each section and then bolted together for easy removal. A flange will typically leak from the seal around which the two pipes are connected together.

A manual valve is a component found on most systems. They are used to manually regulate the flow. These devices will typically leak from threaded connections on them.

An open-ended line (OEL) is any line that is directly open to vent to atmosphere or has only one mechanism (manual valve, regulator, threaded/welded cap) that is stopping flow of gas to atmosphere. They typically leak at the opening location or stopping mechanism.

A pressure relief valve (PRV) is typically attached to the top of a system for safety. A PRV has a set pressure at which it releases any extra pressure to the atmosphere. These can come with a variety of options. The two most common ones are self-resetting and one-time use. The self-resetting PRVs do not require replacement or manual resetting. The one-time-use PRVs require the associated equipment to be shut down in order to replace them. A PRV typically leaks from the pressure regulating seal.

A regulator is an automatic device that regulates the flow or pressure of a gas line. It is typically pneumatically powered. Sometimes pneumatic power comes from natural gas, other instances from compressed air. These regulators typically leak from a designated venting location or from seals located within the device.

A seal is any location where parts can be detached or serviced. These seals are typically rubber or some form of materials which prevent gas from leaking. A leak can be typically found around a seal and occur when the seal wears out.

A threaded connection is one of the most common types of connections that can be found on equipment. These connections require one section to be threaded into the other. They typically can leak from where the threads meet.

A welded connection is the second most common type of connections found on equipment. These connections are typically meant to be permanent. They can be used to connect any two systems that are meant to be permanent. These connections typically leak due to a bad welding

job, or rusting that may cause the welding to detach. However, no leaks were detected from welded connections in this project.

The "other" category refers to any type of components not described above.

# CHAPTER 4:
# Field Measurements and Activities

## 4.1 Introduction

This chapter includes further details pertaining to field activities conducted in this study. These activities included preparatory health and safety training, scheduling of the site visits, and calibration and operation of instruments in the field. A list of the companies involved in the project as well as the facilities visited are also presented.

## 4.2 Preparation for Site Visits

All team members that visited any facility included in this project must have completed health and safety training prior to the first site visit. This facilitated the approvals of the scheduled visits from the facilities. Health and safety training was provided by California State University, Fullerton's environmental compliance manager. The trainer has visited and worked in many of the natural gas and oil industry's facilities and thus is qualified to provide necessary training to the field survey team members. In addition to this preliminary training, each site typically held a health and safety meeting with the survey team before allowing the team to enter the site to survey the equipment.

## 4.3 Facilities Surveyed

Site surveying for fugitive methane emissions is not an easy task, as facilities always have concerns with the safety of the visitors and tend to be busy with their routine operations. In addition, some areas of a facility were deemed unsafe for the team to survey and access was not granted in this study. In total, 25 facilities were surveyed during 27 visits. Of these visits, 24 (including two return visits) were scheduled at least one week in advance. Surprise visits were conducted at three facilities. Scheduled visits were typically confirmed one week in advance. It is plausible that the data from the scheduled visits have a bias created by the site personnel by pre-screening the site for leaks and fixing any that were found prior to the research team's arrival. The first scheduled site survey was performed on 10/22/2009 as part of the preliminary phase of this project; the final scheduled site survey was performed on 3/29/2011. Surprise visits were conducted between 5/24/2011 and 5/26/2011 with the assistance of San Joaquin Valley Air Pollution Control District (SJVAPCD).

To conduct the field activities of this project, access to the California natural gas industry facilities was required. This was facilitated through introductions of the research team members to the industry personnel by the ARB. The following companies allowed the inspection team access to their facilities (in alphabetical order): Aera Energy, Breitburn Energy, Chevron Corporation, City of Palo Alto Utilities Department, Exxon Mobil Corporation, Inergy L.P., Occidental Petroleum Corporation, Pacific Gas and Electric Company, Rosetta Resources Inc., San Diego Gas & Electric, Southern California Gas Company, Seneca Resources

Corporation, The Termo Company, and Venoco Inc. Some of those companies allowed access to multiple facilities. Aera Energy, Chevron Corporation, Inergy L.P., and San Diego Gas & Electric allowed access to two of their facilities. Pacific Gas and Electric Company and Southern California Gas Company allowed access to four of their facilities.

While many facilities conduct operations that fall under multiple sectors of the industry (production, processing, transmission, storage, distribution), this project placed the facilities under their primary operation sector based on observations and the equipment surveyed. While it would be preferable to have the number of facilities surveyed distributed equally between the five sectors, this project surveyed the facilities that were made available to the team and was forced to group the production and processing industry sectors into one category due to lack of facilities available to the research team and the team was only able to inspect one area that represented the distribution sector.

Twelve facilities in the production and processing (P & P) industry sector, three in the storage sector, nine in the transmission sector, and two in the distribution sector were surveyed (Table 4.3.1).

**Table 4.3.1: Counts of Facilities Surveyed by Industry Sector**

| Industry Sector | Counts of Facilities | Industry Sector Distribution |
|---|---|---|
| **P & P** | 12 | 48% |
| **Storage** | 3 | 12% |
| **Transmission** | 8 | 32% |
| **Distribution** | 2 | 8% |

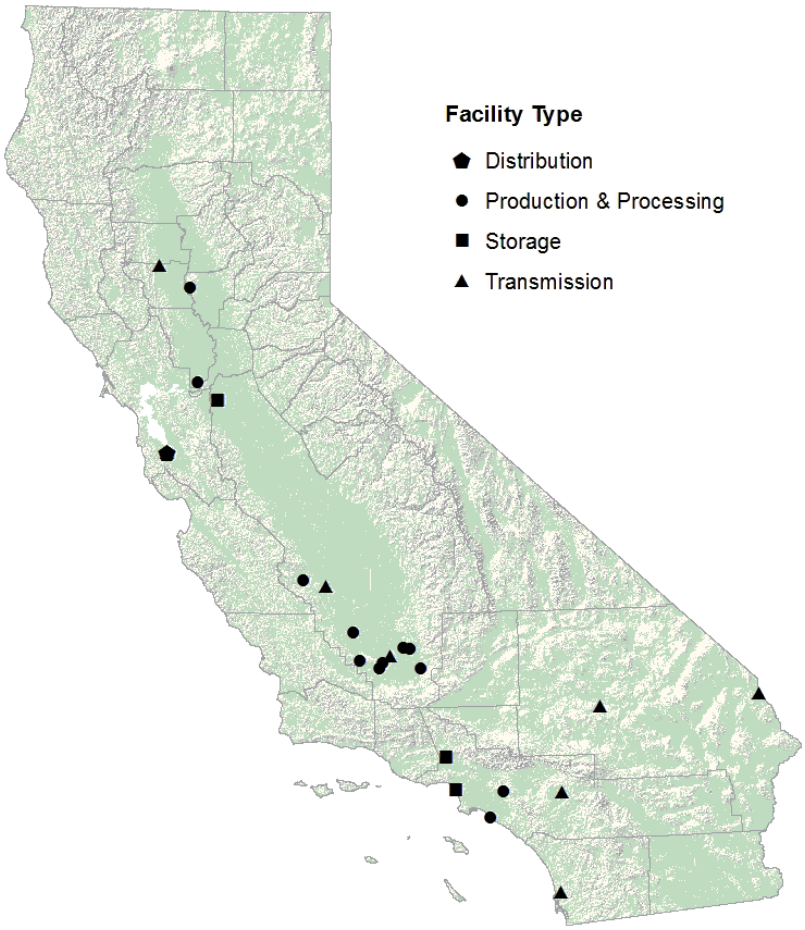
Table 4.3.2 lists the facilities surveyed during this project. The first order of organization is by the industry sector. The designation was assigned by the research team based on observations and the equipment surveyed.

Figure 4.3.1 shows the locations of the facilities inspected during the course of this study. The lines represent the borders of the air pollution control districts. As the majority of natural gas production are located in the San Joaquin Valley District, many of the facilities surveyed during this project were located in that area.

**Table 4.3.2: Facilities Surveyed by Industry Sector**

| Industry Sector | Company Name | City |
|---|---|---|
| **Distribution** | City of Palo Alto Utilities Department | Palo Alto |
| **Distribution** | San Diego Gas & Electric | San Diego |
| **P & P** | Aera Energy | Huntington |
| **P & P** | Aera Energy | McKittrick |
| **P & P** | Breitburn Energy | Brea |
| **P & P** | Chevron | Bakersfield |
| **P & P** | Chevron | Lost Hills |
| **P & P** | Exxon Mobil | McKittrick |
| **P & P** | Inergy | Tupman |
| **P & P** | Occidental | Taft |
| **P & P** | Rosetta Resources | Rio Vista |
| **P & P** | Seneca Resources Corporation | Bakersfield |
| **P & P** | The Termo Company | Arvin |
| **P & P** | Venoco | Meridian |
| **Storage** | PG&E | Stockton |
| **Storage** | So. Cal. Gas Company | Northridge |
| **Storage** | So. Cal. Gas Company | Playa Del Rey |
| **Transmission** | City of Palo Alto Utilities Department | Palo Alto |
| **Transmission** | Inergy | Bakersfield |
| **Transmission** | PG&E | Avenal |
| **Transmission** | PG&E | Palo Alto & Redwood City |
| **Transmission** | PG&E | Stonyford, near Delevan |
| **Transmission** | So. Cal. Gas Company | Newberry Springs |
| **Transmission** | So. Cal. Gas Company | Needles |
| **Transmission** | San Diego Gas & Electric | Moreno Valley |

**Figure 4.3.1: Geographic Locations of Facilities Surveyed**




## 4.4 Equipment Surveyed

This project followed the technical plan developed through the coordination with ARB, with the intention of surveying equipment from natural gas production (through a wellhead) to the distribution for consumption (through a customer meter). The ARB's 2007 Oil and Gas Industry Survey, Draft Report (ARB, 2011) listed many potential sources of fugitive emissions. For example, emissions from active wells and well cellars in the production and storage sectors were in that report; however, this project did not survey any well cellars. Acid gas removal units in the processing sector, as another example, were listed as sources of fugitive emissions in that draft report, but were not surveyed in this study. In addition, fugitive emissions from underground pipelines could be major sources, they were not included in this study.

Equipment types included in this project were:

- Wellheads
- Separators
- Dehydrators
- Piping segments

- Compressors (reciprocating, centrifugal, and rotary)
- Pneumatic devices (actuators and valves)
- Metering and regulating stations
- Hatches
- Pumps
- Customer meters

Many facilities are large and have too many components to survey in their entirety, so representative portions of each facility were screened. Also, while the team was at the facilities, some areas were deemed unsafe for visitors to access by the facility personnel. These areas were also not surveyed. Some equipment is large and could not be accessed completely to screen every component of the system without a manlift. This was especially true for many compressors, dehydrators, and separators. Table 4.4.1 tabulates the types of equipment surveyed in each facility.

Components listed in ARB's 2007 survey were: connectors, manual valves, flanges, threaded components, pump seals, polished rod stuffing boxes, PRVs, meters, hatches, sight glasses, diaphragms, dump lever arms, OELs, bursting discs, and loading arms. Pump seals, polished rod stuffing boxes, sight glasses, diaphragms, dump lever arms, bursting discs, and loading arms were not specifically screened in this study.

The components that are potential fugitive emissions sources surveyed in this project were:

- Flanges
- Manual valves
- OELs
- PRVs
- Regulators
- Seals
- Threaded connections
- Welded connection

**Table 4.4.1: Equipment Surveyed at Each Facility**

| Industry Sector | Company | Facility | Wellheads | Separators | Dehydrators | Piping | Compressors (Reciprocating) | Compressors (Centrifugal) | Compressors (Rotary) | Pneumatic Devices | M&R | Hatches | Pumps | Customer Meters |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Distribution | Palo Alto Utilities | Palo Alto | | | | | | | | | | | | √ |
| Distribution | SDG&E | San Diego | | | | √ | | | | | √ | | | |
| P & P | Aera Energy | Huntington | | √ | | | | | √ | | | | | |
| P & P | Aera Energy | McKittrick | √ | √ | | √ | √ | | √ | √ | | √ | √ | |
| P & P | Breitburn Energy | Brea | | | | | √ | | | | | | | |
| P & P | Chevron | Bakersfield | √ | | | | | | | | | | | |
| P & P | Chevron | Lost Hills | √ | √ | | √ | √ | | | √ | | | | |
| P & P | Exxon Mobil | McKittrick | √ | √ | | | √ | | | √ | | √ | | |
| P & P | Inergy | Tupman | | | | √ | √ | | | | | | | |
| P & P | Occidental | Taft | √ | √ | √ | √ | √ | √ | | √ | | | √ | |
| P & P | Rosetta Resources | Rio Vista | √ | √ | √ | √ | √ | | √ | √ | | √ | | |
| P & P | Seneca Resources | Bakersfield | √ | √ | | √ | √ | | √ | √ | | √ | | |
| P & P | The Termo Company | Arvin | √ | √ | | √ | | | | | | √ | | |
| P & P | Venoco | Meridian | √ | √ | √ | √ | √ | | | √ | | | | |
| Storage | PG&E | Stockton | √ | √ | √ | √ | √ | | | √ | | | | |
| Storage | So. Cal. Gas Company | Northridge | √ | | √ | √ | √ | √ | | | | | | |
| Storage | So. Cal. Gas Company | Playa Del Rey | √ | | | √ | √ | | | | | | | |
| Transmission | Inergy | Bakersfield | | | | √ | | | | | | | | |
| Transmission | Palo Alto Utilities | Palo Alto | | | | √ | | | | √ | | | | |
| Transmission | PG&E | Avenal | | | | √ | | | | √ | √ | | | |
| Transmission | PG&E | Palo Alto | | | | √ | | | | √ | √ | | | √ |
| Transmission | PG&E | Stonyford | | | | | | √ | | | | | | |
| Transmission | So. Cal. Gas Company | Newberry Springs | | | | √ | √ | | | | | | | |
| Transmission | So. Cal. Gas Company | Needles | | | | √ | √ | | | | | | | |
| Transmission | SDG&E | Moreno Valley | | √ | | | | | | | | | | |

## 4.5 Instruments Used to Quantify Fugitive Emissions

EPA Reference Method 21 outlined the procedures and equipment types required for the screening and quantification of VOC leaks. The Draft Test Protocol released by the ARB in November 2009 and December 2010 outlined further requirements (ARB, 2009; ARB, 2010). As the purpose of this project was to produce California-specific EFs, and the technical plan was produced in coordination with the ARB, this project followed the guidelines outlined in the ARB's Draft Test Protocol.

According to the ARB's Draft Test Protocol, fugitive methane leaks are to be located and quantified using three types of instruments. The first instrument is a screening device used to locate the presence of fugitive methane from a distance. When a leak is detected, a detection device is then to be used to locate the specific fugitive leak source. To quantify the fugitive flow rate from the source, either a bagging procedure or a third device is to be used. All the instruments used to detect and quantify fugitive emissions in any explosive environment must be intrinsically safe. If an area is deemed as an explosive environment by facility personnel, only intrinsically safe equipment is to be used in those areas. The minimum detection limit for detection devices is to be at least 100 ppmV, with a range of at least 100 to 10,000 ppmV. For the flow rate quantification device, the minimum detection limit is to be at least 0.5 scfm with a range of at least 0.5 to 8.0 scfm. All of the devices must be calibrated according to manufacturer's standards.

The screening device used to screen a large area from a distance in this project was the Remote Methane Leak Detector (RMLD), purchased from Heath Consultants (Houston, TX). As the RMLD is not intrinsically safe, it could only be used in areas that were not considered to be within an explosive environment. The RMLD uses a Tunable Diode Laser Absorption Spectroscopy (TDLAS) to identify the presence of a gas within a range of 100 feet. For the device to be effectively utilized, there must be a background behind the emitted plume for the device to reflect the laser from. The detection range of the RMLD is 0-99,999 ppmV, with a sensitivity of 5 ppmV at a distance of 0 to 50 ft and 10 ppmV or better at a range of 50 to 100 ft. The device will emit a sound and display a reading, depending upon how concentrated the plume is. Once calibrated, the user points the device in the direction of methane equipment and changes the angle and orientation until the highest value is read from the screen; this would the general location of the leak (Heath Consultants, 2005). These characteristics satisfied the requirements outlined in the ARB's Draft Test Protocol. At the beginning of each day of screening, the RMLD was calibrated according to manufacturer specifications by using a test gas cell which is integrated into the carrying case.

The FLIR GF320 infrared gas detection camera rented from FLIR Systems (Boston, MA) allows the user to visually inspect the area for leaking emissions and rapid source identification in real time by showing the hydrocarbon absorption spectra on screen (FLIR Systems, 2009). In this study, this device was used to help the San Joaquin Valley Air Pollution Control District (SJVAPCD) assess the technology's viability by comparing the productivity and accuracy of

fugitive leak detection by the gas detection camera with methods currently employed by the SJVAPCD.

The detection device used to locate the specific fugitive leak source in this project was the RKI Eagle unit, purchased from RKI Instruments (Union City, CA). The RKI Eagle utilized in this project was intrinsically safe and was configured for four gases: $O_2$, $H_2S$, CO, and $CH_4$. The device can detect oxygen between 0-40 percent by volume, hydrogen sulfide between 0-100 ppmV, and carbon monoxide between 0-500 ppmV. The methane detection range of this instrument is 0 to 50,000 ppmV. The RKI Eagle has a Teflon tube from which the gas is drawn to the sensors, the results from the test are instantaneous and provide representation of the gas 1cm away from the edge of the Teflon tube (RKI Instruments, 2011). Thus, the instrument's tube was placed 1cm around specific components until the largest concentration was found; this is the methane emitting orifice. These characteristics satisfied the requirements outlined in the ARB's Draft Test Protocol. At the beginning of each day of screening, the RKI Eagle was calibrated according to manufacturer's specifications by using a four-gas calibration cylinder with 25 ppmV $H_2S$, 50 ppmV CO, 2.5 percent by volume $CH_4$, 12 percent by volume $O_2$, with inert $N_2$ for the balance, purchased from Argus-Hazco, Anaheim, CA.

The device used to quantify the fugitive methane leak flow rate in this study was the Bacharach Hi-Flow sampler, purchased from Heath Consultants. The Hi-Flow sampler quantification range is between 0.01 and 8 standard cubic feet per minute (scfm). The detection is accomplished using a dual hydrocarbon detector (catalytic oxidization and thermal conductivity). To measure the fugitive methane leak, a large 1.5-inch diameter pipe was used with various connections, depending on the situation, to vacuum the methane through its sensors. In some cases, an anti-static bag was used to aid in the capture of the leaking methane. The device measures the leak for at least 1 minute at the initial high flow rate of 10 cfm, then again measures the leak rate for another minute at the low flow rate of 8 cfm. If these results are within 10 percent of each other, the device reports them to the user. Otherwise, the results are reported with a note that the verification failed, and the quantification was attempted again from a different orientation until the verification succeeded and an accurate measurement was obtained. The Hi-Flow sampler was calibrated according to manufacturer's standards using gas cylinders with 2.5 percent and 100 percent methane concentrations (Bacharach Inc., 2010).

# CHAPTER 5:
# Data Analysis

## 5.1 Introduction

This chapter presents approaches and results of analysis on data collected from field activities. This chapter provides an overview on types of fugitive emission factors (EFs) that are being used in generating emission inventories for the natural gas industry, types of equipment components considered, and leak detection, definition and quantification in this study. The component-level screening ranges EFs are presented in section 5.2. The component-level correlation EFs are presented in section 5.3. The component-level and equipment-level average EFs are presented in section 5.4.

### 5.1.1 Types of Fugitive Emission Factors

Fugitive methane emissions are unintentional releases of methane from processes and equipment to the ambient air. Pressurized equipment has the potential to leak, and these leaks generally occur through equipment components such as valves, flanges, seals, open-ended lines (OELs), and pressure relief valves (PRVs). Fugitive emissions can also be from non-point evaporative sources such as wastewater treatment, pits, and surface impoundment (API, 2004; API, 2009). This study focused on fugitive methane emissions from equipment leaks.

A number of EFs and correlation equations have been generated for estimating fugitive emissions from equipment leaks (EPA, 1995; EPA/GRI, 1996; API, 2004; CEPEI, 2007). With regards to emission inventory estimates, the EFs can be categorized into the following three groups, in the order of increasing data requirements and increasing accuracy (EPA, 1995; API, 2004; API, 2009):

1. Facility-level average EFs
2. Equipment-level average EFs
3. Component-level EFs

When estimating the fugitive leak contribution to an emission inventory or a permitting requirement, the simplest method should be used to meet the required accuracy and for which data are available. The facility-level average EF approach is the simplest method. It requires only the identification of type and capacity of a specific facility or a count of major equipment. The equipment-level average EF approach is one level up which requires an accurate count of all the general equipment. The component-level EF approach requires precise counts (or population data) of the equipment components and/or leak concentrations from a leak detection and repair (LDAR) program (API, 2009).

The component-level EFs can be further categorized into the following four groups, in the order of increasing data requirements and increasing accuracy for estimates of emissions (EPA, 1995; API, 2004):

1. Average EF approach
2. Screening ranges approach
3. Correlation approach
4. Unit-specific correlation approach

The fugitive emission estimates, using the component-level EF factor approach, are based on the population data of components at a given facility. When no monitoring data (e.g., leak concentrations) are available, using this approach would provide more accurate estimates than using the facility-level or equipment-level EFs since it is based on site-specific component population data. However, it should be noted that these component-level average EFs were typically developed for aggregate organic matter such as total organic compounds (TOCs), total hydrocarbon compounds (THCs), or volatile organic compounds (VOCs), rather than for methane (API, 2004). This study attempted to develop this type of EFs for fugitive methane emissions.

Except for the average EF approach, the other three component-level EF approaches require screening data. Screening data are typically collected by using a portable monitoring instrument to sample air from potential leak interfaces on individual components of equipment. A screening value (SV) is a measure of the concentration of leaking compounds in the ambient air and is typically measured in parts per million by volume (ppmV). A portable monitoring instrument typically has a measurement range in which the lower limit is the instrument detection limit and the higher limit is often referred as the pegged value. The screening ranges approach, also known as the "leak/no leak" approach, is based on monitoring data (i.e., leak concentrations) which are categorized into two or more ranges. In older regulations, 10,000 ppmV was often used as the leak definition (EPA/GRI, 1996). For example, when two ranges are used, "leakers" are those with US EPA Reference Method 21 readings greater than or equal to 10,000 ppmV, while "non-leakers" are those with concentrations less than 10,000 ppmV. Each of these categories is assigned an EF (API, 2004). This screening ranges approach should be more accurate than the average EF approach since it also takes site-specific monitoring data into consideration. The approach could be appropriate for facilities that already or plan to have an LDAR program to collect monitoring data.

The correlation approach uses both the SV of a leaking component and the established correlation between the SVs and the leak rates to estimate the extent of emission. The correlation equation is specific to the type of the component. The main difference between this approach and the previously-mentioned (average EF approach and the screening ranges approach) is that the emission rate for each leaking component needs to be calculated individually, rather than as in a group. This can be laborious and the site needs to maintain a specialized database that keeps track of the findings of the LDAR activities (API, 2009).

The unit-specific correlation approach is similar to the above-mentioned correlation approach, except the correlations are unit-specific and/or site specific. Development of unit-specific correlations requires monitoring data of SVs and measured emission rates for a subset of components from the subject process unit. This approach can be expensive and it would

seldom be justified to develop unit-specific correlations to support estimates for greenhouse gases emissions (API, 2004).

In this study three types (average, screening ranges, correlation) of component-level EFs were developed, when appropriate. These component-level average EFs were then used to develop equipment-level average EFs, when appropriate.

### 5.1.2 Types of Equipment Components

In most documents in literature relevant to fugitive emissions from the oil and gas industry, the equipment components are typically categorized into the following groups:

- Compressor seals
- Connectors
- Flanges
- Open-ended lines (OELs)
- "Others"
- Pressure relief valves (PRVs)
- Pump seals
- Sampling connections
- Valves

The components that may be subject to fugitive leaks at natural gas facilities include valves, flanges and other connections, pump and compressor seals, PRVs and OELs. Pump seals and sample connections were considered outside of the natural gas industry boundary (EPA/GRI, 1996).

The following nine groups were used in this study:

- Flanges
- Manual valves
- OELs
- "Others"
- PRVs
- Regulators
- Seals
- Threaded connections
- Welded connections

These nine groups were used per ARB's request as well as to comply with ARB's Draft Test Protocol – *Detection and Quantification of Fugitive and Vented Methane, Carbon Dioxide, and Volatile*

*Organic Compounds from Crude Oil and Natural Gas Facilities* (CARB, 2010). This protocol is referred to as the ARB's Draft Test Protocol in this report. The two lists are very similar except in this study:

- "connectors" were split into "threaded connections" and "welded connections".
- "seals" was for "compressor seals".
- "manual valves" was used instead of "valves".
- "regulators" was added as another type of component.

### 5.1.3 Leak Detection, Definition and Quantification in This Study

This study used two main types of field instruments that were portable monitoring device and flow rate device. The monitoring device refers to an instrument used to identify a specific fugitive leak source and the flow rate device refers to an instrument used to measure flow rate from a fugitive leak source. As stated in the ARB's Draft Test Protocol, the minimum detection limit of a monitoring device shall be at least 100 parts per million (ppm), and the range of the monitoring device shall be at least 100 to 10,000 ppm, calibrated as methane. For flow rate measurements, the detection limit of a flow rate device shall be at least 0.5 standard cubic feet per minute (scfm), and the range of a flow rate device shall be at least 0.5 to 8.0 scfm, calibrated as methane (ARB, 2010).

The portable monitoring device used in this study has a range of up to 50,000 ppm. The flow rate device (the Hi-Flow sampler) used in this study has a range of 0.01 to 8.0+ scfm. Both instruments comply with the test ranges required in the ARB's Draft Test Protocol.

A total of twenty-five facilities were surveyed during twenty-seven visits which include twelve facilities in the production and processing (P&P) sector, three in the storage sector, eight in the transmission sector, and two in the distribution sector. Twenty-four visits were scheduled and three were surprise visits accompanied by local air districts personnel. Most of the facilities were too large to survey in their entirety, so only representative portions of each facility were surveyed. In addition, some equipment items (e.g., compressors, dehydrators, and separators) were large and some of their components could not be readily accessed for surveying. Surveyed equipment included 172 wellheads, 131 separators, 17 dehydrators, 145 piping segments, 66 compressors, 374 pneumatic devices, 19 metering and regulating (M&R) stations, 34 hatches, 2 pumps, and 12 customer meters. A total of 92,157 components were surveyed, including 10,101 flanges, 10,765 manual valves, 384 OELs, 358 PRVs, 930 regulators, 146 seals, 57,061 threaded connections, 12,274 welded connections, and 138 "others".

Out of 92,157 equipment components surveyed, 380 of them (i.e., 0.41%) showed positive SV readings and two of them had concentration less than 100 ppmV. These two components were excluded from further analysis because they might not be picked up by devices that comply with ARB's requirement on the minimum detection limit of 100 ppmV. Consequently, the other 378 locations were considered as leaking components in this study. Table 5.1.1 summarizes the counts of components surveyed and the counts and the percentages of leaking sources.

**Table 5.1.1: Counts of Components Surveyed and Percentages of Leaking Ones**

| | Count of Component Surveyed | Count of Component w/SV ≥100 ppmV | Percentage of Components w/SV ≥100 ppmV |
|---|---|---|---|
| **Flanges** | 10,101 | 56 | 0.55% |
| **Manual Valves** | 10,765 | 49 | 0.46% |
| **OELs** | 384 | 26 | 6.77% |
| **Others** | 138 | 44 | 31.9% |
| **PRVs** | 358 | 6 | 1.68% |
| **Regulators** | 930 | 13 | 1.40% |
| **Seals** | 146 | 61 | 41.8% |
| **Threaded Connections** | 57,601 | 123 | 0.21% |
| **Welded Connections** | 12,274 | 0 | 0% |

## 5.2 Screening Ranges Emission Factors

The first approach of data analysis is to develop screening ranges EFs by using the SVs from the portable monitoring device and the leak rates from the flow rate device.

### 5.2.1 All Components

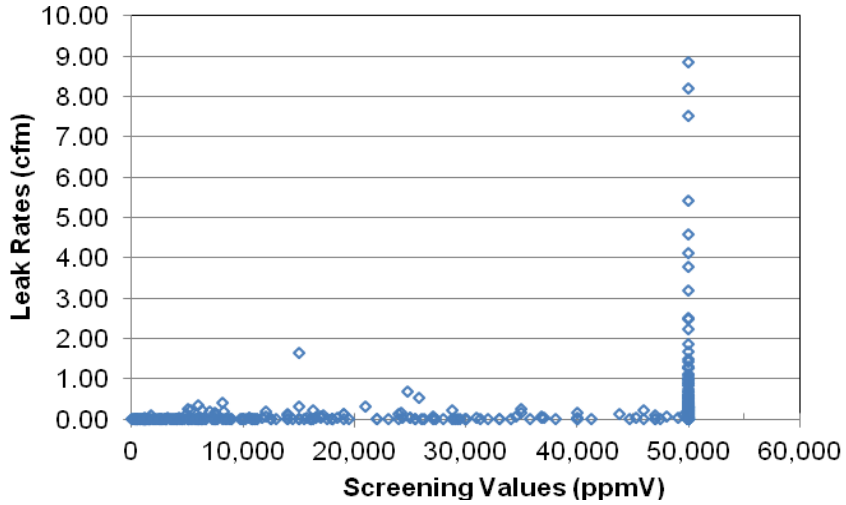
Figure 5.2.1.1 plots the leak rates versus SVs of all 378 leaking components. As shown, the SVs spanned several orders of magnitude and the leak rates were highly variable. It should be noted that the high variability in measured leakage rates was also found in the EPA/GRI 1996 study; as an example, the leak rates of connectors varied more than four orders of magnitude for similar SVs (see Figure 3-11 of Volume 8 of the EPA/GRI 1996 report). The recorded leak rates range from below detection limit (<0.01 cfm) to 8.85 cfm and the SVs range from 100 to ≥50,000 ppmV. The "≥50,000 ppmV" data are for those SVs greater than or equal to 50,000 ppmV. The pegged value of the portable monitoring device used in this study is 50,000 ppmV. Many of the leaking components have large SVs, even ≥50,000 ppmV, but their leak rates are below the detection limit of the flow rate device. This implies a poor correlation between the measured leak rates and the measured SVs. The raw leakage rate data, separated by types of equipment and components and by industry sector, are tabulated in Appendix C.

In this study, two Hi-Flow samplers were used to quantify emissions from the leaking equipment components. The main differences between the uses of the Hi-Flow samplers and the traditional approach, based on the EPA protocol, are (EPA/GRI, 1996):

- Hi-Flow samplers measure the emission rate directly by taking both concentration and sample flow rate measurements. In contrast, the traditional EPA protocol approach requires emission quantification using an enclosure method (e.g., the bagging approach). Bagging data are very costly to obtain and time-consuming.
- Using Hi-Flow samplers is much faster than bagging. However, it should be noted that the data generated from using Hi-Flow samplers are not suitable for generating default

zero emission factors because the higher dilution rate used by the Hi-Flow samplers will lead to lower concentrations (i.e., lower resolution) for small leaks that may become non-detects by the Hi-Flow samplers. On the other hand, the Hi-Flow samplers can measure large leaks more accurately because of the large air flow rates employed during measurements.

**Figure 5.2.1.1: Leak Rates vs. Screening Values of All Leaking Components**




Partly due to the relatively large minimum detection limit (0.01 cfm) of the Hi-Flow samplers, many of the leaking sources have the SV readings registered, but the corresponding leaking rates are below the detection limit. In this study, these leaking sources were assigned a leak rate of 0.005 cfm which is half of the minimum detectable value of 0.01 cfm.

To facilitate the data analysis, the measured ppmV values were first split into two groups: 100 to 9,999 and ≥10,000 ppmV. The choice of 10,000 ppmV as the boundary for these two groups is because 10,000 ppmV was often used as the leak definition in literature (EPA, 1995; EPA/GRI, 1996, API, 2004).

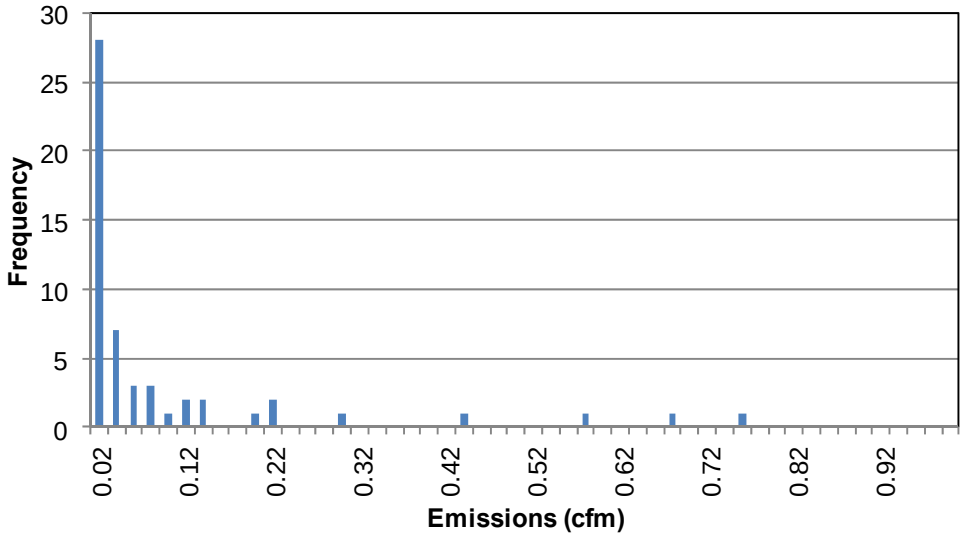
Table 5.2.1.1 tabulates some statistics of the leak rates (count, minimum, maximum, median, arithmetic average, and geometric mean) for two groups of SVs (<10,000 and ≥10,000 ppmV). As shown, the majority of the leaking components (261/378 = 69%) have an SV ≥10,000 ppmV. The leak rates for the <10,000 ppmV group range from 0.005 (below the detection limit of 0.01 cfm) to 0.41 cfm, while those for the ≥10,000 ppmV group range from 0.005 to 8.85 cfm. For both ranges of the SVs, the arithmetic averages of the leak rates are larger than the corresponding median and geometric mean (geomin) values.

The histograms of leak rates were then plotted for flanges, manual valves, OELs, "others", OELs, regulators, seals, and threaded connections surveyed (see Appendix A). Figure 5.2.1.2 shows the leak-rate histogram of flanges as an example. The majority of leak rates were within the range of <0.01 to 0.02 cfm. For emission rates greater than 0.02 cfm, the frequency at which the leakages occurred decreased as the emission rate increased. The histograms of other types of components surveyed appeared to have the same trend.

**Table 5.2.1.1: Leak Rates vs. Screening Values in Two Ranges (All Components)**

| | | Leak Rate (cfm) | | | | |
|---|---|---|---|---|---|---|
| **SV (ppmV)** | **Count** | **Min** | **Max** | **Median** | **Average** | **Geomean** |
| **100 - 9,999** | 117 | 0.005 | 0.410 | 0.005 | 0.024 | 0.0079 |
| **≥10,000** | 261 | 0.005 | 8.850 | 0.040 | 0.378 | 0.0317 |
| **Total** | 378 | 0.005 | 8.850 | 0.010 | 0.269 | 0.0291 |

**Figure 5.2.1.2: Leak-Rate Histogram of Flanges**




The histograms were then further evaluated in Appendix B for probability distribution. The Weibull probability distribution function (PDF) was found to fit the histograms well. A cumulative distribution function (CDF) calculates the probability that a leakage rate will be located between 0 and a random leakage rate, x. The Weibull CDF can be expressed as:

$$P(y < x) = F(x; k, \lambda) = 1 - e^{-(x/\lambda)^k}$$

The cumulative probability for leak rates from 0 cfm to infinite will be equal to unity. Similar to the PDF, the CDF is dependent on the shape parameter, k, and the scale parameter, $\lambda$. The Weibull CDF was used in this study to determine if the geomean or the arithmetic mean is a better indicator as the mean for each range of the leakage rates. The closer the cumulative probability is to 50%, the range is more evenly distributed. The results tabulated in Table B.2.1 (in Appendix B) indicate that using the geomean yields a cumulative probability typically closer to 50% than that using the arithmetic mean for the majority of the component types and for different SV groups. It implies that the geomean is a better indicator than the arithmetic mean as the mean for each group of leak rates found in this study. Consequently, the geomeans, instead of the arithmetic means, were used to derive the EFs in this study. It should also be noted that all these calculated values of leak rates may be larger than the actual averages

because all the non-detects were assigned a leak rate of 0.005 cfm. The default zero emission factors in literature should be better representatives for small leaks.

The portable monitoring device used in this study has a maximum detection limit of 50,000 ppmV. The data set was further divided into the following four groups: 100 to 999, 1,000 to 9,999, 10,000 to 49,999, and ≥50,000 ppmV. The first group, "100-999 ppmV", was chosen because all the measured leak rates in this group were below the detection limit of 0.01 cfm. The second group, "1,000-9,999 ppmV" was chosen to reflect the typical leak definition, 10,000 ppmV, in the earlier regulations. The third group (10,000-49,999 ppmV) and the last group (≥50,000 ppmV) were chosen to reflect and to take advantage of the maximum detection value (50,000 ppmV) of the portable monitoring units used in this study.

Table 5.2.1.2 shows the leak rates in four groups of SVs (100-999, 1,000-9,999, 10,000-49,999 and ≥50,000 ppmV). As shown, almost half of the leaking components (167/378 = 44.2%) have a screening value ≥50,000 ppmV. The leak rates are all below the detection limit of 0.01 cfm for the 100-999 ppmV group and range from 0.005 to 0.410, 0.005 to 1.640, and 0.005 to 8.850 cfm for the 1,000-9,999, 10,000-49,999, and ≥50,000 ppmV groups, respectively. For all three groups with SVs ≥1,000 ppmV, the arithmetic averages of the leak rates are larger than the corresponding median and geomean values. The geometric means of the leak rates are 0.0050, 0.0085, 0.0198, and 0.0901 cfm for the 100-999, 1,000-9,999, 10,000-49,999, and ≥50,000 ppmV groups, respectively. The geometric means of the leak rates increase with the screening values.

**Table 5.2.1.2: Leak Rates vs. Screening Values in Four Ranges (All Components)**

| | | Leak Rate (cfm) | | | | |
|---|---|---|---|---|---|---|
| **SV (ppmV)** | **Count** | **Min** | **Max** | **Median** | **Average** | **Geomean** |
| **100-999** | 16 | 0.005 | 0.005 | 0.005 | 0.005 | 0.0050 |
| **1,000-9,999** | 101 | 0.005 | 0.410 | 0.005 | 0.027 | 0.0085 |
| **10,000-49,999** | 94 | 0.005 | 1.640 | 0.020 | 0.070 | 0.0198 |
| **≥50,000** | 167 | 0.005 | 8.850 | 0.110 | 0.552 | 0.0901 |
| **Total** | 378 | 0.005 | 8.850 | 0.010 | 0.269 | 0.0291 |

The analysis in this section up to this point treated all leaking components as a whole, which included flanges, manual valves, OELs, "others", PRVs, regulators, seals, and threaded connections (no welded connections were found leaking in this study). These components can be quite different in their leak characteristics. Nonetheless, this analysis provides an overview of all the leak data. The following subsections discuss the screening ranges EFs for components that have a reasonable size of data. These components are flanges, manual valves, open-ended lines, "others", seals, and threaded connections (i.e., PRVs and regulators were excluded).

### 5.2.2 Flanges

Figure 5.2.2.1 plots the leak rates versus SVs of flanges. As shown, the SVs spanned several orders of magnitude and the leak rates were highly variable. The leak rates range from below detection limit (<0.01 cfm) to 0.75 cfm and the SVs range from 750 to ≥50,000 ppmV. Many of

the leaking flanges have high SVs, but their leak rates are below the detection limit. This implies a poor correlation between the leak rates and the screening values.

**Figure 5.2.2.1: Leak Rates vs. Screening Values of Flanges**

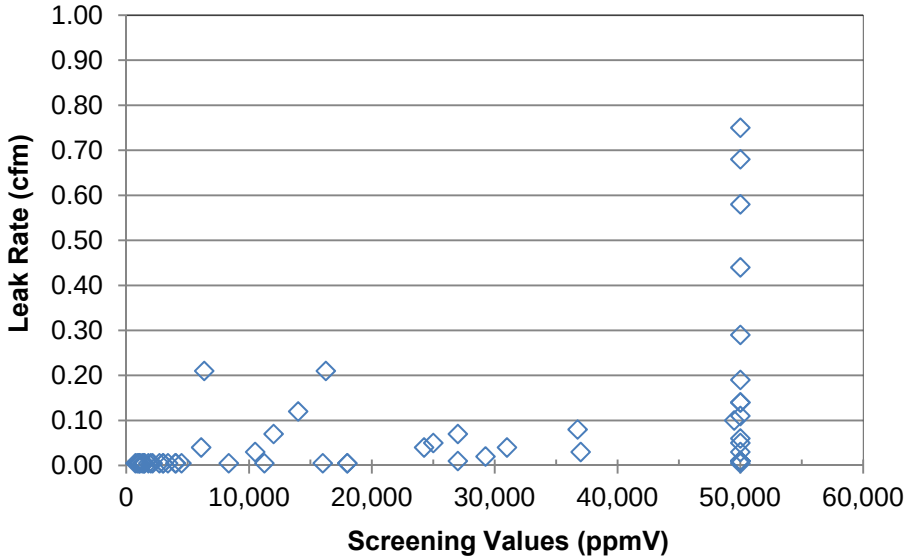



Table 5.2.2.1 tabulates the leak rates in two groups of SVs (<10,000 and ≥10,000 ppmV). As shown, the majority of the leaking flanges (34/56 = 60.7%) have an SV ≥10,000 ppmV. The leak rates for the <10,000 ppmV group range from 0.005 (below the detection limit) to 0.210 cfm, while those for the ≥10,000 ppmV group range from 0.005 to 0.750 cfm. For both groups of the SVs, the arithmetic averages of the leak rates are larger than the corresponding median and geomean values. The geometric mean of leak rates of the "pegged" sources (≥10,000 ppmV here) is 0.0468 cfm.

**Table 5.2.2.1: Leak Rates vs. Screening Values in Two Ranges (Flanges)**

| | | Leak Rate (cfm) | | | | |
|---|---|---|---|---|---|---|
| **SV (ppmV)** | **Count** | **Min** | **Max** | **Median** | **Average** | **Geomean** |
| **100-9,999** | 22 | 0.005 | 0.210 | 0.005 | 0.016 | 0.0065 |
| **≥10,000** | 34 | 0.005 | 0.750 | 0.050 | 0.129 | 0.0468 |
| **Total** | 56 | 0.005 | 0.750 | 0.010 | 0.085 | 0.0216 |

Table 5.2.2.2 tabulates the leak rates in four groups of SVs (100-999, 1,000-9,999, 10,000-49,999 and ≥50,000 ppmV). As shown, almost one-third of the leaking flanges (17/56 = 30.4%) have an SV ≥50,000 ppmV. The leak rates are all below the detection limit of 0.01 cfm for the 100-999 ppmV group and range from 0.005 to 0.21, 0.005 to 0.21, and 0.005 to 0.750 cfm for the 1,000-9,999, 10,000-49,999, and ≥50,000 ppmV ranges, respectively. For all three groups with SV ≥1,000 ppmV, the arithmetic averages of the leak rates are larger than the corresponding median and geomean values. The geometric means of the leak rates are 0.0050, 0.0067, 0.0293, and 0.0747 cfm for the 100-999, 1,000-9,999, 10,000-49,999, and ≥50,000 ppmV ranges, respectively. The geometric means of the leak rates increase with the screening values.

**Table 5.2.2.2: Leak Rates vs. Screening Values in Four Ranges (Flanges)**

| | | Leak Rate (cfm) | | | | |
|---|---|---|---|---|---|---|
| **SV (ppmV)** | **Count** | **Min** | **Max** | **Median** | **Average** | **Geomean** |
| **100-999** | 2 | 0.005 | 0.005 | 0.005 | 0.005 | 0.0050 |
| **1,000-9,999** | 20 | 0.005 | 0.210 | 0.005 | 0.017 | 0.0067 |
| **10,000-49,999** | 17 | 0.005 | 0.210 | 0.040 | 0.052 | 0.0293 |
| **≥50,000** | 17 | 0.005 | 0.750 | 0.110 | 0.206 | 0.0747 |
| **Total** | 56 | 0.005 | 0.750 | 0.010 | 0.085 | 0.0216 |

### 5.2.3 Manual Valves

Figure 5.2.3.1 plots the leak rates versus SVs of manual valves. As shown, the SVs spanned several orders of magnitude and the leak rates were highly variable. The leak rates range from below detection limit (<0.01 cfm) to 0.16 cfm and the SVs range from 500 to ≥50,000 ppmV. Many of the leaking manual valves have large SVs, but their leak rates are below the detection limit. This implies a poor correlation between the leak rates and the screening values.

**Figure 5.2.3.1: Leak Rates vs. Screening Values of Manual Valves**

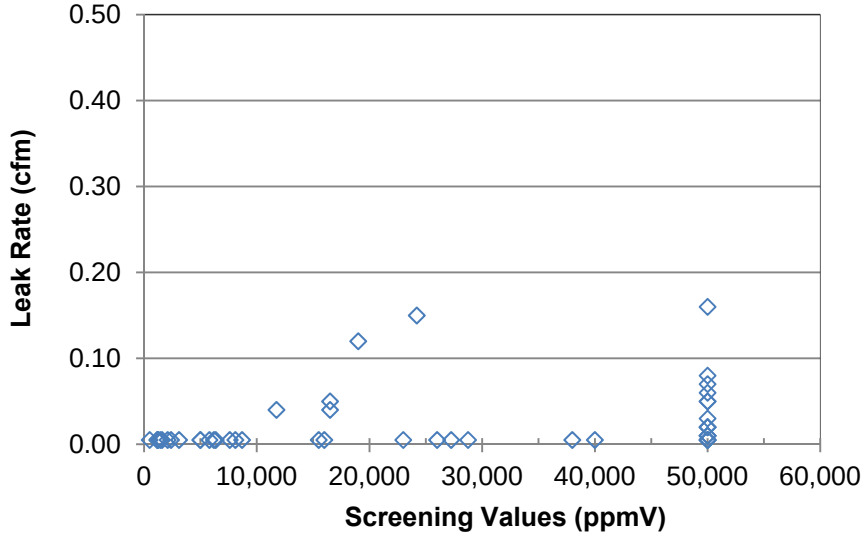



Table 5.2.3.1 tabulates the leak rates in two groups of SVs (<10,000 and ≥10,000 ppmV). As shown, the majority of the leaking manual valves (31/49 = 63.2 percent ) have an SV ≥10,000 ppmV. The leak rates for the <10,000 ppmV group are all below the detection limit of 0.01 cfm, while those for the ≥10,000 ppmV group range from 0.005 to 0.160 ppmV. For SVs ≥10,000 ppmV, the arithmetic average of the leak rates is larger than the corresponding median and geomean values. The geometric mean of leak rates of the "pegged" sources (≥10,000 ppmV here) is 0.0169 cfm.

**Table 5.2.3.1: Leak Rates vs. Screening Values in Two Ranges (Manual Valves)**

| | | Leak Rate (cfm) | | | | |
|---|---|---|---|---|---|---|
| **SV (ppmV)** | **Count** | **Min** | **Max** | **Median** | **Average** | **Geomean** |
| **100-9,999** | 18 | 0.005 | 0.005 | 0.005 | 0.005 | 0.0050 |
| **≥10,000** | 31 | 0.005 | 0.160 | 0.010 | 0.034 | 0.0169 |
| **Total** | 49 | 0.005 | 0.160 | 0.005 | 0.023 | 0.0108 |

**Table 5.2.3.2: Leak Rates vs. Screening Values in Four Ranges (Manual Valves)**

| | | Leak Rate (cfm) | | | | |
|---|---|---|---|---|---|---|
| **SV (ppmV)** | **Count** | **Min** | **Max** | **Median** | **Average** | **Geomean** |
| **100-999** | 1 | 0.005 | 0.005 | 0.005 | 0.005 | 0.0050 |
| **1,000-9,999** | 17 | 0.005 | 0.005 | 0.005 | 0.005 | 0.0050 |
| **10,000-49,999** | 13 | 0.005 | 0.150 | 0.005 | 0.034 | 0.0136 |
| **≥50,000** | 18 | 0.005 | 0.160 | 0.020 | 0.034 | 0.0197 |
| **Total** | 49 | 0.005 | 0.160 | 0.005 | 0.023 | 0.0108 |

Table 5.2.3.2 tabulates the leak rates in four groups of SVs (100-999, 1,000-9,999, 10,000-49,999 and ≥50,000 ppmV). As shown, approximately one third of the leaking manual valves (18/49 = 36.7%) have an SV ≥50,000 ppmV. The leak rates are all below the detection limit of 0.01 cfm for the 100-999 and 1,000-9,999 ppmV groups and range from 0.005 to 0.150 and 0.005 to 0.160 cfm for the 10,000-49,999 and ≥50,000 ppmV ranges, respectively. For two ranges with SVs ≥10,000 ppmV, the arithmetic averages of the leak rates are larger than the corresponding median and geomean values. The geometric means of the leak rates are 0.0050, 0.0050, 0.0136, and 0.0197 cfm for the 100-999, 1,000-9,999, 10,000-49,999, and ≥50,000 ppmV ranges, respectively. The geometric means of the leak rates increase with the screening values.

### 5.2.4 Open-Ended Lines

Figure 5.2.4.1 plots the leak rates versus SVs of OELs. As shown, the SVs spanned several orders of magnitude and the leak rates were highly variable. The leak rates range from below detection limit (<0.01 cfm) to 8.85 cfm and the SVs range from 1,000 to ≥50,000 ppmV. Many of the leaking OELs have large SVs, but their leak rates are below the detection limit. This implies a poor correlation between the leak rates and the screening values.

Table 5.2.4.1 tabulates the leak rates in two groups of SVs (<10,000 and ≥10,000 ppmV). As shown, the majority of leaking OELs (23/26 = 88.5%) have an SV ≥10,000 ppmV. The leak rates for the <10,000 ppmV group are all below the detection limit of 0.01 cfm, while those for the ≥10,000 ppmV group range from 0.005 to 8.85 ppmV. For SVs ≥10,000 ppmV, the arithmetic average of the leak rates is larger than the corresponding median and geomean values. The geometric mean of leak rates of the "pegged" sources (≥10,000 ppmV here) is 0.1191 cfm.

**Figure 5.2.4.1: Leak Rates vs. Screening Values of OELs**

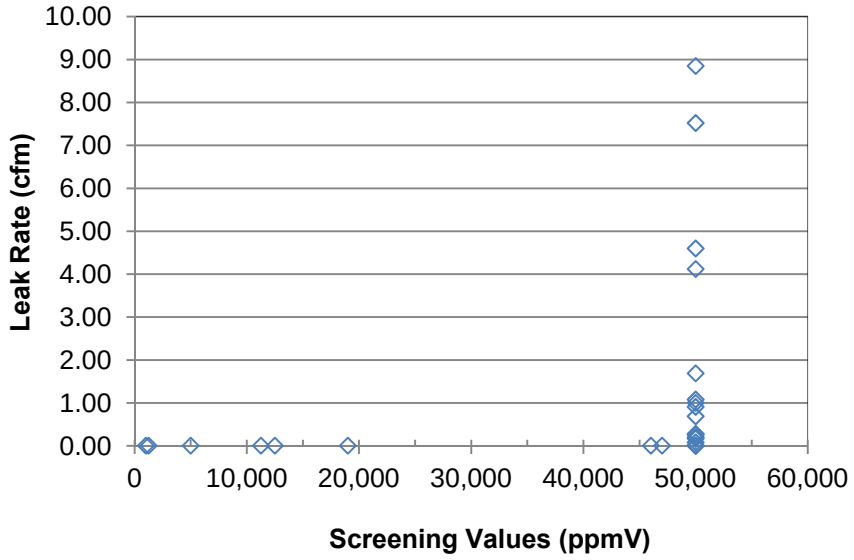



**Table 5.2.4.1: Leak Rates vs. Screening Values in Two Ranges (OELs)**

| | | Leak Rate (cfm) | | | | |
|---|---|---|---|---|---|---|
| **SV (ppmV)** | **Count** | **Min** | **Max** | **Median** | **Average** | **Geomean** |
| **100-9,999** | 3 | 0.005 | 0.005 | 0.005 | 0.005 | 0.0050 |
| **≥10,000** | 23 | 0.005 | 8.850 | 0.200 | 1.369 | 0.1191 |
| **Total** | 26 | 0.005 | 8.850 | 0.125 | 1.212 | 0.0826 |

Table 5.2.4.2 tabulates the leak rates in four groups of SVs (100-999, 1,000-9,999, 10,000-49,999 and ≥50,000 ppmV). As shown, the majority of the leaking OELs (18/26 = 69.2 percent ) have an SV ≥50,000 ppmV. No SVs between 100 and 999 ppmV were registered. The leak rates were all below the detection limit of 0.01 scfm for the 1,000-9,999 and 10,000 to 49,999 ppmV groups and ranged from 0.005 to 8.85 scfm for the ≥50,000 ppmV group. For the ≥50,000 ppmV group, the arithmetic average of the leak rates is larger than the corresponding median and geomean values. The geometric means of the leak rates are "not applicable", 0.0050, 0.0050, and 0.2874 cfm for the 100-999, 1,000-9,999, 10,000-49,999, and ≥50,000 ppmV groups, respectively. The geometric mean of the leak rates was the largest when the SVs ≥50,000 ppmV.

**Table 5.2.4.2: Leak Rates vs. Screening Values in Four Ranges (OELs)**

| | | Leak Rate (cfm) | | | | |
|---|---|---|---|---|---|---|
| **SV (ppmV)** | **Count** | **Min** | **Max** | **Median** | **Average** | **Geomean** |
| **0-999** | 0 | - | - | - | - | - |
| **1,000-9,999** | 3 | 0.005 | 0.005 | 0.005 | 0.005 | 0.0050 |
| **10,000-49,999** | 5 | 0.005 | 0.005 | 0.005 | 0.005 | 0.0050 |
| **≥50,000** | 18 | 0.005 | 8.850 | 0.485 | 1.748 | 0.2874 |
| **Total** | 26 | 0.005 | 8.850 | 0.125 | 1.212 | 0.0826 |

### 5.2.5 Others

Figure 5.2.5.1 plots the leak rates versus SVs of components in the "others" group. As shown, the SVs spanned several orders of magnitude and the leak rates were highly variable. The leak rates range from below detection limit (<0.01 cfm) to 3.18 cfm and the SVs range from 1,000 to ≥50,000 ppmV. Many of the leaking components have high SVs, but their leak rates are below the detection limit. This implies a poor correlation between the leak rates and the screening values.

**Figure 5.2.5.1: Leak Rates vs. Screening Values of 'Others"**

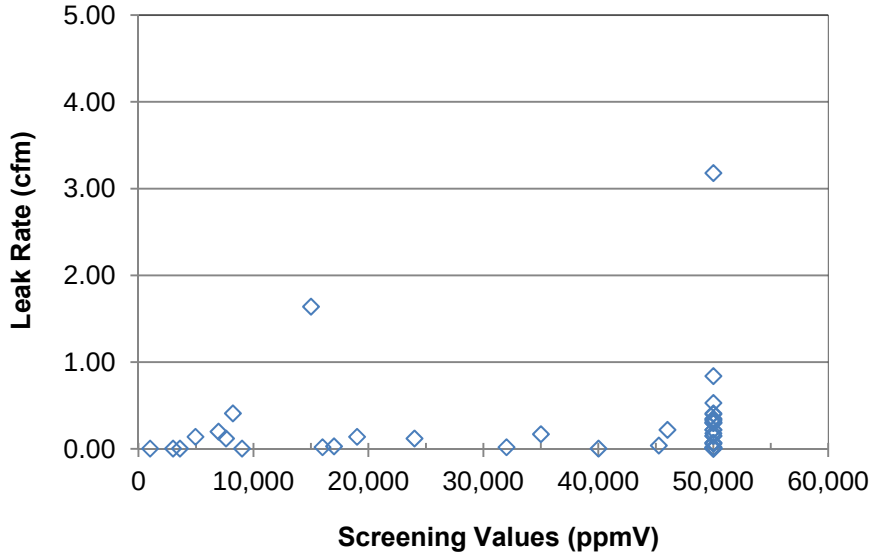



Table 5.2.5.1 tabulates the leak rates in two groups of SVs (<10,000 and ≥10,000 ppmV). As shown, the majority of the leaking components (36/44 = 81.8%) have an SV ≥10,000 ppmV. The leak rates for the <10,000 ppmV group range from 0.005 to 0.410 cfm, while those for the ≥10,000 ppmV group range from 0.005 to 3.180 cfm. For both groups, the arithmetic averages of the leak rates are larger than the corresponding median and geomean values. The geometric mean of leak rates of the "pegged" sources (≥10,000 ppmV here) is 0.1002 cfm.

**Table 5.2.5.1: Leak Rates vs. Screening Values in Two Ranges (Others)**

| | | Leak Rate (cfm) | | | | |
|---|---|---|---|---|---|---|
| **SV (ppmV)** | **Count** | **Min** | **Max** | **Median** | **Average** | **Geomean** |
| 100-9,999 | 8 | 0.005 | 0.410 | 0.063 | 0.111 | 0.0310 |
| ≥10,000 | 36 | 0.005 | 3.180 | 0.150 | 0.304 | 0.1002 |
| **Total** | 44 | 0.005 | 3.180 | 0.140 | 0.269 | 0.0810 |

Table 5.2.5.2 tabulates the leak rates in four groups of SVs (100-999, 1,000-9,999, 10,000-49,999 and ≥50,000 ppmV). As shown, the majority of the leaking components (26/44 = 59.1%) have an SV ≥50,000 ppmV. No SVs between 100 and 999 ppmV were registered. The leak rates range from 0.005 to 0.410, 0.005 to 1.640, and 0.005 to 3.180 cfm for the 1,000-9,999, 10,000 to 49,999,

and ≥50,000 ppmV groups, respectively. For the three groups with SV ≥1,000 ppmV, the arithmetic averages of the leak rates are larger than the corresponding median and geomean values. The geometric means of the leak rates are "not applicable", 0.0310, 0.0691, and 0.1157 cfm for the 100-999, 1,000-9,999, 10,000-49,999, and ≥50,000 ppmV groups, respectively. The geometric means of the leak rates increase with the screening values.

**Table 5.2.5.2: Leak Rates vs. Screening Values in Four Ranges (Others)**

| | | Leak Rate (cfm) | | | | |
|---|---|---|---|---|---|---|
| **SV (ppmV)** | **Count** | **Min** | **Max** | **Median** | **Average** | **Geomean** |
| **100-999** | 0 | - | - | - | - | - |
| **1,000-9,999** | 8 | 0.005 | 0.410 | 0.063 | 0.111 | 0.0310 |
| **10,000 - 49,999** | 10 | 0.005 | 1.640 | 0.080 | 0.241 | 0.0691 |
| **≥50,000** | 26 | 0.005 | 3.180 | 0.200 | 0.328 | 0.1157 |
| **Total** | 44 | 0.005 | 3.180 | 0.140 | 0.269 | 0.0810 |

### 5.2.6 Seals

Figure 5.2.6.1 plots the leak rates versus SVs of seals. As shown, the SVs spanned several orders of magnitude and the leak rates were highly variable. The leak rates range from below detection limit (<0.01 cfm) to 8.220 cfm and the SVs range from 200 to ≥50,000 ppmV. Many of the leaking seals have large SVs, but their leak rates are below the detection limit. This implies a poor correlation between the leak rates and the screening values.

**Figure 5.2.6.1: Leak Rates vs. Screening Values of Seals**

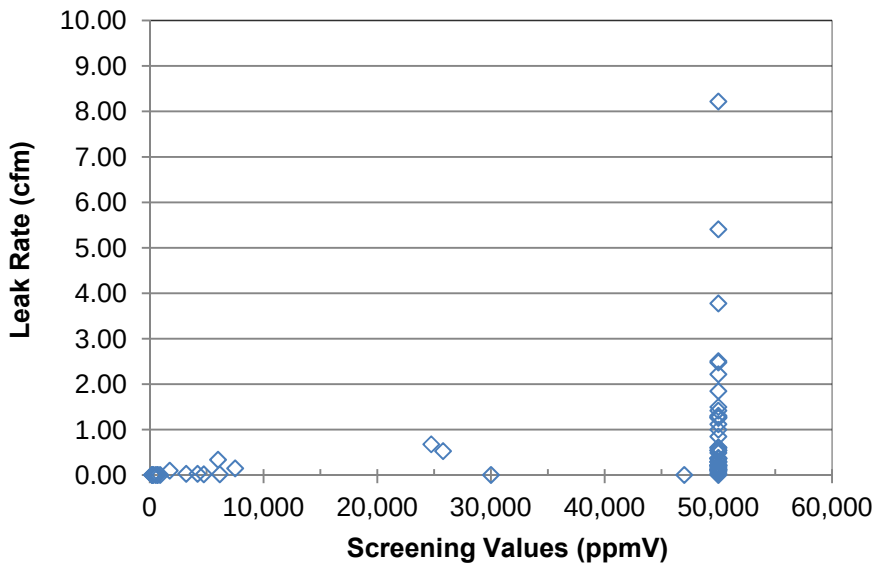



Table 5.2.6.1 tabulates the leak rates in two groups of SVs (<10,000 and ≥10,000 ppmV). As shown, the majority of the leaking seals (48/61 = 78.7%) have an SV ≥10,000 ppmV. The leak rates for the <10,000 ppmV group range from below detection limit of 0.01 cfm to 0.340 cfm, while those for the ≥10,000 ppmV group range from 0.005 to 8.220 cfm. For both groups, the

arithmetic averages of the leak rates are larger than the corresponding median and geomean values. The geometric mean of leak rates of the "pegged" sources (≥10,000 ppmV here) is 0.3632 cfm.

**Table 5.2.6.1: Leak Rates vs. Screening Values in Two Ranges (Seals)**

| | | Leak Rate (scfm) | | | | |
|---|---|---|---|---|---|---|
| **SV (ppmV)** | **Count** | **Min** | **Max** | **Median** | **Average** | **Geomean** |
| **100-9,999** | 13 | 0.005 | 0.340 | 0.005 | 0.042 | 0.0124 |
| **≥10,000** | 48 | 0.005 | 8.220 | 0.375 | 0.959 | 0.3632 |
| **Total** | 61 | 0.005 | 8.220 | 0.290 | 0.763 | 0.1768 |

Table 5.2.6.2 tabulates the leak rates in four groups of SVs (100-999, 1,000-9,999, 10,000-49,999 and ≥50,000 ppmV). As shown, most of the leaking seals (45/61 = 73.8 percent ) have an SV ≥50,000 ppmV. The leak rates are all below the detection limit of 0.01 cfm for the 100-999 ppmV group and range from 0.020 to 0.340, 0.005 to 0.680 and 0.005 to 8.220 cfm for the 1,000-9,999, 10,000-49,999 and ≥50,000 ppmV groups, respectively. For the three ranges with SVs ≥1,000 ppmV, the arithmetic averages of the leak rates are larger than the corresponding median and geomean values. The geometric means of the leak rates are 0.0050, 0.0527, 0.1217, and 0.3907 cfm for the 100-999, 1,000-9,999, 10,000-49,999, and ≥50,000 ppmV groups, respectively. The geometric means of the leak rates increase with the screening values.

**Table 5.2.6.2: Leak Rates vs. Screening Values in Four Ranges (Seals)**

| | | Leak Rate (cfm) | | | | |
|---|---|---|---|---|---|---|
| **SV (ppmV)** | **Count** | **Min** | **Max** | **Median** | **Average** | **Geomean** |
| **100-999** | 8 | 0.005 | 0.005 | 0.005 | 0.005 | 0.0050 |
| **1,000-9,999** | 5 | 0.020 | 0.340 | 0.030 | 0.102 | 0.0527 |
| **10,000-49,999** | 3 | 0.005 | 0.680 | 0.530 | 0.405 | 0.1217 |
| **≥50,000** | 45 | 0.005 | 8.220 | 0.370 | 0.996 | 0.3907 |
| **Total** | 61 | 0.005 | 8.220 | 0.290 | 0.763 | 0.1768 |

### 5.2.7 Threaded Connections

Figure 5.2.7.1 plots the leak rates versus SVs of threaded connections. As shown, the SVs spanned several orders of magnitude and the leak rates were highly variable. The leak rates range from below detection limit (<0.01 cfm) to 0.430 cfm and the SVs range from 300 to ≥50,000 ppmV. Many of the leaking threaded connections have large SVs, but their leak rates are below the detection limit. This implies a poor correlation between the leak rates and the screening values.

Table 5.2.7.1 tabulates the leak rates in two groups of SVs (<10,000 and ≥10,000 ppmV). As shown, the majority of the leaking threaded connections (80/123 = 65.0%) have an SV ≥10,000 ppmV. The leak rates for the <10,000 ppmV group range from below the detection limit of 0.01 cfm to 0.120 cfm, while those for the ≥10,000 ppmV group range from 0.005 to 0.430 cfm. For

both groups, the arithmetic averages of the leak rates are larger than the corresponding median and geomean values. The geometric mean of leak rates of the "pegged" sources (≥10,000 ppmV here) is 0.0155 cfm.

**Figure 5.2.7.1: Leak Rates vs. Screening Values of Threaded Connections**

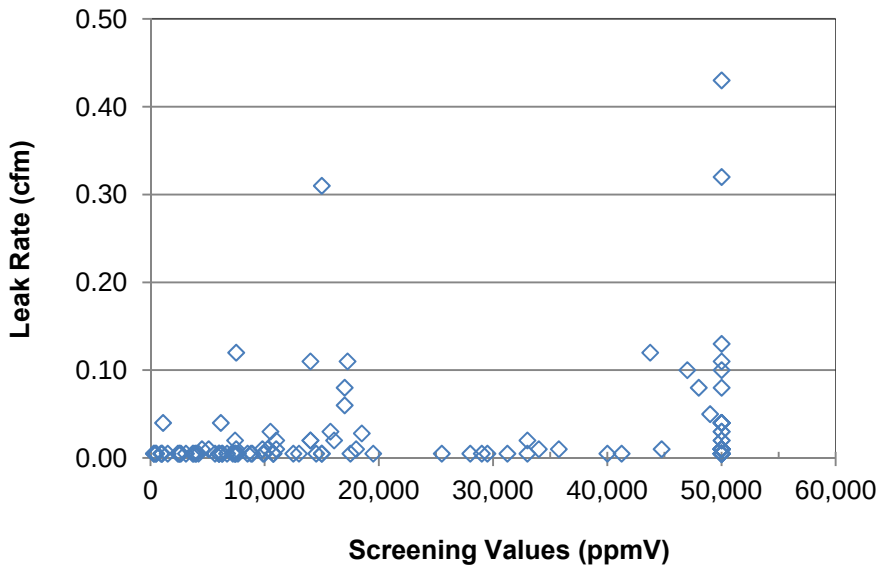



**Table 5.2.7.1: Leak Rates vs. Screening Values in Two Ranges (Threaded Connections)**

| | | Leak Rate (cfm) | | | | |
|---|---|---|---|---|---|---|
| **SV (ppmV)** | **Count** | **Min** | **Max** | **Median** | **Average** | **Geomean** |
| **100-9,999** | 43 | 0.005 | 0.120 | 0.005 | 0.010 | 0.0065 |
| **≥10,000** | 80 | 0.005 | 0.430 | 0.010 | 0.038 | 0.0155 |
| **Total** | 123 | 0.005 | 0.430 | 0.005 | 0.028 | 0.0114 |

**Table 5.2.7.2: Leak Rates vs. Screening Values in Four Ranges (Threaded Connections)**

| | | Leak Rate (cfm) | | | | |
|---|---|---|---|---|---|---|
| **SV (ppmV)** | **Count** | **Min** | **Max** | **Median** | **Average** | **Geomean** |
| **100-999** | 5 | 0.005 | 0.005 | 0.005 | 0.005 | 0.0050 |
| **1,000-9,999** | 38 | 0.005 | 0.120 | 0.005 | 0.011 | 0.0068 |
| **10,000-49,999** | 41 | 0.005 | 0.310 | 0.010 | 0.033 | 0.0143 |
| **≥50,000** | 39 | 0.005 | 0.430 | 0.010 | 0.043 | 0.0168 |
| **Total** | 123 | 0.005 | 0.430 | 0.005 | 0.028 | 0.0114 |

Table 5.2.7.2 tabulates the leak rates in four groups of SVs (100-999, 1,000-9,999, 10,000-49,999 and ≥50,000 ppmV). As shown, almost one third of the leaking threaded connections (39/123 = 31.7%) have an SV ≥50,000 ppmV. The leak rates are all below the detection limit of 0.01 cfm for the 100-999 ppmV group and range from 0.005 to 0.120, 0.005 to 0.310 and 0.005 to 0.430 cfm for

the 1,000-9,999, 10,000-49,999 and ≥50,000 ppmV groups, respectively. For the three groups with SVs ≥1,000 ppmV, the arithmetic averages of the leak rates are larger than the corresponding median and geomean values. The geometric means of the leak rates are 0.0050, 0.0068, 0.0143, and 0.0168 cfm for the 100-999, 1,000-9,999, 10,000-49,999, and ≥50,000 ppmV ranges, respectively. The geometric means of the leak rates increase with the screening values.

### 5.2.8 Ranges of Leak Rates and Pegged EFs for Equipment Components

The screening-ranges EFs for flanges, manual valves, OELs, "others", seals, and threaded connections are summarized in Table 5.2.8.1 (PRVs and regulators were not included in this part of data analysis because of small sample sizes of leaking sources and welded connections were also not included because there were no leaking sources found). The geomeans of the leak rates increase with the screening values.

**Table 5.2.8.1: Leak Rates (in cfm) versus SVs in Four Ranges**

| SV (ppmV) | 100 - 999 | 1,000 - 9,999 | 10,000 - 49,999 | ≥50,000 |
|---|---|---|---|---|
| **Flanges** | 0.0050 (2)* | 0.0067 (20) | 0.0293 (17) | 0.0747 (17) |
| **Manual Valves** | 0.0050 (1) | 0.0050 (17) | 0.0136 (13) | 0.0197 (18) |
| **OELs** | - | 0.0050 (3) | 0.0050 (5) | 0.2874 (18) |
| **Others** | - | 0.0310 (8) | 0.0691 (10) | 0.1157 (26) |
| **Seals** | 0.0050 (8) | 0.0527 (5) | 0.1217 (3) | 0.3907 (45) |
| **Threaded Connections** | 0.0050 (5) | 0.0068 (38) | 0.0143 (41) | 0.0168 (39) |

Note: * = counts of leaking components

Table 5.2.8.2 tabulates the ranges of leak rates of all leaking components in this study. As shown, the maximum leak rates from leaking OELs and seals are an order of magnitude larger than those of flanges, valves, and threaded connections. The table also shows the pegged EFs for ≥10,000 ppmV and ≥50,000 ppmV. As expected, the pegged EFs for seals and OELs are larger than those of flanges, manual valves, and threaded connections. It should also be noted the pegged EFs for ≥10,000 ppmV are essentially the same as those for ≥50,000 ppmV for manual valves, "others", seals, and threaded connections. For flanges and OELs, the pegged EFs for ≥50,000 ppmV are approximately twice larger than those for ≥10,000 ppmV.

**Table 5.2.8.2: Ranges of Component Leak Rates and Pegged EFs**

| | Leak Rate (cfm) | | | | |
|---|---|---|---|---|---|
| | **Count** | **Min** | **Max** | **≥10,000 ppmV** | **≥50,000 ppmV** |
| **Flanges** | 56 | 0.005 | 0.750 | 0.0468 | 0.0747 |
| **Manual Valves** | 49 | 0.005 | 0.160 | 0.0169 | 0.0197 |
| **OELs** | 26 | 0.005 | 8.850 | 0.1191 | 0.2874 |
| **Others** | 44 | 0.005 | 3.180 | 0.1002 | 0.1157 |
| **Seals** | 61 | 0.005 | 8.220 | 0.3632 | 0.3907 |
| **Threaded Connections** | 123 | 0.005 | 0.430 | 0.0155 | 0.0168 |

In 1999, California Air Pollution Control Officers Association (CAPCOA) and California ARB revised some of the EFs reported in the 1996 EPA/GRI study (CAPCOA, 1999). Table 5.2.8.3

compares the pegged EFs of this study with those of the two studies. Similar to the findings in this study, the EFs of a larger pegged value (100,000 ppmV) are similar to or approximately twice as large as the corresponding values of a much smaller pegged value (10,000 ppmV) in the 1996 EPA/GRI study. Comparing the EFs with a pegged value of 10,000 ppmV, flanges and threaded connections surveyed in this study have smaller EFs than those in the 1996 EPA/GRI and 1999 CAPCOA studies; they are (2.81 vs. 4.50 vs. 3.22 lb/day), and (0.93 vs. 1.48 vs. 1.37 lb/day), respectively. On the other hand, those of OELs and "others" in this study are larger (7.14 vs. 1.59 vs. 2.90 lb/day) and (6.01 vs. 3.86 vs. 0.73 lb/day). That of manual valves in this study falls between those of the two studies (1.01 vs. 3.39 vs. 0.73 lb/day). The data for seals are not really comparable because the seals in this study were mainly compressor seals while those in the EPA/GRI study were pump seals. It should also be noted the differences in the units (lb $CH_4$/d for this study vs. lb total hydrocarbon (THC)/d for those two studies).

**Table 5.2.8.3: Comparison of Pegged Emission Factors**

| | CEC (2012) | | EPA/GRI (1996) | | CAPCOA (1999) |
|---|---|---|---|---|---|
| | ≥10,000 ppmV | ≥50,000 ppmV | ≥10,000 ppmV | ≥100,000 ppmV | ≥10,000 ppmV |
| | (lb $CH_4$/d)* | | (lb THC/day) | | (lb THC/d) |
| **Flanges** | 2.81 | 4.48 | 4.50 | 4.44 | 3.22 |
| **Manual Valves** | 1.01 | 1.18 | 3.39 | 7.41 | 0.73 |
| **OELs** | 7.14 | 17.24 | 1.59 | 4.18 | 2.90 |
| **Others** | 6.01 | 6.94 | 3.86 | 5.82 | 0.73 |
| **Seals** | 21.79 | 23.43 | 3.92 | 8.47 | N/A |
| **Threaded Connections** | 0.93 | 1.01 | 1.48 | 1.59 | 1.37 |

Note: *1 cubic feet methane/minute = 1.136 kg methane/hr = 9.906 tonne methane/yr = 59.98 lb methane/day

## 5.3 Component-Level Correlation Emission Factors

The component-level correlation EF approach is often used to estimate an emission rate from a leaking component using a corresponding SV, especially for facilities with LDAR programs in place. In this section, the correlation equations between the SVs and the leak rates were developed based on the data collected from the field visits. The correlation equations are commonly expressed as:

$$LR_{methane} = a \times (SV)^b$$

where $LR_{methane}$ = methane leak rate (e.g., in cfm in this study)
a, b = constants developed from the correlation fitting
SV = screening value (e.g., in ppmV in this study)

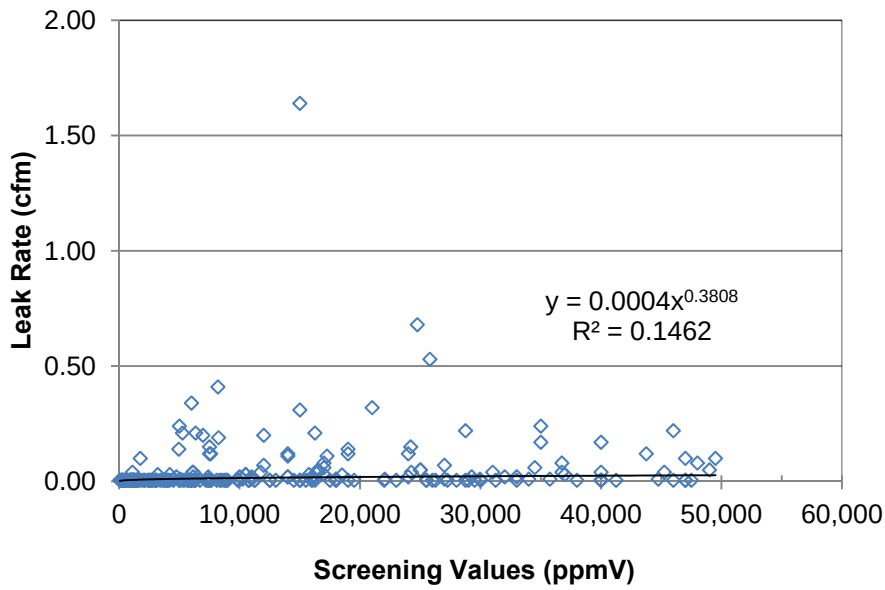
### 5.3.1 All Components

The first attempt was to find a correlation equation for all the leaking components with SVs up to 49,999 ppmV. As shown in Figure 5.3.1.1, the correlation equation was derived as

$$LR_{methane} = 0.0004 \times (SV)^{0.3808} \qquad (R^2 = 0.1462)$$
(For SVs ≤ 49,999 ppmV)

The correlation is relatively poor with $R^2 = 0.1462$.

**Figure 5.3.1.1: Correlation Equation for All Components (SVs ≤49,999 ppmV)**




The data set was then split into two ranges, ≤24,999 and 25,000-49,999 ppmV, to see if better correlations could be found. Figure 5.3.1.2 shows the data fitting of all leaking components with SVs from 100 to 24,999 ppmV, while Figure 5.3.1.3 is for the range of 25,000 to 49,999 ppmV. The correlation equations for these two ranges were derived as:

$$LR_{methane} = 0.00008 \times (SV)^{0.5816} \qquad (R^2 = 0.1528)$$
(For SVs ≤ 24,999 ppmV)

$$LR_{methane} = 0.000001 \times (SV)^{0.9217} \qquad (R^2 = 0.0199)$$
(For SVs from 25,000 to 49,999 ppmV)

The $R^2$ (= 0.1528) of the correlation equation for the sub-range from 100 to 24,999 ppmV is essentially the same as that for the entire range from 100 to 49,999 ppmV ($R^2 = 0.1462$). The index value of the correlation equation for the sub-range from 25,000 to 49,999 is equal to 0.9217 which is close to unity and indicates a linear relationship between the leak rates and screening values. However the correlation is extremely poor with $R^2 = 0.0199$.

**Figure 5.3.1.2: Correlation Equation for All Components (0 to 24,999 ppmV)**

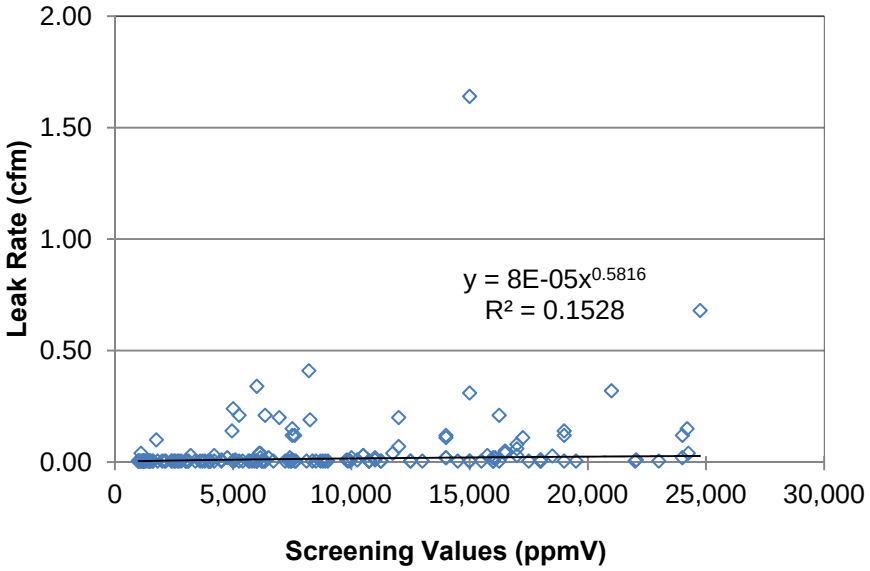
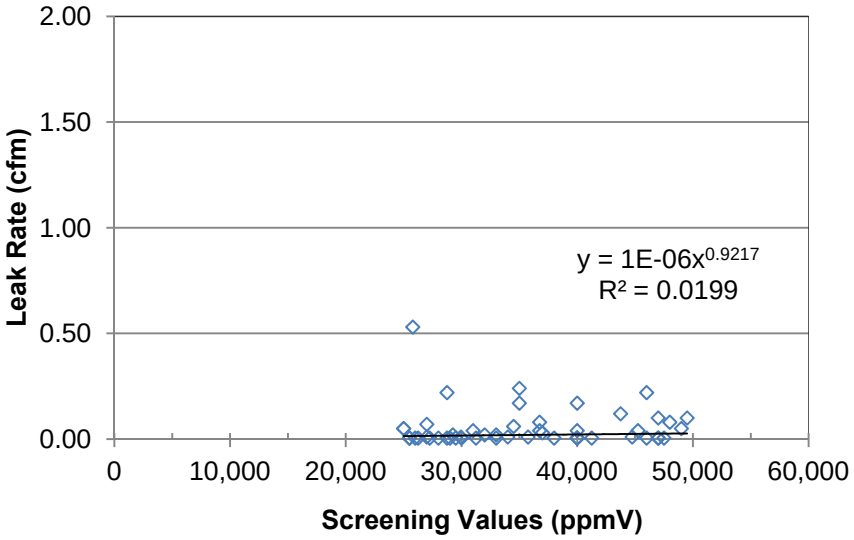



**Figure 5.3.1.3: Correlation Equation for All Components (25,000 to 49,999 ppmV)**




The analysis in this subsection treated all leaking components as a whole, which included flanges, manual valves, OELs, "others", PRVs, regulators, seals, and threaded connections. These components can be quite different in their leak characteristics. Nonetheless, this analysis provides an overview of all the leak data. The following subsections discuss the correlation approach for components that have a reasonable size of data. These components are flanges, manual valves, OELs, seals, and threaded connections. The correlation equations would only be derived for the entire range of SVs up to 49,999 ppmV.

It should be noted again that the high variability in measured leakage rates was also found in the EPA/GRI 1996 study; as an example the leak rates of connectors varied more than four orders of magnitude for similar SVs (see Figure 3-11 of Volume 8 of the EPA/GRI 1996 report).

Although the correlation coefficients for the correlation equations were not reported in that report, the values of the correlation coefficients should also be relatively small.

### 5.3.2 Flanges

As shown in Figure 5.3.2.1, the correlation equation for the flanges was derived as

$$LR_{methane} = 0.00004 \times (SV)^{0.6549} \qquad (R^2 = 0.4277)$$
$$\text{(For SVs} \leq 49{,}999 \text{ ppmV)}$$

The correlation, with $R^2 = 0.4277$, is better than that for all leaking components as a whole.

**Figure 5.3.2.1: Correlation Equation for Flanges (SVs ≤49,999 ppmV)**

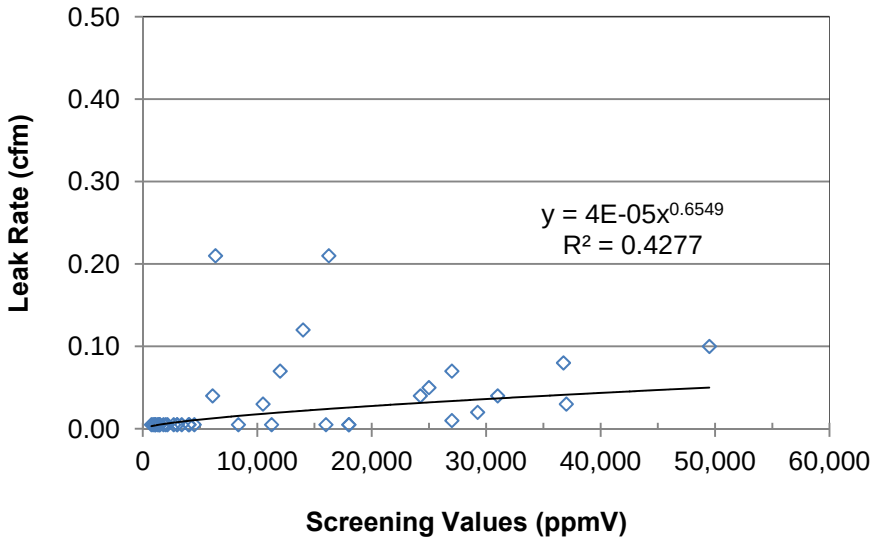
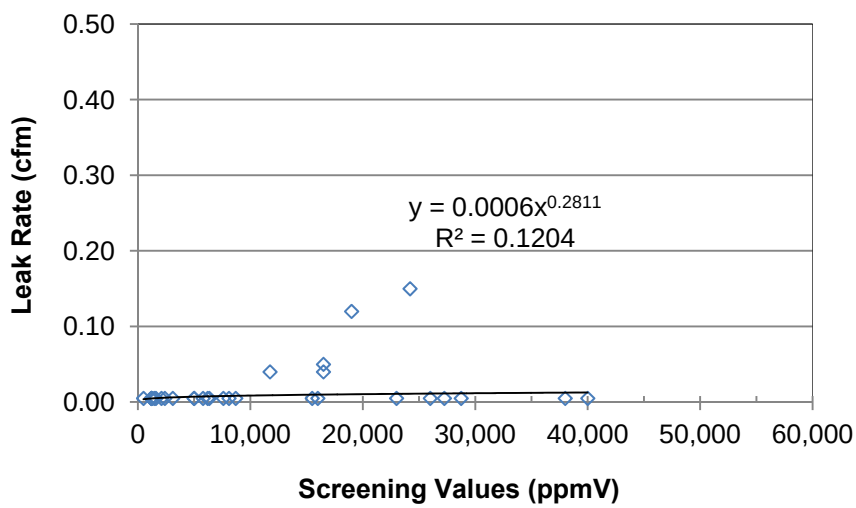



**Figure 5.3.3.1: Correlation Equation for Manual Valves (SVs ≤49,999 ppmV)**




### 5.3.3 Manual Valves

As shown in Figure 5.3.3.1, the correlation equation for the manual valves was derived as

$$LR_{methane} = 0.0006 \times (SV)^{0.2811} \qquad (R^2 = 0.1204)$$
(For SVs ≤ 49,999 ppmV)

The correlation is relatively poor with $R^2 = 0.1204$.

### 5.3.4 Open-Ended Lines

Figure 5.3.4.1 plots the leak rates versus screening values for leaking OELs with screening values up to 49,999 ppmV. There were eight leaking OELs with SVs in this range, but their corresponding leak rates are all below the detection limit of the Hi-Flow sampler, therefore, assigned a leak rate of 0.005 cfm. No correlation equation could be found (or $LR_{methane}$ = 0.005 cfm).

**Figure 5.3.4.1: Correlation Equation for OELs (SVs ≤49,999 ppmV)**

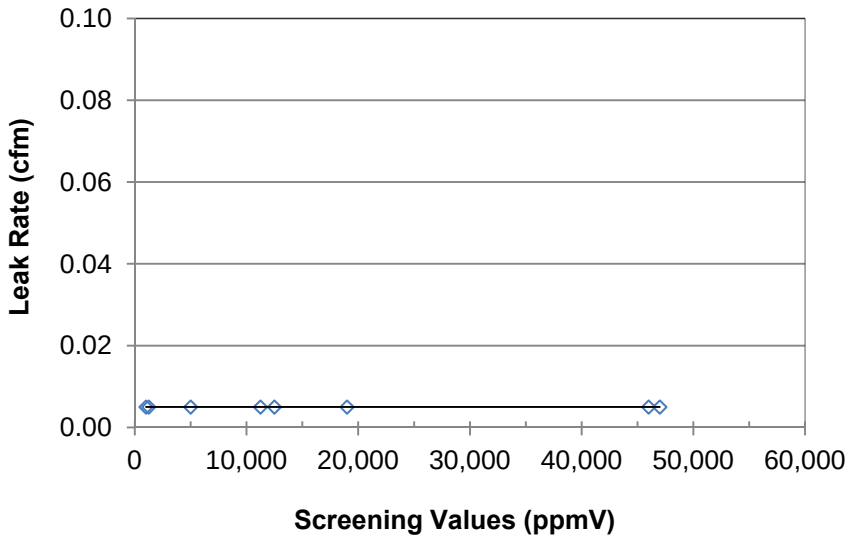
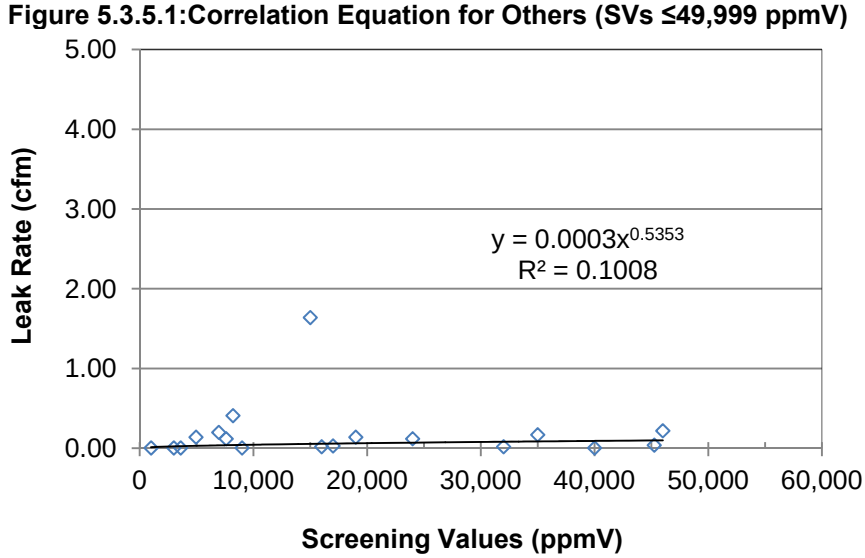



**Figure 5.3.5.1:Correlation Equation for Others (SVs ≤49,999 ppmV)**



### 5.3.5 Others

As shown in Figure 5.3.5.1, the correlation equation for the "others" was derived as

$$LR_{methane} = 0.0003 \times (SV)^{0.5353} \qquad (R^2 = 0.1008)$$
$$\text{(For SVs} \leq 49{,}999 \text{ ppmV)}$$

The correlation is relatively poor with $R^2 = 0.1008$.

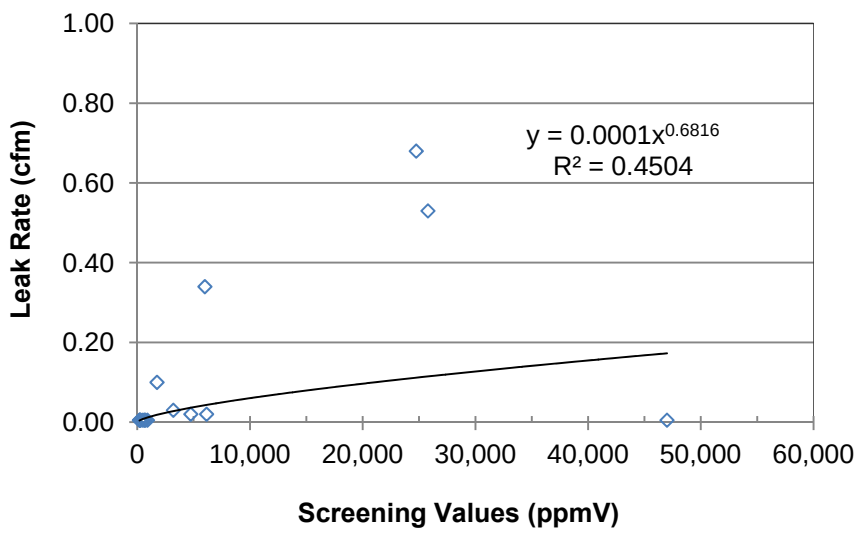
### 5.3.6 Seals

As shown in Figure 5.3.6.1, the correlation equation for the seals was derived as

$$LR_{methane} = 0.0001 \times (SV)^{0.6816} \qquad (R^2 = 0.4504)$$
$$\text{(For SVs} \leq 49{,}999 \text{ ppmV)}$$

The correlation, with $R^2 = 0.4504$, is better than that for all leaking components as a whole.

**Figure 5.3.6.1: Correlation Equation for Seals (SVs ≤49,999 ppmV)**



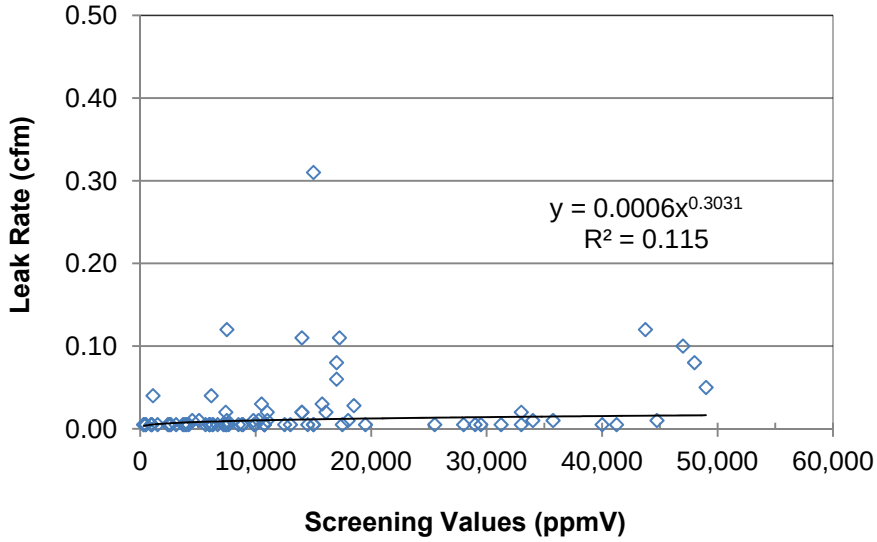

### 5.3.7 Threaded Connections

As shown in Figure 5.3.7.1, the correlation equation for the threaded connections was derived as

$$LR_{methane} = 0.0006 \times (SV)^{0.3031} \qquad (R^2 = 0.115)$$
$$\text{(For SVs} \leq 49{,}999 \text{ ppmV)}$$

The correlation is relatively poor with $R^2 = 0.115$.

**Figure 5.3.7.1: Correlation Equation for Threaded Connections (SVs ≤49,999 ppmV)**




### 5.3.8 Comparison of Correlation Equations

The correlation equations for flanges, manual valves, others, seals, and threaded connections along with their $R^2$ values are tabulated in Table 5.3.8.1 for SVs ranging from 100 to 49,999 ppmV. Although there were leaking OELs with SVs < 50,000 ppmV, the corresponding leak rates were all below the detection limit of 0.01 cfm. Consequently, no correlation equation was derived. As shown, all the $R^2$ values are relatively small (i.e., ≤0.4504).

**Table 5.3.8.1: Correlation Equations for Leak Rates (in cfm) (SVs ≤49,999 ppmV)**

| | Correlation Equation | $R^2$ |
|---|---|---|
| **Flanges** | $LR_{methane} = 0.00004 \times (SV)^{0.6549}$ | 0.4277 |
| **Manual Valves** | $LR_{methane} = 0.0006 \times (SV)^{0.2811}$ | 0.1204 |
| **Others** | $LR_{methane} = 0.0003 \times (SV)^{0.5353}$ | 0.1008 |
| **Seals** | $LR_{methane} = 0.0001 \times (SV)^{0.6816}$ | 0.4504 |
| **Threaded Connections** | $LR_{methane} = 0.0006 \times (SV)^{0.3031}$ | 0.1150 |

Figure 5.3.8.1 plots the leak rates versus SVs using the correlation equations derived in this study (Table 5.3.8.1). As shown, the calculated leak rates for the same SV are different for different component types. For a specific SV, the calculated leak rates will be in the following decreasing order: seals, "others", flanges, threaded connections, and manual valves.

**Figure 5.3.8.1: Leak Rates vs. SVs Using the Correlation Equations**

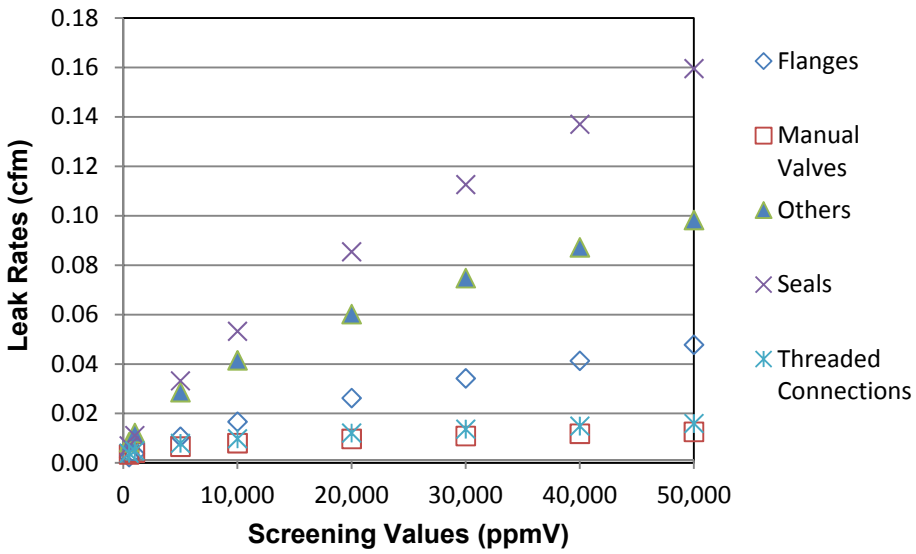



Table 5.3.8.2 tabulates the correlation equations for leak rates (in kg/hr) of the 1996 EPA/GRI study, the 1999 CAPCOA study and this study. The correlation equations for the EPA/GRI and CAPCOA studies were similar. The calculated leak rates using the correlation equations of this study would be several times larger than those using the EPA/GRI or CAPCOA correlation equations. The differences may be partly attributed to the poor correlation between the leak rates and the SVs in this study and the larger detection limit of the High-Flow samplers. In addition, the correlation equations in this study only used data from the natural gas industry and those of the EPA/GRI and the CAPCOA studies were based on data from petroleum refineries, marketing terminals, and oil and gas production and were combined for all service types (i.e., gas, light liquid, heavy liquid).

**Table 5.3.8.2: Comparison of Correlation Equations for Leak Rates (in kg/hr)**

| | EPA/GRI (1996) | CAPCOA (1999) | CEC (2012) |
|---|---|---|---|
| **Connectors** | $(1.52 \times 10^{-6}) \times (SV)^{0.735}$ | $(1.53 \times 10^{-6}) \times (SV)^{0.736}$ | $(6.78 \times 10^{-4}) \times (SV)^{0.3031}$ |
| **Flanges** | $(4.44 \times 10^{-6}) \times (SV)^{0.703}$ | $(4.53 \times 10^{-6}) \times (SV)^{0.706}$ | $(4.52 \times 10^{-5}) \times (SV)^{0.6549}$ |
| **OELs** | $(2.16 \times 10^{-6}) \times (SV)^{0.704}$ | $(1.90 \times 10^{-6}) \times (SV)^{0.724}$ | N/A |
| **Pump Seals** | $(4.82 \times 10^{-5}) \times (SV)^{0.610}$ | $(5.07 \times 10^{-5}) \times (SV)^{0.622}$ | N/A |
| **Valves** | $(2.29 \times 10^{-6}) \times (SV)^{0.746}$ | $(2.27 \times 10^{-6}) \times (SV)^{0.747}$ | $(6.78 \times 10^{-4}) \times (SV)^{0.2811}$ |
| **Others** | $(1.32 \times 10^{-5}) \times (SV)^{0.589}$ | $(8.69 \times 10^{-6}) \times (SV)^{0.642}$ | $(3.39 \times 10^{-4}) \times (SV)^{0.5353}$ |

The following figures compare the correlation equations derived from the data generated in this study and those of the EPA/GRI study by plotting the calculated leak rates versus screening values, as shown in Figures 5.3.8.2 to 5.3.8.5 for flanges, manual valves, "others", and threaded connections. No plot was made for seals because the EPA/GRI and CAPCOA correlation equations are for pump seals, while the correlation equation in this study is mainly for

compressor seals. In addition, no plot for open-ended lines was made because a correlation equation cannot be derived for OELs in this study.

**Figure 5.3.8.2: Comparison of Correlation Equations (Flanges)**

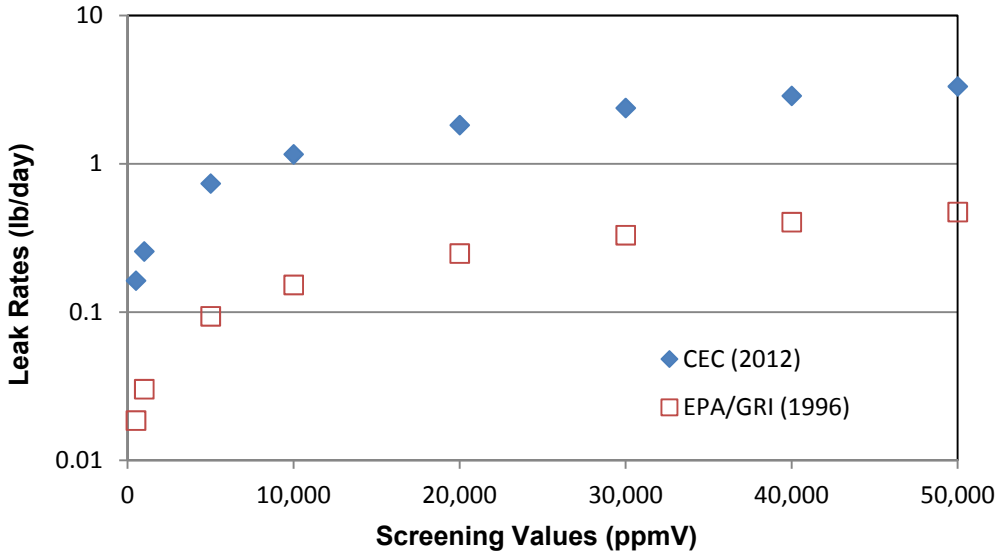



**Figure 5.3.8.3: Comparison of Correlation Equations (Manual Valves)**

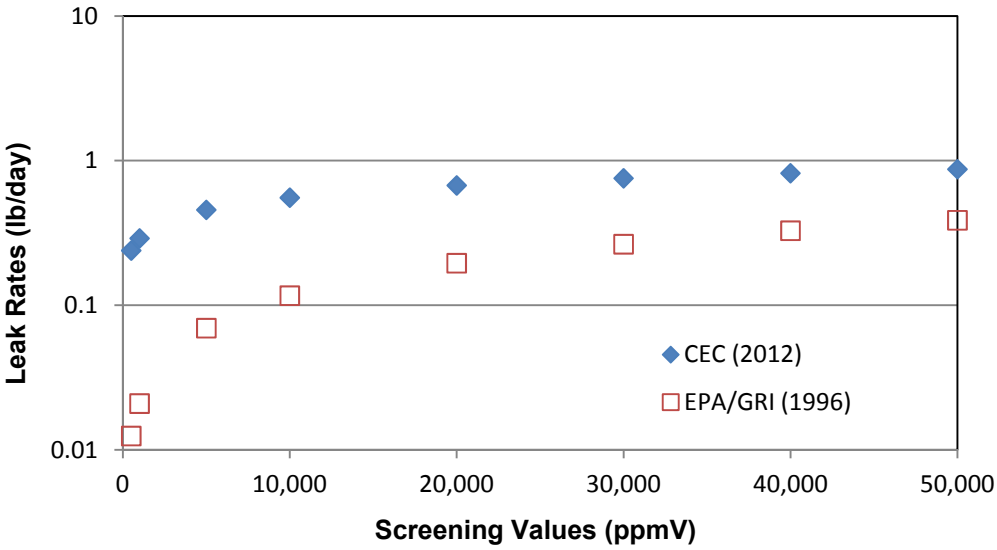


**Figure 5.3.8.4: Comparison of Correlation Equations (Others)**

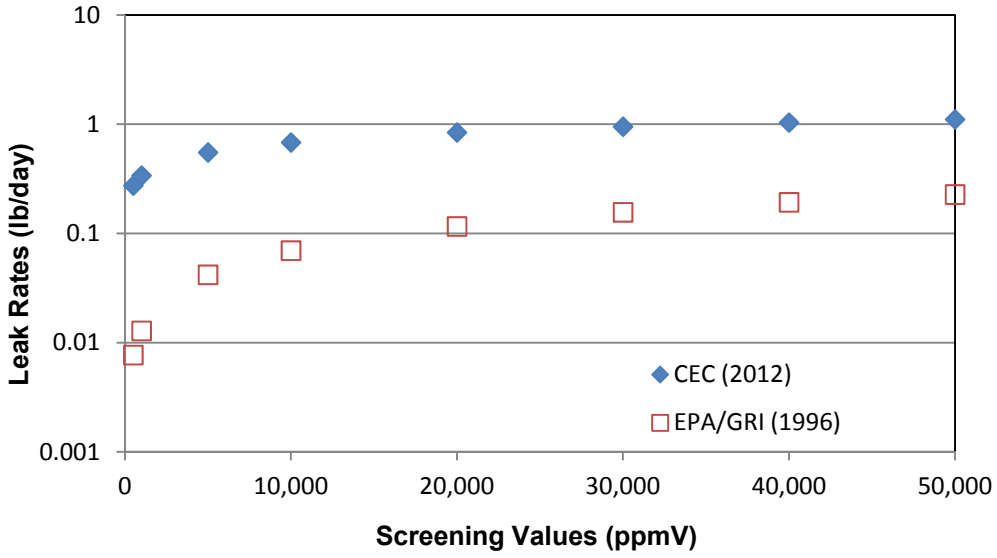
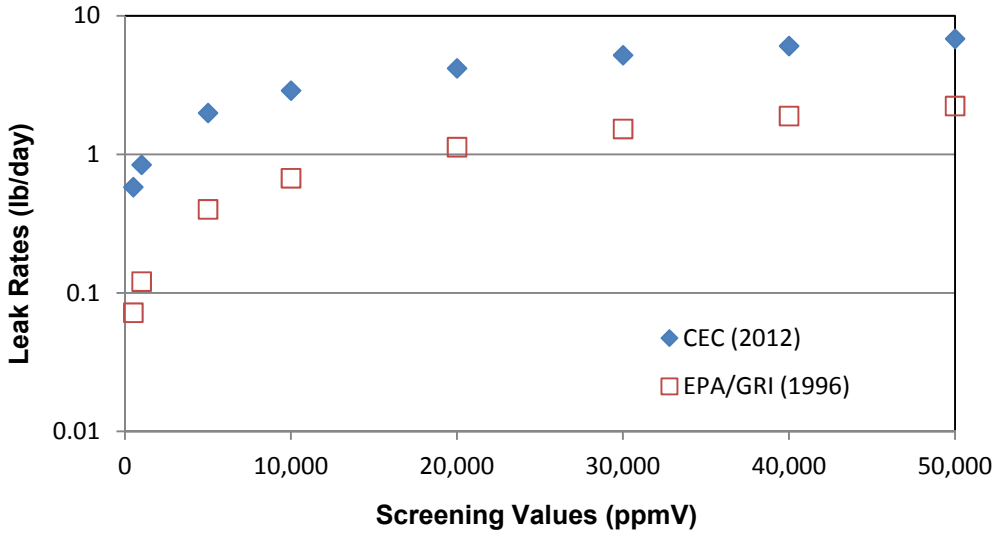



**Figure 5.3.8.5: Comparison of Correlation Equations (Threaded Connections)**




As shown in Figures 5.3.8.2 to 5.3.8.5, the general trend is that the calculated leak rates using the correlation equations derived in this study are typically a few times larger than the corresponding ones using the EPA/GRI correlation equations for all four types of components (flanges, manual valves, "others", and threaded connections). The differences may be partly attributed to the poor correlation between the leak rates and the SVs in this study and the relatively large minimum detection limit of the High-Flow samplers. However, it should be mentioned that the pegged EFs are relatively comparable between this study and the 1996 EPA/GRI study. In addition, the correlation equations in this study only used data from the

natural gas industry and those of the 1996 EPA/GRI study came from a variety of operations and services. This may also contribute to the apparent differences.

## 5.4 Component-Level and Equipment-Level Average EFs

This section uses the data obtained from the field activities to generate component-level average EFs. The component-level average EFs are then used to develop equipment-level average EFs, when appropriate. The types of equipment/system in this study include the following ten types:

- Wellheads (section 5.4.1)
- Separators (section 5.4.2)
- Dehydrators (section 5.4.3)
- Piping segments (section 5.4.4)
- Compressors (section 5.4.5)
    - Reciprocating compressors (section 5.4.5a)
    - Centrifugal compressors (section 5.4.5b)
    - Rotary compressors (section 5.4.5c)
- Pneumatic devices (section 5.4.6)
    - Pneumatic actuators (section 5.4.6a)
    - Pneumatic valves (section 5.4.6b)
- Metering and regulating (M&R) stations (section 5.4.7)
- Hatches (section 5.4.8)
- Pumps (section 5.4.9)
- Customer meters (section 5.4.10)

### 5.4.1 Wellheads

A wellhead is the uppermost part of a natural gas well located at production or storage facilities of the natural gas industry. They typically consist of many flanges, valves, connections and a few other components. For each wellhead surveyed, all components were screened from the ground up.

Wellheads are only used in the production or storage sectors of the natural gas industry. The research team visited eight facilities having wellheads; five of them were in the production sector and the other three were in the storage sector (Table 5.4.1.1). A total of 172 wellheads surveyed, and the majority of them were in the production sector (75.9 percent).

**Table 5.4.1.1: Number of Facilities and Wellheads Surveyed**

| Industry Sector | Number of Facilities Surveyed | Number of Wellheads Surveyed | % of Total Wellheads Surveyed |
|---|---|---|---|
| **Production** | 5 | 128 | 75.9% |
| **Storage** | 3 | 44 | 24.1% |
| **Overall** | 8 | 172 | 100% |

Table 5.4.1.2 tabulates the ranges of component counts per wellhead by industry sector. The average counts of components per wellhead in the storage sector are larger than those in the production sector. The larger count of components per wellhead implies that the wellheads surveyed in the storage sector are larger than those in the production sector. For the purposes of calculating the equipment-level average EFs, the averages of component counts are taken to one decimal place.

**Table 5.4.1.2: Component Counts Surveyed per Wellheads**

| | Production (128*) | | Storage (44) | |
|---|---|---|---|---|
| | Range | Average | Range | Average |
| **Flanges** | 0-23 | 5.8 | 3-44 | 20.4 |
| **Manual Valves** | 4-20 | 7.5 | 1-41 | 24.0 |
| **OELs** | 0-0 | 0.0 | 0-12 | 0.8 |
| **Others** | 0-2 | 0.5 | 0-1 | 0.0 |
| **PRVs** | 0-2 | 0.2 | 0-2 | 0.3 |
| **Regulators** | 0-2 | 0.2 | 0-7 | 1.3 |
| **Seals** | 0-2 | 0.8 | 0-0 | 0 |
| **Threaded Connections** | 3-111 | 27.5 | 5-212 | 102.9 |
| **Welded Connections** | 0-14 | 2.5 | 0-36 | 9.1 |

Note: * = number of wellheads surveyed.

Table 5.4.1.3 shows the leaking percentage of each component. The leaking percentage was calculated by dividing the number of leaking components with the total count of that type of components surveyed.

The leak rates of leaking components were measured by using the Hi-Flow samplers. It should be noted that the minimum detectable leak rate is equal to 0.01 cfm. For those leaking components, with SVs registered by the portable monitoring device but below the leak rates threshold, were assigned a leak rate of 0.005 cfm which is half of the detection limit.

There were at least two different methods of calculating the mean of a data set. While the arithmetic mean (average) is used for a straight average among data points, the geometric mean (geomean) is often used for a data set with a wider range of values. Since the measured leak rates in this study vary to a great extent, the geometric mean is a better indicator of the mean of the leak rates by component, as shown in Section 5.2.1 earlier. Table 5.4.1.4 tabulates the ranges and geomeans of leak rates of leaking components by industry sector.

**Table 5.4.1.3: Leaking Percentages of Components (Wellheads)**

| | Production (128) | | Storage (44) | |
|---|---|---|---|---|
| | Leaking/Total | Percentage | Leaking/Total | Percentage |
| **Flanges** | 5/742 | 0.67% | 0/899 | 0% |
| **Manual Valves** | 2/958 | 0.21% | 25/1,057 | 2.37% |
| **OELs** | 0/0 | - | 8/133 | 6.02% |
| **Others** | 0/70 | 0% | 1/1 | 100% |
| **PRVs** | 0/23 | 0% | 0/14 | 0% |
| **Regulators** | 0/24 | 0% | 0/59 | 0% |
| **Seals** | 9/107 | 8.41% | 0/0 | - |
| **Threaded Connections** | 7/3,515 | 0.20% | 14/4,529 | 0.31% |
| **Welded Connections** | 0/324 | 0% | 0/400 | 0% |

**Table 5.4.1.4: Leak Rates (in cfm) of Leaking Components (Wellheads)**

| | Production (128) | | Storage (44) | |
|---|---|---|---|---|
| | Range | Geomean | Range | Geomean |
| **Flanges** | 0.005-0.10 | 3.14E-04 | - | - |
| **Manual Valves** | 0.005-0.20 | 2.83E-02 | 0.005-0.35 | 3.88E-02 |
| **OELs** | - | - | 0.02-1.35 | 1.75E-02 |
| **Others** | - | - | 0.22-0.22 | 2.20E-01 |
| **PRVs** | - | - | - | - |
| **Regulators** | - | - | - | - |
| **Seals** | 0.005-0.08 | 7.05E-03 | - | - |
| **Threaded Connections** | 0.005-0.16 | 3.14E-02 | 0.005-1.25 | 4.16E-02 |
| **Welded Connections** | - | - | - | - |

Table 5.4.1.5 shows the component-level average EFs by industry sector. As discussed in Section 5.2.1, the geometric mean is a better indicator than the corresponding arithmetic mean as the mean for each group of leakage rates in this study. Consequently, the EFs were calculated by using the geometric mean of the leak rates of the leaking components while taking into account the total count of the components surveyed. While the production sector contained leakages from flanges, manual valves, seals, and threaded connections, the wellheads in the storage sector tested positive for leakages in manual valves, OELs, others, and threaded connections. For wellheads in the production sector, the component-level average EF for seals is the largest at $5.93\times10^{-4}$ cfm, followed by $2.12\times10^{-4}$ cfm for flanges, $6.25\times10^{-5}$ cfm for threaded connections, and $5.90\times10^{-5}$ cfm for manual valves. For the storage sector, the largest component-level average EF is $2.20\times10^{-1}$ cfm for "others", followed by $1.05\times10^{-3}$ cfm for OELs, $9.18\times10^{-4}$ cfm for manual valves, and $1.28\times10^{-4}$ cfm for threaded connections. The EFs in Table 5.4.1.5 are also given in units of tonne $CH_4$/year/component. In this study the leak rates were measured in cubic feet $CH_4$ per minute. A conversion to tonne $CH_4$/year is to facilitate a comparison to the

benchmark EF values reported by the 1996 EPA/GRI study. The conversion factor from cfm to tonne methane/year is equal to 9.906.

**Table 5.4.1.5: Component-Level Average EFs by Industry Sector (Wellheads)**

| | Production | | Storage | |
|---|---|---|---|---|
| | cfm $CH_4$ /component | tonne $CH_4$ /yr/component | cfm $CH_4$ /component | tonne $CH_4$ /yr/component |
| **Flanges** | 2.12E-04 | 2.10E-03 | - | - |
| **Manual Valves** | 5.90E-05 | 5.85E-04 | 9.18E-04 | 9.09E-03 |
| **OELs** | - | - | 1.05E-03 | 1.04E-02 |
| **Others** | - | - | 2.20E-01 | 2.18E-00 |
| **PRVs** | - | - | - | - |
| **Regulators** | - | - | - | - |
| **Seals** | 5.93E-04 | 5.87E-03 | - | - |
| **Threaded Connections** | 6.25E-05 | 6.20E-04 | 1.28E-04 | 1.27E-03 |
| **Welded Connections** | - | - | - | - |

Table 5.4.1.6 compares the component-level average EFs derived in this study with those from the 1996 EPA/GRI study. Not all the components have EF values from both studies, but the values of the corresponding EFs are relatively comparable. The EFs of this study are smaller than those of the EPA/GRI study, except the EF of OELs in the storage sector.

**Table 5.4.1.6: Comparison of Component-Level EFs (in tonne $CH_4$/yr/component) - Wellheads**

| | Production | | Storage | |
|---|---|---|---|---|
| | [CEC, 2012] | [EPA/GRI, 1996] | [CEC, 2012] | [EPA/GRI, 1996] |
| **Flanges** | 2.10E-03 | - | - | - |
| **Manual Valves** | 5.85E-04 | 1.57E-02 | 9.09E-03 | 1.73E-02 |
| **OELs** | - | 4.05E-03 | 1.04E-02 | 4.47E-03 |
| **Others** | - | - | 2.18E-00 | - |
| **PRVs** | - | - | - | 2.76E-02 |
| **Regulators** | - | - | - | - |
| **Seals** | 5.87E-03 | - | - | - |
| **Threaded Connections** | 6.20E-04 | 2.15E-03 | 1.27E-03 | 2.36E-03 |
| **Welded Connections** | - | - | - | - |

To derive a fugitive EF for a wellhead as a whole, the EF of each component was first multiplied by the average count of that component per wellhead. The multiplication products of all components were then summed to be the average EF of a wellhead. The contribution of each component type to the overall EF depends on the magnitude of its component-level average EF and its average count per wellhead. Table 5.4.1.7 calculates the equipment-level EF for a wellhead using the data of this study. As shown, the fugitive methane EF for a wellhead in the production sector is $3.83\times10^{-2}$ tonne $CH_4$/year. Most of the contributions come from flanges and threaded connections. The EF for a wellhead in the storage sector is almost one order of

magnitude larger, at $3.49\times10^{-1}$ tonne $CH_4$/year, and the main contributors are manual valves and threaded connections.

**Table 5.4.1.7: Equipment-Level Fugitive EFs for Wellheads (this Study)**

| | Production | | | Storage | | |
|---|---|---|---|---|---|---|
| | Count /Wellhead | Tonne $CH_4$ /yr/component | Tonne $CH_4$ /yr/wellhead | Components /Wellhead | Tonne $CH_4$ /yr/component | Tonne $CH_4$ /yr/wellhead |
| **Flanges** | 5.8 | 2.10E-03 | 1.22E-02 | 20.4 | - | - |
| **Manual Valves** | 7.5 | 5.85E-04 | 4.39E-03 | 24.0 | 9.09E-03 | 2.18E-01 |
| **OELs** | 0 | - | - | 0.8 | 1.04E-02 | 1.04E-02 |
| **Others** | 0.5 | - | - | 0.0 | 2.18E-00 | - |
| **PRVs** | 0.2 | - | - | 0.3 | - | - |
| **Regulators** | 0.2 | - | - | 1.3 | - | - |
| **Seals** | 0.8 | 5.87E-03 | 4.70E-03 | 0 | - | - |
| **Threaded Connections** | 27.5 | 6.20E-04 | 1.70E-02 | 102.9 | 1.27E-03 | 1.31E-01 |
| **Welded Connections** | 2.5 | - | - | 9.1 | - | - |
| **Total** | | | 3.83E-02 | | | 3.49E-01 |

Table 5.4.1.8 calculates the equipment-level EF for a wellhead using the data from the 1996 EPA/GRI study. As shown, the EFs for wellheads from the 1996 EPA/GRI are 0.254 and 0.788 tonne $CH_4$/year for the production sector and the storage sector, respectively.

**Table 5.4.1.8: Equipment-Level Fugitive EFs for Wellheads (the 1996 EPA/GRI Study)**

| | EPA/GRI (1996) | | | | | |
|---|---|---|---|---|---|---|
| | Production | | | Storage | | |
| | Components /Wellhead | Tonne $CH_4$ /yr/component | Tonne $CH_4$ /yr/wellhead | Components/ Wellhead | Tonne $CH_4$ /yr/component | Tonne $CH_4$ /yr/wellhead |
| **Flanges** | - | - | - | - | - | - |
| **Manual Valves** | 11 | 1.57E-02 | 1.73E-01 | 30 | 1.73E-02 | 5.19E-01 |
| **OELs** | 1 | 4.05E-03 | 4.05E-03 | 7 | 4.47E-03 | 3.13E-02 |
| **Others** | - | - | - | - | - | - |
| **PRVs** | - | - | - | 1 | 2.76E-02 | 2.76E-02 |
| **Regulators** | - | - | - | - | - | - |
| **Seals** | - | - | - | - | - | - |
| **Threaded Connections** | 36 | 2.15E-03 | 7.73E-02 | 89 | 2.36E-03 | 2.10E-01 |
| **Welded Connections** | - | - | - | - | - | - |
| **Total** | | | 2.54E-01 | | | 7.88E-01 |

Table 5.4.1.9 tabulates these equipment-level EFs for wellheads; the wellhead EFs of this study are comparable to the corresponding ones of the 1996 EPA/GRI study, but smaller.

**Table 5.4.1.9: Comparison of Equipment-Level EFs for Wellheads**

| | Production | Storage |
|---|---|---|
| | tonne $CH_4$/yr/wellhead | |
| **CEC (2012)** | 3.83E-02 | 3.49E-01 |
| **EPA/GRI (1996)** | 2.54E-01 | 7.88E-01 |

## 5.4.2 Separators

A separator is a piece of equipment utilized to remove condensate and oil from natural gas. Many separators are very large and therefore some sections are inaccessible without the use of a manlift. All accessible components of each separator surveyed in this study were surveyed, including valves which might be used to sample the condensate.

The research team visited seven facilities having separators and a total of 131 separators were surveyed. The numbers of facilities visited and separators surveyed were heavily weighted towards the P & P sector of the natural gas industry; 87.8% of the separators surveyed are in the P&P sector (Table 5.4.2.1).

**Table 5.4.2.1: Number of Facilities and Equipment Surveyed (Separators)**

| Industry Sector | Number of Facilities Surveyed | Number of Separators Surveyed | % of Total Separators Surveyed |
|---|---|---|---|
| **Production and Processing** | 5 | 115 | 87.8% |
| **Storage** | 1 | 14 | 10.7% |
| **Transmission** | 1 | 2 | 1.5% |
| **Overall** | 7 | 131 | 100% |

Table 5.4.2.2 illustrates the range of component counts per separator surveyed by industry sector. It should be noted here that not all the sections were screened for the separators surveyed.

**Table 5.4.2.2: Component Counts Screened per Surveyed Equipment (Separators)**

| | P & P (115*) | Storage (14) | Transmission (2) |
|---|---|---|---|
| **Flanges** | 0-121 | 1-32 | 8-9 |
| **Manual Valves** | 0-86 | 4-52 | 4-29 |
| **OELs** | 0-12 | 0-7 | 0-1 |
| **Other** | 0-1 | 0-5 | 0 |
| **PRVs** | 0-4 | 0-3 | 0-1 |
| **Regulators** | 0-12 | 0-4 | 0 |
| **Seals** | 0-2 | 0 | 0 |
| **Threaded Connections** | 0-334 | 4-136 | 27-132 |
| **Welded Connections** | 0-308 | 5-101 | 23-56 |

Note: * = number of separators surveyed.

Table 5.4.2.3 shows the percentage leaking by component. The percentage leaking was calculated by taking the number of leaking components divided by the total count of components surveyed.

**Table 5.4.2.3: Percentage Leaking and Total Component Counts (Separators)**

| | P & P (115) | | Storage (14) | | Transmission (2) | |
|---|---|---|---|---|---|---|
| | Leaking/Total | % | Leaking/Total | % | Leaking/Total | % |
| **Flanges** | 5/1,596 | 0.31% | 0/207 | 0% | 0/17 | 0% |
| **Manual Valves** | 5/1,611 | 0.31% | 0/291 | 0% | 0/33 | 0% |
| **OELs** | 0/34 | 0% | 2/37 | 5.41% | 0/1 | 0% |
| **Other** | 0/0 | - | 2/17 | 11.8% | 0/0 | - |
| **PRVs** | 1/92 | 1.09% | 0/4 | 0% | 0/0 | - |
| **Regulators** | 2/237 | 0.84% | 0/5 | 0% | 0/0 | - |
| **Seals** | 0/3 | 0% | 0/0 | - | 0/0 | - |
| **Threaded Connections** | 6/8,378 | 0.07% | 1/862 | 0.12% | 0/159 | 0% |
| **Welded Connections** | 0/2,981 | 0% | 0/536 | 0% | 0/79 | 0% |

The component fugitive leak rates were measured and recorded using the Hi-Flow samplers. It should be noted that the minimum detectable leak rate is equal to 0.01 cfm. Any leaking component with a leak rate below the minimum limit was assigned a leak rate of 0.005 cfm. Table 5.4.2.4 tabulates the ranges and geomeans of the leak rates of leaking components by industry sector. No leaks were found from the two separators surveyed in the transmission sector.

**Table 5.4.2.4: Leak Rates (in cfm) from Leaking Components (Separators)**

| | P & P (115) | | Storage (14) | | Transmission (2) | |
|---|---|---|---|---|---|---|
| | Range | Geomean | Range | Geomean | Range | Geomean |
| **Flanges** | 0.005-0.005 | 5.00E-03 | - | - | - | - |
| **Manual Valves** | 0.005-0.02 | 7.07E-03 | - | - | - | - |
| **OELs** | - | - | 0.005-0.005 | 5.00E-03 | - | - |
| **Other** | 0.02-0.02 | 2.00E-02 | 0.005-0.005 | 5.00E-03 | - | - |
| **PRVs** | 0.02-0.02 | 2.00E-02 | - | - | - | - |
| **Regulators** | 0.005-0.21 | 3.24E-02 | - | - | - | - |
| **Seals** | - | - | - | - | - | - |
| **Threaded Connections** | 0.005-0.03 | 8.49E-03 | 0.005-0.005 | 5.00E-03 | - | - |
| **Welded Connections** | - | - | - | - | - | - |

Table 5.4.2.5 shows the component-level average EFs by industry sector. They were calculated by using the geomean and the total count of the components surveyed. For the separators in the P&P sector, the component-level average EF for the "others" is the largest at $2.00\times10^{-2}$ cfm, followed by $2.73\times10^{-4}$ cfm for regulators, $2.17\times10^{-4}$ cfm for PRVs, $2.63\times10^{-5}$ cfm for manual valves, $1.57\times10^{-5}$ cfm for flanges, and $6.08\times10^{-6}$ cfm for threaded connections. For the separators in the storage sector, components which tested positive for leakages include "others" ($5.88\times10^{-4}$ cfm), OELs ($2.70\times10^{-4}$ cfm), and threaded connections ($5.80\times10^{-6}$ cfm).

**Table 5.4.2.5: Component-Level Average EFs by Industry Sector (Separators)**

| | P & P | | Storage | |
|---|---|---|---|---|
| | cfm $CH_4$ /component | tonne $CH_4$ /yr/component | cfm $CH_4$ /component | tonne methane /yr/component |
| **Flanges** | 1.57E-05 | 1.55E-04 | - | - |
| **Manual Valves** | 2.63E-05 | 2.61E-04 | - | - |
| **OELs** | - | - | 2.70E-04 | 2.68E-03 |
| **Others** | 2.00E-02 | 1.98E-01 | 5.88E-04 | 5.83E-03 |
| **PRVs** | 2.17E-04 | 2.15E-03 | - | - |
| **Regulators** | 2.73E-04 | 2.71E-03 | - | - |
| **Seals** | - | - | - | - |
| **Threaded Connections** | 6.08E-06 | 6.02E-05 | 5.80E-06 | 5.75E-05 |
| **Welded Connections** | - | - | - | - |

Note: 1 cubic feet methane/minute = 9.906 tonne methane/yr

Table 5.4.2.6 tabulates the component-level average EFs derived in this study and those from the 1996 EPA/GRI study for the P&P sector. Both studies have average EFs for manual valves, OELs, PRVs, and threaded connections. The EFs of this study are smaller than the corresponding values of the 1996 EPA/GRI study.

**Table 5.4.2.6: Comparison of Component-Level EFs (in tonne $CH_4$/yr/component) - Separators**

| | P & P | | Storage |
|---|---|---|---|
| | [CEC, 2012] | [EPA/GRI, 1996] | [CEC, 2012] |
| **Flanges** | 1.55E-04 | - | - |
| **Manual Valves** | 2.61E-04 | 1.57E-02 | - |
| **OELs** | - | 4.05E-03 | 2.68E-03 |
| **Others** | 1.98E-01 | - | 5.83E-03 |
| **PRVs** | 2.15E-03 | 2.51E-02 | - |
| **Regulators** | 2.71E-03 | - | - |
| **Seals** | - | - | - |
| **Threaded Connections** | 6.02E-05 | 2.15E-03 | 5.75E-05 |

### 5.4.3 Dehydrators

A dehydrator refers to a unit used to remove water from natural gas. A dehydrator is typically composed of a contactor and a reboiler. These devices have large tanks which process the natural gas. Dehydrator surveys included the screening of components of the dehydrator that deemed as part of the dehydrator up to the mainline from which the gas is supplied. Dehydrators can be very large and therefore some sections are inaccessible without the use of a manlift. All accessible components of each dehydrator surveyed in this study were screened.

The research team visited four facilities having dehydrators and a total of 17 dehydrators were surveyed. The percentages of dehydrators surveyed were 47.1 percent in the P & P sector and

52.9 percent in the storage sector. There were no dehydrators surveyed in the transmission sector or the distribution sector.

**Table 5.4.3.1: Number of Facilities and Equipment Surveyed (Dehydrators)**

| Industry Sector | Number of Facilities Surveyed | Number of Dehydrators Surveyed | % of Total Dehydrators Surveyed |
|---|---|---|---|
| **Production and Processing** | 2 | 8 | 47.1% |
| **Storage** | 2 | 9 | 52.9% |
| **Overall** | 4 | 17 | 100% |

Table 5.4.3.2 illustrates the range of component counts per dehydrator surveyed by industry sector. It should be noted here that not all the sections were screened for the dehydrators surveyed. The most common components surveyed, in decreasing order, are connections, manual valves, and flanges.

**Table 5.4.3.2: Component Counts Screened per Surveyed Equipment (Dehydrators)**

| | P & P (8*) | Storage (9) |
|---|---|---|
| **Flanges** | 2-54 | 23-94 |
| **Manual Valves** | 11-147 | 11-68 |
| **OELs** | 0-3 | 0-3 |
| **Other** | - | - |
| **PRVs** | 0-9 | - |
| **Regulators** | 0-16 | - |
| **Seals** | - | - |
| **Threaded Connections** | 80-1,030 | 10-228 |
| **Welded Connections** | 5-55 | 0-105 |

Note: * = number of dehydrators tested.

**Table 5.4.3.3: Percentage Leaking and Total Component Counts (Dehydrators)**

| | P & P (8) | | Storage (9) | |
|---|---|---|---|---|
| | Leaking/Total | Percentage | Leaking/Total | Percentage |
| **Flanges** | 1/187 | 0.53% | 0/353 | 0% |
| **Manual Valves** | 0/454 | 0% | 0/229 | 0% |
| **OELs** | 0/3 | 0% | 0/11 | 0% |
| **Other** | - | - | - | - |
| **PRVs** | 0/26 | 0% | - | - |
| **Regulators** | 1/41 | 2.44% | - | - |
| **Seals** | - | - | - | - |
| **Threaded Connections** | 3/3191 | 0.09% | 0/542 | 0% |
| **Welded Connections** | 0/242 | 0% | 0/487 | 0% |

Table 5.4.3.3 shows the percentage leaking by component type. The percentage leaking was calculated by using the number of leaking components and the total count of the surveyed components. For the P&P sector, the percentages of leaking for regulators, flanges, and

threaded connections were 2.44, 0.53, and 0.09%, respectively. The percentages of leaking for manual valves, OELs, PRVs, and welded connections are all zero. For the storage sector, the percentages of leaking for flanges, manual valves, OELs, threaded connections, and welded connections are all zero.

The component fugitive leak rate were measured and recorded using the Hi-Flow samplers. It should be noted that the minimum detectable leak rate is equal to 0.01 cfm. Any leaking component with a leak rate below the minimum limit was assigned a leak rate of 0.005 cfm. Table 5.4.3.4 tabulates the ranges and geomeans of leak rates of leaking components by industry sector.

**Table 5.4.3.4: Leak Rates (in cfm) of Leaking Components (Dehydrators)**

| | P & P (8) | | Storage (9) | |
|---|---|---|---|---|
| | Range | Geomean | Range | Geomean |
| **Flanges** | 0.03-0.03 | 3.00E-02 | - | - |
| **Manual Valves** | - | - | - | - |
| **OELs** | - | - | - | - |
| **Other** | - | - | - | - |
| **PRVs** | | | - | - |
| **Regulators** | 0.26-0.26 | 2.60E-01 | - | - |
| **Seals** | - | - | - | - |
| **Threaded Connections** | 0.02-0.03 | 2.62E-02 | - | - |
| **Welded Connections** | - | - | - | - |

**Table 5.4.3.5: Component-Level Average EFs (Dehydrators)**

| | P&P | |
|---|---|---|
| | cfm $CH_4$ /component | tonne $CH_4$ /yr/component |
| **Flange** | 1.60E-04 | 1.58E-03 |
| **Manual Valve** | - | - |
| **OELs** | - | - |
| **Other** | - | - |
| **PRVs** | - | - |
| **Regulators** | 6.34E-03 | 6.28E-02 |
| **Seal** | - | - |
| **Threaded Connection** | 2.46E-05 | 2.44E-04 |
| **Welded Connections** | - | - |

Table 5.4.3.5 shows the component-level average EFs by industry sector. They were calculated by using the geometric mean while taking into account the total count of the surveyed components. For dehydrators in the P&P sector, the component-level average EF for the regulators is the largest at $6.34\times10^{-3}$ cfm, followed by $1.60\times10^{-4}$ cfm for flanges, and $2.46\times10^{-5}$ cfm for threaded connections. For dehydrators in the storage sector, no leaking sources were found,

thus no component-level average EFs were derived. The EFs are given in both cfm of methane and tonne/year of methane. The conversion rate from cfm $CH_4$ to tonne $CH_4$/year is equal to 9.906.

Table 5.4.3.6 tabulated the component-level average EFs derived in this study and those from the 1996 EPA/GRI study. Only threaded connections have EFs in both studies and the EF value from this study is smaller.

**Table 5.4.3.6: Comparison of Component-Level Average EFs (in tonne $CH_4$/yr/component) - Dehydrators**

| | P & P | |
|---|---|---|
| | [CEC, 2012] | [EPA/GRI, 1996] |
| **Flanges** | 1.58E-03 | - |
| **Manual Valves** | - | 1.57E-02 |
| **OELs** | - | 4.05E-03 |
| **Others** | - | - |
| **PRVs** | - | 2.51E-02 |
| **Regulators** | 6.28E-02 | - |
| **Seals** | - | - |
| **Threaded Connections** | 2.44E-04 | 2.15E-03 |

### 5.4.4 Piping Segments

A piping segment is any portion of piping between equipment systems. It transmits the natural gas from one system to another. Most surveyed piping segments were between two systems that were easily accessed. It was impractical to measure the total length of each piping segment due to the general complexity of the piping arrangements. Therefore, piping segment EFs do not take the lengths or densities of pipes and the associated components into account.

The research team visited fifteen facilities to survey a total of 145 piping segments. As shown in Table 5.4.4.1, the percentages of piping segments surveyed are 44.1% in the P & P industry sector, 14.5% in storage, 19.3% in transmission, and 22.1% in distribution sector.

**Table 5.4.4.1: Number of Facilities and Equipment Tested (Piping Segments)**

| Industry Sector | Number of Facilities Surveyed | Number of Piping Segments Surveyed | % of Total Piping Segments Surveyed |
|---|---|---|---|
| **Production and Processing** | 5 | 64 | 44.1% |
| **Storage** | 2 | 21 | 14.5% |
| **Transmission** | 6 | 28 | 19.3% |
| **Distribution** | 2 | 32 | 22.1% |
| **Overall** | 15 | 145 | 100% |

Table 5.4.4.2 shows the percentage leaking by component. The percentage leaking was calculated by dividing the number of leaking components with the total count of components surveyed. For the P&P sector, the percentages of leaking for the "others", OELs, regulators, manual valves, flanges, and threaded connections were at 28.6, 14.4, 3.08, 0.25, 0.09 , and 0.05% ,

respectively. No PRVs and welded connections were found leaking. For the storage sector, the percentages of leaking for PRVs, regulators, OELs, flanges, threaded connections, and manual valves were 50, 4.55, 2.20, 0.31, 0.22, and 0.21%, respectively. No welded connections and the "others" were found leaking. For the transmission sector, the percentages of leaking for OELs, manual valves, threaded connections, and flanges were at 100, 1.50, 0.71, and 0.22%, respectively. No PRVs, regulators, and welded connections were found leaking. For the distribution sector, the percentages of leaking for manual valves and threaded connections were 2.98 and 0.44% , respectively. No flanges, OELs, PRVs, regulators, and welded connections were found leaking.

**Table 5.4.4.2: Leaking Percentage and Total Component Counts (Piping Segments)**

| | P&P(64*) | | Storage(21) | | Transmission(28) | | Distribution(32) | |
|---|---|---|---|---|---|---|---|---|
| | Leaking/Total | % | Leaking/Total | % | Leaking/Total | % | Leaking/Total | % |
| **Flanges** | 1/1,066 | 0.09% | 2/644 | 0.31% | 2/899 | 0.22% | 0/225 | 0% |
| **Manual Valves** | 3/1,192 | 0.25% | 2/936 | 0.21% | 15/1,006 | 1.50% | 10/336 | 2.98% |
| **OELs** | 1/7 | 14.4% | 2/91 | 2.20% | 6/6 | 100% | 0/6 | 0% |
| **Others** | 2/7 | 28.6% | 0/12 | 0% | 0/0 | - | 0/0 | - |
| **PRVs** | 0/31 | 0% | 2/4 | 50% | 0/1 | 0% | 0/15 | 0% |
| **Regulators** | 2/65 | 3.08% | 1/22 | 4.55% | 0/40 | 0% | 0/10 | 0% |
| **Seals** | 0/0 | - | 0/0 | - | 0/0 | - | 0/0 | - |
| **Threaded Connections** | 22/4,341 | 0.05% | 7/3,161 | 0.22% | 16/2,259 | 0.71% | 8/1,834 | 0.44% |
| **Welded Connections** | 0/1,346 | 0% | 0/1,162 | 0% | 0/606 | 0% | 0/169 | 0% |

Note: * = number of piping segments surveyed.

**Table 5.4.4.3: Leak Rates (in cfm) from Leaking Components (Piping Segments)**

| | P&P(64) | | Storage(21) | | Transmission(28) | | Distribution (32) | |
|---|---|---|---|---|---|---|---|---|
| | Range | Geomin | Range | Geomin | Range | Geomin | Range | Geomin |
| **Flanges** | 0.005-0.01 | 7.07E-03 | 0.005-0.11 | 2.35E-02 | 0.005-0.005 | 5.00E-03 | - | - |
| **Manual Valves** | 0.005-0.06 | 9.44E-03 | 0.005-0.02 | 1.00E-02 | 0.005-0.05 | 9.65E-03 | 0.005-0.005 | 5.00E-03 |
| **OELs** | 0.005-0.005 | 5.00E-03 | 0.005-0.005 | 5.00E-03 | 0.28-8.85 | 1.51E-00 | - | - |
| **Others** | 0.005-0.06 | 1.73E-02 | - | - | - | - | - | - |
| **PRVs** | - | - | 0.04-0.06 | 4.90E-02 | - | - | - | - |
| **Regulators** | 0.01-0.02 | 1.41E-02 | 1.02-1.02 | 1.02E-00 | - | - | - | - |
| **Seals** | - | - | - | - | - | - | - | - |
| **Threaded Connections** | 0.005-0.06 | 1.32E-02 | 0.005-0.12 | 2.94E-02 | 0.005-0.11 | 9.07E-03 | 0.005-0.005 | 5.00E-03 |
| **Welded Connections** | - | - | - | - | - | - | - | - |

The component fugitive leakage rates were measured and recorded using the Hi-Flow samplers. It should be noted that the minimum detectable leakage rate is equal to 0.01 cfm. Any leaking component with a leak rate below the minimum limit was assigned a leak rate of 0.005 cfm. Table 5.4.4.3 tabulates the ranges and geomeans of leak rates of the leaking components by industry sector.

Table 5.4.4.4 shows the component-level average EFs by industry sector. The component-level average EFs were calculated by using the geometric mean and the total count of the components surveyed. For piping in the P&P sector, the largest component-level average EF is for "others" at $4.94\times10^{-3}$ cfm, followed by $7.14\times10^{-4}$ cfm for OELs, $4.34\times10^{-4}$ cfm for regulators, $6.69\times10^{-5}$ cfm for threaded connections, $2.38\times10^{-5}$ cfm for manual valves, and $6.63\times10^{-6}$ cfm for flanges. For piping in the storage sector, the component-level average EF for regulators is $4.6\times10^{-2}$ cfm, followed by $2.45\times10^{-2}$ cfm for PRVs, $1.10\times10^{-4}$ cfm for OELs, $7.30\times10^{-5}$ cfm for flanges, $6.51\times10^{-5}$ for threaded connections, and $2.14\times10^{-5}$ cfm for manual valves. For the transmission sector, the component-level average EF for OELs is 1.51 cfm, followed by $1.44\times10^{-4}$ cfm for manual valves, $6.42\times10^{-5}$ cfm for threaded connections, and $1.11\times10^{-5}$ cfm for flanges. For the distribution sector, the component-level average EFs are $1.49\times10^{-4}$ cfm for manual valves and $2.18\times10^{-5}$ cfm for threaded connections.

**Table 5.4.4.4: Component-Level Average EFs (Piping Segments)**

| | P&P(64) | | Storage(21) | | Transmission(28) | | Distribution(32) | |
|---|---|---|---|---|---|---|---|---|
| | cfm $CH_4$ /comp. | tonne $CH_4$ /yr/comp. | cfm $CH_4$ /comp. | tonne $CH_4$ /yr/comp. | cfm $CH_4$ /comp. | tonne $CH_4$ /yr/comp. | cfm $CH_4$ /comp. | tonne $CH_4$ /yr/comp. |
| **Flanges** | 6.63E-06 | 6.57E-05 | 7.30E-05 | 7.23E-04 | 1.11E-05 | 1.10E-04 | - | - |
| **Manual Valves** | 2.38E-05 | 2.35E-04 | 2.14E-05 | 2.12E-04 | 1.44E-04 | 1.43E-03 | 1.49E-04 | 1.47E-03 |
| **OELs** | 7.14E-04 | 7.08E-03 | 1.10E-04 | 1.09E-03 | 1.51E-00 | 1.50E+01 | - | - |
| **Others** | 4.94E-03 | 4.90E-02 | - | - | - | - | - | - |
| **PRVs** | - | - | 2.45E-02 | 2.43E-01 | - | - | - | - |
| **Regulators** | 4.34E-04 | 4.30E-03 | 4.64E-02 | 4.59E-01 | - | - | - | - |
| **Seals** | - | - | - | - | - | - | - | - |
| **Threaded Connections** | 6.69E-05 | 6.63E-04 | 6.51E-05 | 6.45E-04 | 6.42E-05 | 6.36E-04 | 2.18E-05 | 2.16E-04 |
| **Welded Connections** | - | - | - | - | - | - | - | - |

Table 5.4.4.5 tabulates the component-level average EFs of the piping segment by industry sector. Across the industry sectors, the EFs of flanges, manual valves, and threaded connections are relatively comparable. On the other hand, the EF for OELs in the transmission sector is larger than those of the P&P and storage sectors, and the EF of regulators in the storage sector is larger than that in the P&P sector. The large values are mainly due to a small number of large leaks found in surveying.

The last column lists the EFs of the production sector in the 1996 EPA/GRI study for comparison. As shown, the EFs of manual valves and threaded connections of this study are smaller than the corresponding ones of the EPA/GRI study; those of OELs of the P&P and transmission sectors are larger while that of the storage sector is smaller. Since the piping

segment screened can be of any size, no reasonable average component counts per piping segment could be derived. Consequently, no equipment-level EF for piping segment is derived here.

**Table 5.4.4.5 – Comparison of Component-Level Average EFs (Piping Segments)**

| | P&P | Storage | Transmission | Distribution | [EPA/GRI, 1996] |
|---|---|---|---|---|---|
| | tonne $CH_4$ /yr/ component | | | | |
| **Flanges** | 6.57E-05 | 7.23E-04 | 1.10E-04 | - | - |
| **Manual Valves** | 2.35E-04 | 2.12E-04 | 1.43E-03 | 1.47E-03 | 1,57E-02 |
| **OELs** | 7.08E-03 | 1.09E-03 | 1.50E+01 | - | 4.05E-03 |
| **Others** | 4.90E-02 | - | - | - | - |
| **PRVs** | - | 2.43E-01 | - | - | 2.52E-02 |
| **Regulators** | 4.30E-03 | 4.59E-01 | - | - | - |
| **Seals** | - | - | - | - | - |
| **Threaded Connections** | 6.63E-04 | 6.45E-04 | 6.36E-04 | 2.16E-04 | 2.15E-03 |
| **Welded Connections** | - | - | - | - | - |

## 5.4.5 Compressors

Compressors are commonly used throughout the natural gas industry to pressurize gas. Each compressor is classified according to the mechanism it utilizes to compress the natural gas. These types (reciprocating, centrifugal, and rotary) of compressors were surveyed in this study.

### 5.4.5a Reciprocating Compressors

A reciprocating compressor refers to a compressor which uses pistons to compress and pressurize the natural gas and then discharge it. The reciprocating compressor is the most popular compressor type in the industry. These compressors typically use natural gas as the fuel source. They vary in sizes and can be very large complex systems. Some sections of a larger compressor are inaccessible without the use of a manlift. All accessible components of each reciprocating compressor surveyed in this study were screened.

The research team visited nine facilities to survey a total of 51 reciprocating compressors. As shown in Table 5.4.5a.1, the percentages of reciprocating compressors surveyed are 70.6% in the P&P industry sector, 13.7% in storage, and 15.7% in transmission.

**Table 5.4.5a.1: Number of Facilities and Equipment Surveyed (Reciprocating Compressors)**

| Industry Sector | Number of Facilities Surveyed | Number of Reciprocating Compressors Surveyed | % of Total Reciprocating Compressors Surveyed |
|---|---|---|---|
| **Production and Processing** | 6 | 36 | 70.6% |
| **Storage** | 2 | 7 | 13.7% |
| **Transmission** | 1 | 8 | 15.7% |
| **Overall** | 9 | 51 | 100% |

Table 5.4.5a.2 illustrates the ranges of component counts per reciprocating compressor surveyed by industry sector. It should be noted here that not all the sections were screened for each reciprocating compressors surveyed. The most common components surveyed are connections, flanges, and manual valves.

**Table 5.4.5a.2: Component Counts Screened per Surveyed Equipment (Reciprocating Compressors)**

| | P&P(36*) | Storage(7) | Transmission(8) |
|---|---|---|---|
| **Flanges** | 0-118 | 18-94 | 53-102 |
| **Manual Valves** | 0-123 | 27-68 | 20-43 |
| **OELs** | 0-1 | 0-3 | 0-0 |
| **Others** | 0-0 | 0-19 | 0-0 |
| **PRVs** | 0-10 | 0-0 | 0-0 |
| **Regulators** | 0-26 | 0-2 | 0-15 |
| **Seals** | 0-2 | 0-4 | 0-9 |
| **Threaded Connections** | 0-644 | 228-1413 | 128-931 |
| **Welded Connections** | 0-247 | 0-46 | 31-37 |

Note: * = number of reciprocating compressors surveyed.

Table 5.4.5a.3 shows the percentage leaking by component. The percentage leaking was calculated by using the number of leaking components and the total count of components surveyed. No PRVs, welded connections, and "others" were found leaking in all the reciprocating compressors surveyed.

**Table 5.4.5a.3: Leaking Percentage and Total Component Counts (Reciprocating Compressors)**

| | P&P(36) | | Storage(7) | | Transmission(8) | |
|---|---|---|---|---|---|---|
| | Leaking/ Total | % | Leaking/ Total | % | Leaking/ Total | % |
| **Flanges** | 34/1,650 | 2.06% | 0/319 | 0% | 12/473 | 2.54% |
| **Manual Valves** | 1/1,458 | 0.07% | 1/245 | 0.41% | 1/183 | 0.55% |
| **OELs** | 2/9 | 22.2% | 0/10 | 0% | 0/0 | - |
| **Others** | 0/0 | - | 0/32 | 0% | 0/0 | - |
| **PRVs** | 0/113 | 0% | 0/0 | - | 0/0 | - |
| **Regulators** | 5/314 | 1.59% | 0/6 | 0 % | 0/15 | 0% |
| **Seals** | 0/8 | 0% | 0/16 | 0% | 3/9 | 33.0% |
| **Threaded Connections** | 23/12,360 | 0.19% | 0/6,473 | 0% | 18/1,827 | 0.99% |
| **Welded Connections** | 0/2,556 | 0% | 0/89 | 0% | 0/290 | 0% |

The leak rates of leaking components were measured by using the Hi-Flow samplers. It should be noted that the minimum detectable leak rate is equal to 0.01 cfm. Any leaking component with a leak rate below the threshold was assigned a leak rate of 0.005 cfm. Table 5.4.5a.4 tabulates the ranges and geomeans of leak rates of leaking components by industry sector.

Table 5.4.5a.5 shows the component-level average EFs by industry sector. They were calculated by using the geometric mean and the total count of components surveyed. For the reciprocating compressors in the P&P sector, the component-level EF of OELs is the largest at $6.69\times10^{-2}$ cfm,

followed by $9.58\times10^{-4}$ cfm for flanges, $1.05\times10^{-4}$ cfm for regulators, $2.90\times10^{-5}$ cfm for threaded connections, and $1.51\times10^{-5}$ cfm for manual valves. For the storage sector, only manual valves were found leaking at $1.63\times10^{-4}$ cfm. For the transmission sector, the component-level average EF of seals is the largest at $1.52\times10^{-2}$ cfm, followed by $4.62\times10^{-3}$ cfm for flanges, $7.49\times10^{-5}$ cfm for threaded connections, and $2.73\times10^{-5}$ cfm for manual valves.

**Table 5.4.5a.4: Leak Rates (in cfm) from Leaking Components (Reciprocating Compressors)**

| | P&P(36) | | Storage(7) | | Transmission(8) | |
|---|---|---|---|---|---|---|
| | Range | Geomean | Range | Geomin | Range | Geomean |
| Flanges | 0.005-0.58 | 4.65E-02 | - | - | 0.02-1.42 | 1.82E-01 |
| Manual Valves | 0.005-0.15 | 2.20E-02 | 0.04-0.04 | 4.00E-02 | 0.005-0.005 | 5.00E-03 |
| OELs | 0.005-7.522 | 3.01E-01 | - | - | - | - |
| Others | - | - | - | - | - | - |
| PRVs | - | - | - | - | - | - |
| Regulators | 0.005-0.02 | 6.60E-03 | - | - | - | - |
| Seals | - | - | - | - | 0.005-8.22 | 5.90E-02 |
| Threaded Connections | 0.005-0.43 | 1.56E-02 | - | - | 0.005-0.12 | 7.60E-03 |
| Welded Connections | - | - | - | - | - | - |

**Table 5.4.5a.5: Component-Level Average EFs (Reciprocating Compressors)**

| | P&P(36) | | Storage(7) | | Transmission(8) | |
|---|---|---|---|---|---|---|
| | cfm $CH_4$ /comp. | tonne $CH_4$ /yr/comp. | cfm $CH_4$ /comp. | tonne $CH_4$ /yr/comp. | cfm $CH_4$ /comp. | tonne $CH_4$ /yr/comp. |
| Flanges | 9.58E-04 | 9.49E-03 | - | - | 4.62E-03 | 4.58E-02 |
| Manual Valves | 1.51E-05 | 1.49E-04 | 1.63E-04 | 1.62E-03 | 2.73E-05 | 2.71E-04 |
| OELs | 6.69E-02 | 6.63E-01 | - | - | - | - |
| Others | - | - | - | - | - | - |
| PRVs | - | - | - | - | - | - |
| Regulators | 1.05E-04 | 1.04E-03 | - | - | - | - |
| Seals | - | - | - | - | 1.52E-02 | 1.51E-01 |
| Threaded Connections | 2.90E-05 | 2.88E-04 | - | - | 7.49E-05 | 7.42E-04 |
| Welded Connections | - | - | - | - | - | - |

## 5.4.5b Centrifugal Compressors

A centrifugal compressor compresses gas by accelerating the particles using a turbine and then converting this velocity into compression. These compressors typically use natural gas as the fuel source. They vary in size and can be very large complex systems. Some sections of a larger compressor are inaccessible without the use of a manlift. All accessible components of each centrifugal compressor surveyed in this study were screened.

In this study centrifugal compressors in the P&P, storage, and transmission sectors were surveyed. The research team visited three facilities having centrifugal compressors and a total of nine centrifugal compressors were surveyed (Table 5.4.5b.1).

**Table 5.4.5b.1: Number of Facilities and Equipment Surveyed (Centrifugal Compressors)**

| Industry Sector | Number of Facilities Surveyed | Number of Centrifugal Compressors Surveyed | % of Total Centrifugal Compressors Surveyed |
|---|---|---|---|
| **Production and Processing** | 1 | 4 | 44.4% |
| **Storage** | 1 | 3 | 33.3% |
| **Transmission** | 1 | 2 | 22.2% |
| **Overall** | 3 | 9 | 100% |

Table 5.4.5b.2 illustrates the range of component counts per centrifugal compressor surveyed and separated by industry sector. It should be noted that not all the sections were screened for the centrifugal compressors surveyed. The most common components surveyed in a decreasing order are: connections, flanges, and manual valves.

**Table 5.4.5b.2: Component Counts Screened per Surveyed Equipment (Centrifugal Compressors)**

| | P & P (4*) | Storage (3) | Transmission (2) |
|---|---|---|---|
| **Flanges** | 25-30 | 94-94 | 5-10 |
| **Manual Valves** | 29-31 | 68-68 | 26-28 |
| **OELs** | 1-1 | - | 1-5 |
| **Other** | - | - | - |
| **PRVs** | 3-3 | - | 0-1 |
| **Regulators** | 4-4 | - | 1-2 |
| **Seals** | - | - | 1-1 |
| **Threaded Connections** | 122-149 | 228-228 | 161-408 |
| **Welded Connections** | 60-86 | - | 25-25 |

Note: * = number of centrifugal compressors surveyed.

Table 5.4.5b.3 shows the percentage leaking by component. The percentage leaking was calculated by dividing the number of leaking components with the total count of components surveyed. For the P&P sector, the only leakage is from a threaded connection (0.19%). For the storage sector, the leakages are only from manual valves (2.54%) and threaded connections (0.29%). For the transmission sector, the only leakages are from flanges (26.7%) and seals (50%).

The leak rates of leaking components were measured by using the Hi-Flow samplers. It should be noted that the minimum detectable leak rate is equal to 0.01 cfm. Any leaking component with a leak rate below the threshold was assigned a leak rate of 0.005 cfm. 5.4.5b.4 tabulates the ranges and geomeans of leak rates of leaking components by industry sector.

**Table 5.4.5b.3: Leaking Percentage and Total Component Counts (Centrifugal Compressors)**

| | P & P (4) | | Storage (3) | | Transmission (2) | |
|---|---|---|---|---|---|---|
| | Leaking/Total | % | Leaking/Total | % | Leaking/Total | % |
| Flanges | 0/107 | 0% | 0/282 | 0% | 4/15 | 26.7% |
| Manual Valves | 0/120 | 0% | 5/204 | 2.45% | 0/54 | 0% |
| OELs | 0/4 | 0% | 0/0 | - | 0/6 | 0% |
| Other | 0/0 | - | 0/0 | - | 0/0 | - |
| PRVs | 0/12 | 0% | 0/0 | - | 0/1 | 0% |
| Regulators | 0/16 | 0% | 0/0 | - | 0/3 | 0% |
| Seals | 0/0 | - | 0/0 | - | 1/2 | 50% |
| Threaded Connections | 1/531 | 0.19% | 2/684 | 0.29% | 0/569 | 0% |
| Welded Connections | 0/292 | 0% | 0/0 | - | 0/50 | 0% |

**Table 5.4.5b.4: Leak Rates (in cfm) from Leaking Components (Centrifugal Compressors)**

| | P & P (4) | | Storage (3) | | Transmission (2) | |
|---|---|---|---|---|---|---|
| | Range | Geomean | Range | Geomean | Range | Geomean |
| Flanges | - | - | - | - | 0.005-0.005 | 5.00E-03 |
| Manual Valves | - | - | 0.02-0.11 | 3.31E-02 | - | - |
| OELs | - | - | - | - | - | - |
| Other | - | - | - | - | - | - |
| PRVs | - | - | - | - | - | - |
| Regulators | - | - | - | - | - | - |
| Seals | - | - | - | - | 0.12-0.12 | 1.20E-01 |
| Threaded Connections | 0.005-0.005 | 5.00E-03 | 0.005-0.04 | 1.41E-02 | - | - |
| Welded Connections | - | - | - | - | - | - |

**Table 5.4.5b.5: Component-Level Average EFs (Centrifugal Compressors)**

| | P & P | | Storage | | Transmission | |
|---|---|---|---|---|---|---|
| | cfm $CH_4$ /comp. | tonne $CH_4$ /yr/comp. | cfm $CH_4$ /comp. | tonne $CH_4$ /yr/comp. | cfm $CH_4$ /comp. | tonne $CH_4$ /yr/comp. |
| Flanges | - | - | - | - | 1.33E-03 | 1.21E-02 |
| Manual Valves | - | - | 8.12E-04 | 8.04E-03 | - | - |
| OELs | - | - | - | - | - | - |
| Other | - | - | - | - | - | - |
| PRVs | - | - | - | - | - | - |
| Regulators | - | - | - | - | - | |
| Seals | - | - | - | - | 6.00E-02 | 5..94E-01 |
| Threaded Connections | 9.42E-06 | 9.33E-05 | 4.14E-05 | 4.10E-04 | - | - |
| Welded Connections | - | - | - | - | - | - |

Table 5.4.5b.5 shows the component-level average EFs by industry sector. They were calculated by using the geometric mean and the total count of components surveyed. For the centrifugal compressors in the P&P sector, the component-level average EF is $9.42\times10^{-6}$ cfm for threaded connections. For the storage sector, the component-level average EFs are $8.12\times10^{-4}$ cfm for manual valves and $4.14\times10^{-5}$ cfm for threaded connections. For the transmission sector, the component-level average EFs are $1.33\times10^{-3}$ cfm for flanges and $6.00\times10^{-2}$ cfm for seals. The EFs are given in units of both cfm of methane and tonne/yr of methane.

### 5.4.5c Rotary Compressors

A rotary compressor uses a rotating pair of screws which compressed the gas as it flows through them. These compressors typically use natural gas as the fuel source. They vary in sizes and can be very large complex systems. Some sections of a larger compressor are inaccessible without the use of a manlift. All accessible components of each rotary compressor surveyed in this study were screened. In this study the research team visited one facility having rotary compressors in the P&P sector and a total of six rotary compressors were surveyed (Table 5.4.5c.1).

**Table 5.4.5c.1: Number of Facilities and Equipment Surveyed (Rotary Compressors)**

| Industry Sector | Number of Facilities Tested | Number of Rotary Compressors Tested | % of Total Tested Rotary Compressors |
|---|---|---|---|
| **Production and Processing** | 1 | 6 | 100% |
| **Overall** | 1 | 6 | 100% |

Table 5.4.5c.2 illustrates the range of component counts per rotary compressor screened by industry sector. It should be noted here that not all the sections were screened for the rotary compressors surveyed.

**Table 5.4.5c.2: Component Counts Screened per Surveyed Equipment (Rotary Compressors)**

| | P & P / Overall (6*) |
|---|---|
| **Flanges** | 3-41 |
| **Manual Valves** | 1-42 |
| **OELs** | 0-2 |
| **Other** | 0-0 |
| **PRVs** | 0-2 |
| **Regulators** | 0-12 |
| **Seals** | 0-1 |
| **Threaded Connections** | 45-236 |
| **Welded Connections** | 2-125 |

Note: * = number of rotary compressors tested.

Table 5.4.5c.3 shows the percentage leaking by component. The percentage leaking was calculated by dividing the number of leaking components with the total count of components surveyed. For all the components surveyed, no leaking sources were found and no leak rates were measured.

**Table 5.4.5c.3: Leaking Percentage and Total Component Counts (Rotary Compressors)**

| | P & P / Overall (6) | |
|---|---|---|
| | Leaking/Total | % |
| **Flanges** | 0/118 | 0% |
| **Manual Valves** | 0/139 | 0% |
| **OELs** | 0/3 | 0% |
| **Other** | 0/0 | - |
| **PRVs** | 0/7 | 0% |
| **Regulators** | 0/20 | 0% |
| **Seals** | 0/1 | 0% |
| **Threaded Connections** | 0/715 | 0% |
| **Welded Connections** | 0/380 | 0% |

## 5.4.6 Pneumatic Devices

A pneumatic device is controlled by pressurized gas which can be air or natural gas. It typically consists of a pneumatic actuator and a pneumatic valve.

## 5.4.6a Pneumatic Actuators

A pneumatic actuator here refers to a natural gas powered device used to control a pneumatic valve. These devices were screened completely from the mainline they control to all components and seals located on the device. In this study the research team surveyed a total of 196 pneumatic actuators in nine facilities (Table 5.4.6a.1).

**Table 5.4.6a.1: Number of Facilities and Equipment Surveyed (Pneumatic Actuators)**

| Industry Sector | Number of Facilities Tested | Number of Pneumatic Actuators Tested | % of Total Tested Pneumatic Actuators |
|---|---|---|---|
| **Production and Processing** | 5 | 115 | 58.7% |
| **Storage** | 1 | 52 | 26.5% |
| **Transmission** | 2 | 13 | 6.6% |
| **Distribution** | 1 | 16 | 8.2% |
| **Overall** | 9 | 196 | 100% |

Table 5.4.6a.2 shows the emissions per pneumatic actuator in cfm and tonne/year. The EFs were derived by dividing the total emission rate with the number of pneumatic actuators surveyed. The EF for pneumatic actuators in the P&P sector is $7.29 \times 10^{-2}$ cfm $CH_4$/pneumatic actuator, or $7.22 \times 10^{-1}$ tonne $CH_4$/yr/pneumatic actuator; that in the storage sector is $5.77 \times 10^{-4}$ cfm $CH_4$/pneumatic actuator, or $5.72 \times 10^{-3}$ tonne $CH_4$/yr/pneumatic actuator; and that in the transmission sector is $1.54 \times 10^{-3}$ cfm $CH_4$/pneumatic actuator, or $1.52 \times 10^{-2}$ tonne $CH_4$/yr/pneumatic actuator.

**Table 5.4.6a.2: Emission Factors for Pneumatic Actuators**

| Industry Sector | (cfm $CH_4$/pneumatic actuator) | (tonnage $CH_4$/yr/pneumatic actuator) |
|---|---|---|
| **Production and Processing** | 7.29E-02 | 7.22E-01 |
| **Storage** | 5.77E-04 | 5.72E-03 |
| **Transmission** | 1.54E-03 | 1.52E-02 |

### 5.4.6b Pneumatic Valves

A pneumatic valve refers to a valve controlled by a pneumatic actuator to control the flow of liquids or gases. A pneumatic valve here does not include flanges or threaded connections used to install the device. These devices were screened completely from the mainline they control to all components and seals located on the device. In this study the research team surveyed a total of 178 pneumatic valves at eight facilities (Table 5.4.6b.1).

**Table 5.4.6b.1: Number of Facilities and Equipment Surveyed (Pneumatic Valves)**

| Industry Sector | Number of Facilities Surveyed | Number of Pneumatic Valves Surveyed | % of Total Pneumatic Valves Surveyed |
|---|---|---|---|
| **Production and Processing** | 7 | 177 | 99.4% |
| **Storage** | 1 | 1 | 0.6% |
| **Overall** | 8 | 178 | 100% |

Table 5.4.6b.2 shows the emissions per pneumatic valve in cfm and tonne/year. The EFs were derived by dividing the total emission rate with the number of pneumatic valves surveyed. No leaks were detected from the pneumatic valve surveyed in the storage sector. The EF for pneumatic valves in the production and processing sector is $6.44 \times 10^{-2}$ cfm $CH_4$/pneumatic valve, or $6.38 \times 10^{-1}$ tonne $CH_4$/yr/pneumatic valve.

**Table 5.4.6b.2: Emission Factors by Industry Sector (Pneumatic Valves)**

| Industry Sector | (cfm $CH_4$/pneumatic valve) | (tonne $CH_4$ /yr/pneumatic valve |
|---|---|---|
| **Production and Processing** | 6.44E-02 | 6.38E-01 |

### 5.4.7 M&R Stations

Metering and regulating (M&R) stations are typically designed to provide a constant output from the facility with constant pressure and other characteristics to the downstream facility. M&R stations are usually composed of many piping components without much complex equipment and therefore all components were screened, excluding any compressed air systems to control flow. In this study the research team visited two facilities in the transmission sector and one facility in the distribution sector. A total of nineteen M&R stations were surveyed (Table 5.4.7.1).

Table 5.4.7.2 illustrates the range of component counts per M&R station tested by industry sector. The most common components in decreasing order are: connections, flanges, manual valves, regulators, PRVs, and OELs.

**Table 5.4.7.1: Number of Facilities and Equipment Surveyed (M&R Stations)**

| Industry Sector | Number of Facilities Tested | Number of M&R Stations Tested | % of Total Tested M&R Stations |
|---|---|---|---|
| Transmission | 2 | 4 | 21.1% |
| Distribution | 1 | 15 | 78.9% |
| Overall | 3 | 19 | 100% |

**Table 5.4.7.2: Component Counts Screened per Surveyed Equipment (M&R Stations)**

| | Transmission(4*) | Distribution(15) |
|---|---|---|
| Flanges | 8-14 | 0-34 |
| Manual Valves | 1-4 | 6-44 |
| OELs | 0-0 | 0-3 |
| Others | 0-0 | 0-0 |
| PRVs | 0-3 | 0-2 |
| Regulators | 0-2 | 1-8 |
| Seals | 0-0 | 0-0 |
| Threaded Connections | 40-67 | 8-117 |
| Welded Connections | 0-20 | 0-51 |

Note: * = number of M&R stations tested.

Table 5.4.7.3 shows the percentage leaking by component. The percentage leaking was calculated by dividing the number of leaking components with the total count of components surveyed.

**Table 5.4.7.3: Leaking Percentage and Total Component Counts (M&R Stations)**

| | Transmission(4) | | Distribution(15) | |
|---|---|---|---|---|
| | Leaking/Total | Percentage | Leaking/Total | Percentage |
| Flanges | 0/48 | 0% | 2/167 | 1.20% |
| Manual Valves | 0/12 | 0% | 1/234 | 0.43% |
| OELs | 0/0 | - | 0/5 | 0% |
| Others | 0/0 | - | 0/0 | - |
| PRVs | 0/6 | 0% | 0/3 | 0% |
| Regulators | 0/4 | 0% | 0/36 | 0% |
| Seals | 0/0 | - | 0/0 | - |
| Threaded Connections | 0/201 | 0% | 0/515 | 0% |
| Welded Connections | 0/48 | 0% | 0/135 | 0% |

The leak rates of leaking components were measured by using the Hi-Flow samplers. It should be noted that the minimum detectable leak rate is equal to 0.01 cfm. Any leaking component with a leak rate below the threshold was assigned a leak rate of 0.005 cfm. Table 5.4.7.4 tabulates the ranges and geomeans of leak rates of leaking components by industry sector. No leaking sources were found from the M&R statins surveyed in the transmission sector.

**Table 5.4.7.4: Leak Rates (in cfm) from Leaking Components (M&R Station)**

| | Transmission(4) | | Distribution(15) | |
|---|---|---|---|---|
| | Range | Geomean | Range | Geomean |
| Flanges | - | - | 0.005-0.005 | 5.00E-03 |
| Manual Valves | - | - | 0.005-0.005 | 5.00E-03 |
| OELs | - | - | - | - |
| Others | - | - | - | - |
| PRVs | - | - | - | - |
| Regulators | - | - | - | - |
| Seals | - | - | - | - |
| Threaded Connections | - | - | - | - |
| Welded Connections | - | - | - | - |

Table 5.4.7.5 shows the component-level average EFs by industry sector. They were calculated using the geometric mean and the total count of components surveyed. The component-level average EFs are $5.99\times10^{-5}$ cfm for flanges and $2.14\times10^{-5}$ cfm for manual valves in the distribution sector.

**Table 5.4.7.5: Component-Level Average EFs (M&R Station)**

| | Distribution(15) | |
|---|---|---|
| | cfm $CH_4$/ component | tonnage $CH_4$ /yr/ component |
| Flanges | 5.99E-05 | 5.93E-04 |
| Manual Valves | 2.14E-05 | 2.12E-04 |
| OELs | - | - |
| Others | - | - |
| PRVs | - | - |
| Regulators | - | - |
| Seals | - | - |
| Threaded Connections | - | - |
| Welded Connections | - | - |

### 5.4.8 Hatches

A hatch refers to any access door or cover that can be manually opened in order to access a tank or vessel. Each hatch was surveyed around the door seal and any other components if they existed. In this study the research team visited five facilities having hatches in the P&P sector and a total of 34 hatches were surveyed (Table 5.4.8.1).

**Table 5.4.8.1: Number of Facilities and Equipment Surveyed (Hatches)**

| Industry Sector | Number of Facilities Surveyed | Number of Hatches Surveyed | % of Total Hatches Surveyed |
|---|---|---|---|
| Production and Processing | 5 | 34 | 100% |
| Overall | 5 | 34 | 100% |

Table 5.4.8.2 shows the emissions per hatches in cfm $CH_4$ and tonne $CH_4$/year/hatch. The EFs were derived by dividing the total emission rate with the number of hatches surveyed. The EF for hatches in the P&P sector is $1.55 \times 10^{-1}$ cfm $CH_4$/hatch, or 1.54 tonne $CH_4$/yr/hatch.

**Table 5.4.8.2: Emission Factors for Hatches**

| Industry Sector | (cfm $CH_4$/hatch) | (tonnage $CH_4$/yr/hatch) |
|---|---|---|
| Production and Processing | 1.55E-01 | 1.54E+00 |

## 5.4.9 Pumps

A pump is used to deliver fluid to a system. These can be electric or gas driven and may have pistons and/or diaphragms (AGA, 2008). In this study the research team visited two facilities having pumps in the P&P sector and a total of two pumps (same model) that are powered by natural gas were surveyed (Table 5.4.9.1).

**Table 5.4.9.1: Number of Facilities and Equipment Surveyed (Pumps)**

| Industry Sector | Number of Facilities Surveyed | Number of Pumps Surveyed | % of Total Pumps Surveyed |
|---|---|---|---|
| Production and Processing | 2 | 2 | 100% |
| Overall | 2 | 2 | 100% |

Table 5.4.9.2 tabulates the range of component counts per pump surveyed by industry sector. The most common components in decreasing order are: connections, flanges, and seals. For all the components screened, no leaking sources were found and no leak rates were measured.

**Table 5.4.9.2: Component Counts Surveyed per Surveyed Equipment (Pumps)**

| | P & P (2 identical pumps) | |
|---|---|---|
| | Range | Avg. |
| Flanges | 3-3 | 3-3 |
| Manual Valves | - | - |
| Open-Ended Lines | - | - |
| Other | - | - |
| Pressure Relief Valves | - | - |
| Regulators | - | - |
| Seals | 1-1 | 1-1 |
| Threaded Connections | 17-17 | 17-17 |
| Welded Connections | 2-2 | 2-2 |

### 5.4.10 Customer Meter

A customer meter is a meter which records the flow and other characteristics of the natural gas that passes through it. These meters are typically installed at the beginning and the end of the stream ownerships to monitor the flow of gas. Some of these meters are located near households. The meters were screened on all natural gas components up to the mainline. In this study the research team visited one facility in the transmission sector and one facility in the distribution sector having customer meters. A total of 12 customer meters were surveyed (see Table 5.4.10.1).

**Table 5.4.10.1: Number of Facilities and Equipment Surveyed (Customer Meter)**

| Industry Sector | Number of Facilities Surveyed | Number of Customer Meters Surveyed | % of Total Customer Meters Surveyed |
|---|---|---|---|
| **Transmission** | 1 | 2 | 16.7% |
| **Distribution** | 1 | 10 | 83.3% |
| **Overall** | 2 | 12 | 100% |

The leak rates of leaking components were measured by using the Hi-Flow samplers. It should be noted that the minimum detectable leak rate is equal to 0.01 cfm. The leaking components with screening values registered by the portable monitoring device but having leak rates below the threshold were assigned a leak rate of 0.005 cfm. Table 5.4.10.2 tabulates the ranges and geomeans of leak rates of leaking components by industry sector. As shown, the only leaking source is the flanges in the distribution sector.

**Table 5.4.10.2: Leak Rates (in cfm) from Leaking Components (Customer Meters)**

| | Transmission(2*) | | Distribution(10) | |
|---|---|---|---|---|
| | Range | Geomean | Range | Geomean |
| **Flanges** | - | - | 0.005-0.005 | 5.00E-03 |
| **Manual Valves** | - | - | - | - |
| **OELs** | - | - | - | - |
| **Others** | - | - | - | - |
| **PRVs** | - | - | - | - |
| **Regulators** | - | - | - | - |
| **Seals** | - | - | - | - |
| **Threaded Connections** | - | - | - | - |
| **Welded Connections** | - | - | - | - |

Note: * = number of Customer Meters tested.

Table 5.4.10.3 shows the component-level average EFs by industry sector. They were calculated by using the geometric mean and the total count of components surveyed. The component-level average EF is $3.45 \times 10^{-4}$ cfm for flanges in the distribution sector.

**Table 5.4.10.3: Component-Level Average EFs (Customer Meters)**

| | Distribution | |
|---|---|---|
| | cfm $CH_4$ /component | tonne $CH_4$ /yr/component |
| **Flanges** | 3.45E-04 | 3.42E-03 |
| **Manual Valves** | - | - |
| **OELs** | - | - |
| **Others** | - | - |
| **PRVs** | - | - |
| **Regulators** | - | - |
| **Seals** | - | - |
| **Threaded Connections** | - | - |
| **Welded Connections** | - | - |

## 5.5 Compressor Vents

Compressor vents are designed to release vented emissions. The field research team was granted access to sampling ports of twenty-two compressor vents that are associated with eight reciprocating compressors at one facility. This facility was in the transmission industry sector. Vented emissions were quantified at each sampling port, with only one not detected by the Hi-Flow sampler. The maximum value measured was 5.41 cfm. Table 5.5.1 shows the average vented emission in cfm per vent and tonne methane per year per vent. While these data were associated with the reciprocating compressors, they are reported separately here because they are vented emissions while the objective of this study was related to equipment fugitive emissions.

**Table 5.5.1: Emissions from Vents of Reciprocating Compressors**

| Vented EF (cfm $CH_4$/vent) | Vented EF (tonne $CH_4$/vent/year) |
|---|---|
| 1.03 | 10.19 |

# CHAPTER 6: Conclusion

## 6.1 Introduction

This study produced California-specific fugitive emission factors (EFs) for natural gas industry in support of AB32. Quantitative measurements of fugitive emissions were collected and analyzed to produce fugitive EFs for components, as well as for individual systems, when appropriate. These fugitive EFs can be used in conjunction with activity factors collected by the ARB to produce emissions estimates for components and systems surveyed in this study.

## 6.2 Results

The research team surveyed many equipment/systems in all five sectors of California natural gas industry (production, processing, storage, transmission, and distribution). Equipment/systems screened included 172 wellheads, 131 separators, 17 dehydrators, 145 piping segments, 66 compressors (51 reciprocating, 9 centrifugal, 6 rotary), 374 pneumatic devices, 19 metering and regulating stations, 34 hatches, 2 pumps, and 12 customer meters. Components screened on the equipment/system consisted of 10,101 flanges, 10,765 manual valves, 384 open-ended lines (OELs), 358 pressure relief valves (PRVs), 930 regulators, 146 seals, 57,061 threaded connections, 12,274 welded connections, and 138 "others". Using the data generated from field activities during this study, three types (average, screening ranges, correlation) of component-level EFs were developed, when appropriate. These component-level emission factors were then used to develop equipment-level average emission factors, when appropriate. In this study, based on ARB's Draft Test Protocol (ARB, 2010), the equipment components were categorized into nine groups: flanges, manual valves, OELs, "others", PRVs, regulators, seals, threaded connections, and welded connections.

### 6.2.1 Screening Ranges Emission Factors

Table 6.2.1.1 tabulates the ranges of leak rates of all leaking components in this study. As shown, the maximum leak rates from leaking OELs and seals are an order of magnitude larger than those of flanges, valves, and threaded connections. The table also shows the pegged EFs for ≥10,000 ppmV and ≥50,000 ppmV. As expected, the pegged EFs for seals and OELs are larger than those of flanges, manual valves, and threaded connections. It should also be noted the pegged EFs for ≥10,000 ppmV are essentially the same as those for ≥50,000 ppmV for manual valves, "others", seals, and threaded connections. For flanges and OELs, the pegged EFs for ≥50,000 ppmV are approximately twice larger than those for ≥10,000 ppmV.

**Table 6.2.1.1: Component Leak Rates and Pegged Emission Factors**

| | Leak Rate (cfm) | | | | |
|---|---|---|---|---|---|
| | Count | Min | Max | ≥10,000 ppmV | ≥50,000 ppmV |
| **Flanges** | 56 | 0.005 | 0.750 | 0.0468 | 0.0747 |
| **Manual Valves** | 49 | 0.005 | 0.160 | 0.0169 | 0.0197 |
| **OELs** | 26 | 0.005 | 8.850 | 0.1191 | 0.2874 |
| **Others** | 44 | 0.005 | 3.180 | 0.1002 | 0.1157 |
| **Seals** | 61 | 0.005 | 8.220 | 0.3632 | 0.3907 |
| **Threaded Connections** | 123 | 0.005 | 0.430 | 0.0155 | 0.0168 |

In 1999, California Air Pollution Control Officers Association (CAPCOA) and California ARB revised some of the EFs reported in the 1996 EPA/GRI study (CAPCOA, 1999). Table 6.2.1.2 compares the pegged EFs of this study with those of the two studies. Similar to the findings in this study, the EFs of a larger pegged value (100,000 ppmV) are similar to or approximately twice as large as the corresponding values of a much smaller pegged value (10,000 ppmV) in the 1996 EPA/GRI study. Comparing the EFs with a pegged value of 10,000 ppmV, flanges and threaded connections surveyed in this study have smaller EFs than those in the 1996 EPA/GRI and 1999 CAPCOA studies; they are (2.81 vs. 4.50 vs. 3.22 lb/day), and (0.93 vs. 1.48 vs. 1.37 lb/day), respectively. On the other hand, those of OELs and "others" in this study are larger (7.14 vs. 1.59 vs. 2.90 lb/day) and (6.01 vs. 3.86 vs. 0.73 lb/day). That of manual valves in this study falls between those of the two studies (1.01 vs. 3.39 vs. 0.73 lb/day). The data for seals are not really comparable because the seals in this study were mainly compressor seals while those in the EPA/GRI study were pump seals. It should also be noted the differences in the units (lb $CH_4$/d for this study vs. lb total hydrocarbon (THC)/d for those two studies).

**Table 6.2.1.2: Comparison of Pegged Emission Factors**

| | CEC (2012) | | EPA/GRI (1996) | | CAPCOA (1999) |
|---|---|---|---|---|---|
| | ≥10,000 ppmV | ≥50,000 ppmV | ≥10,000 ppmV | ≥100,000 ppmV | ≥10,000 ppmV |
| | (lb $CH_4$/d)* | | (lb THC/day) | | (lb THC/d) |
| **Flanges** | 2.81 | 4.48 | 4.50 | 4.44 | 3.22 |
| **Manual Valves** | 1.01 | 1.18 | 3.39 | 7.41 | 0.73 |
| **OELs** | 7.14 | 17.24 | 1.59 | 4.18 | 2.90 |
| **Others** | 6.01 | 6.94 | 3.86 | 5.82 | 0.73 |
| **Seals** | 21.79 | 23.43 | 3.92 | 8.47 | N/A |
| **Threaded Connections** | 0.93 | 1.01 | 1.48 | 1.59 | 1.37 |

Note: *1 cubic feet methane/minute = 1.136 kg methane/hr = 9.906 tonne methane/yr = 59.98 lb methane/day

## 6.2.2 Component-Level Correlation Emission Factors

The correlation equations between the leak rates and the screening values (SVs) were also derived for several components. In general, the correlations are relatively poor due to the wide ranges of leak rates found for each type of component.

Table 6.2.2.1 tabulates the correlation equations for leak rates (in kg/hr) of the 1996 EPA/GRI study, the 1999 CAPCOA study and this study. The correlation equations for the EPA/GRI and CAPCOA studies were similar. The calculated leak rates using the correlation equations of this study would be several times larger than those using the EPA/GRI or CAPCOA correlation equations. The differences may be partly attributed to the poor correlation between the leak rates and the SVs in this study and the larger detection limit of the High-Flow samplers. In addition, the correlation equations in this study only used data from the natural gas industry and those of the EPA/GRI and the CAPCOA studies were based on data from petroleum refineries, marketing terminals, and oil and gas production and were combined for all service types (i.e., gas, light liquid, heavy liquid).

**Table 6.2.2.1: Comparison of Correlation Equations for Leak Rates (in kg/hr)**

| | EPA/GRI (1996) | CAPCOA (1999) | CEC (2012) |
|---|---|---|---|
| **Connectors** | $(1.52 \times 10^{-6}) \times (SV)^{0.735}$ | $(1.53 \times 10^{-6}) \times (SV)^{0.736}$ | $(6.78 \times 10^{-4}) \times (SV)^{0.3031}$ |
| **Flanges** | $(4.44 \times 10^{-6}) \times (SV)^{0.703}$ | $(4.53 \times 10^{-6}) \times (SV)^{0.706}$ | $(4.52 \times 10^{-5}) \times (SV)^{0.6549}$ |
| **OELs** | $(2.16 \times 10^{-6}) \times (SV)^{0.704}$ | $(1.90 \times 10^{-6}) \times (SV)^{0.724}$ | N/A |
| **Pump Seals** | $(4.82 \times 10^{-5}) \times (SV)^{0.610}$ | $(5.07 \times 10^{-5}) \times (SV)^{0.622}$ | N/A |
| **Valves** | $(2.29 \times 10^{-6}) \times (SV)^{0.746}$ | $(2.27 \times 10^{-6}) \times (SV)^{0.747}$ | $(6.78 \times 10^{-4}) \times (SV)^{0.2811}$ |
| **Others** | $(1.32 \times 10^{-5}) \times (SV)^{0.589}$ | $(8.69 \times 10^{-6}) \times (SV)^{0.642}$ | $(3.39 \times 10^{-4}) \times (SV)^{0.5353}$ |

### 6.2.3 Component-Level and Equipment-Level Average Emission Factors

For wellheads in the production sector, the component-level average EF for seals is the largest at $5.93\times10^{-4}$ cfm, followed by $2.12\times10^{-4}$ cfm for flanges, $6.25\times10^{-5}$ cfm for threaded connections, and $5.90\times10^{-5}$ cfm for manual valves. For the storage sector, the largest component-level average EF is $2.20\times10^{-1}$ cfm for "others", followed by $1.05\times10^{-3}$ cfm for OELs, $9.18\times10^{-4}$ cfm for manual valves, and $1.28\times10^{-4}$ cfm for threaded connections. The fugitive methane EF for a wellhead in the production sector is $3.83\times10^{-2}$ tonne $CH_4$/yr and that in the storage sector is $3.49\times10^{-1}$ tonne $CH_4$/yr. The wellhead EFs of this study are comparable to the corresponding ones of the 1996 EPA/GRI study, but smaller.

For separators in the P&P sector, the component-level average EF for the "others" is the largest, at $2.00\times10^{-2}$ cfm, , followed by $2.73\times10^{-4}$ cfm for regulators, $2.17\times10^{-4}$ cfm for PRVs, $2.63\times10^{-5}$ cfm for manual valves, $1.57\times10^{-5}$ cfm for flanges, and $6.08\times10^{-6}$ cfm for threaded connections. For the separators in the storage sector, components which tested positive for leakages include "others" ($5.88\times10^{-4}$ cfm), OELs ($2.70\times10^{-4}$ cfm), and threaded connections ($5.80\times10^{-6}$ cfm). Both this study and the 1996 EPA/GRI study have average EFs for manual valves, OELs, PRVs, and threaded connections in the P&P sector. The EFs of this study are smaller than the corresponding ones of the 1996 EPA/GRI study.

For dehydrators in the P&P sector, the component-level average EF for the regulators is the largest at $6.34\times10^{-3}$ cfm, followed by $1.60\times10^{-4}$ cfm for flanges, and $2.46\times10^{-5}$ cfm for threaded

connections. For dehydrators in the storage sector, no leaking sources were found, thus no component average EFs were derived.

For piping in the P&P sector, the component-level average EF is $4.94\times10^{-3}$ cfm for "others", followed by $7.14\times10^{-4}$ cfm for OELs, $4.34\times10^{-4}$ cfm for regulators, $6.69\times10^{-5}$ cfm for threaded connections, $2.38\times10^{-5}$ cfm for manual valves, and $6.63\times10^{-6}$ cfm for flanges. For piping in the storage sector, the component-level average EF is $4.60\times10^{-2}$ cfm for regulators, followed by $2.45\times10^{-2}$ cfm for PRVs, $1.10\times10^{-4}$ cfm for OELs, $7.30\times10^{-5}$ cfm for flanges, $6.51\times10^{-5}$ for threaded connections, and $2.14\times10^{-5}$ cfm for manual valves. For the transmission sector, the component-level average EF is 1.51 cfm for OELs, followed by $1.44\times10^{-4}$ cfm for manual valves, $6.42\times10^{-5}$ cfm for threaded connections, and $1.11\times10^{-5}$ cfm for flanges. For the distribution sector, the component-level average EFs are $1.49\times10^{-4}$ cfm for manual valves and $2.18\times10^{-5}$ cfm for threaded connections.

For the reciprocating compressors in the P&P sector, the component-level EF of OELs is the largest at $6.69\times10^{-2}$ cfm, followed by $9.58\times10^{-4}$ cfm for flanges, $1.05\times10^{-4}$ cfm for regulators, $2.90\times10^{-5}$ cfm for threaded connections, and $1.51\times10^{-5}$ cfm for manual valves. For the storage sector, only manual valves were found leaking at $1.63\times10^{-4}$ cfm. For the transmission sector, the component-level average EF of seals is the largest at $1.52\times10^{-2}$ cfm, followed by $4.62\times10^{-3}$ cfm for flanges, $7.49\times10^{-5}$ cfm for threaded connections, and $2.73\times10^{-5}$ cfm for manual valves. For the centrifugal compressors in the P&P sector, the component-level average EF is $9.42\times10^{-6}$ cfm for threaded connections. For the storage sector, the component-level average EFs are $8.12\times10^{-4}$ cfm for manual valves and $4.14\times10^{-5}$ cfm for threaded connections. For the transmission sector, the component-level average EFs are $1.33\times10^{-3}$ cfm for flanges and $6.00\times10^{-2}$ cfm for seals.

The EF for pneumatic actuators in the P&P sector is $7.29\text{x}10^{-2}$ cfm $CH_4$/pneumatic actuator; that in the storage sector is $5.77\text{x}10^{-4}$ cfm $CH_4$/pneumatic actuator; and that in the transmission sector is $1.54\text{x}10^{-3}$ cfm $CH_4$/pneumatic actuator. The EF for pneumatic valves in the production and processing sector is $6.44\text{x}10^{-2}$ cfm $CH_4$/pneumatic valve, or $6.38\text{x}10^{-1}$ tonne $CH_4$/yr/pneumatic valve.

For the M&R stations, the component-level average EFs are $5.99\times10^{-5}$ cfm for flanges and $2.14\times10^{-5}$ cfm for manual valves in the distribution sector. The EF for hatches in the P&P sector is $1.55\text{x}10^{-1}$ cfm $CH_4$/hatch. For the customer meters, the component-level average EF is $3.45\text{x}10^{-4}$ cfm for flanges in the distribution sector.

## 6.3 Concluding Remarks

The following are the concluding remarks of this study:

(1) Twenty-seven California natural gas facilities from all five sectors (production, processing, storage, transmission, and distribution) were surveyed to quantify the screening values and the fugitive emission rates from leaking equipment components. The systems surveyed include wellheads, separators, dehydrators, piping segments, compressors, pneumatic devices, metering and regulating stations, hatches, pumps, and customer meters, while the

components studied are flanges, manual valves, open-ended lines, "others", pressure relief valves, regulators, seals, threaded connections, and welded connections.

(2) Hi-Flow samplers were used to quantify fugitive emission rates. Using Hi-Flow samplers is much faster than the bagging approach, but the higher dilution rate used by the Hi-Flow samplers would lead to lower concentrations (i.e., lower resolution) for small leaks that may become non-detects.

(3) For a given screening value range, the measured leak rates spanned several orders of magnitude. The recorded leak rates ranged from below detection limit (<0.01 cfm) to 8.85 cfm and the screening values ranged from 100 to ≥50,000 ppmV. Many of the leaking components had high screening values, but their leak rates were below the detection limit of the flow rate device, even at ≥50,000 ppmV. This implies a poor correlation between the leak rates and the screening values.

(4) All the component leakage rate histograms appeared to have the same trend. The majority of leakage rates were within the range of 0 to 0.02 cfm. For emission rates greater than 0.02 cfm, the frequency at which the leakages occurred decreased as the emission rate increased.

(5) The Weibull probability distribution function (PDF) was found to fit the leakage rate histograms well. Using the cumulative distribution function (CDF), it was found that the geometric mean is a better indicator than the arithmetic mean as the mean for each group of leakage rates found in this study. Consequently, the geometric means, instead of arithmetic means were used to derive the emission factors in this study.

(6) Pegged emission factors for screening values of ≥10,000 ppmV and for ≥50,000 ppmV were derived. For each component type, the two values are relatively similar. The pegged emission factors for seals and open-ended lines are larger than those of flanges, manual valves, and threaded connections. The emission factors with a pegged value of 10,000 ppmV are either smaller than, comparable to, or larger than the corresponding ones in the 1996 EPA/GRI study.

(7) The correlation equations between the leak rates and the screening values were also derived for leaking components. In general, the correlations are relatively poor due to the wide ranges of leakage rates found for each type of component. The correlation equations derived in this study are different from the EPA/GRI or CAPCOA correlation equations. The differences may be partly attributed to the poor correlation between the leak rates and the screening values in this study and the relatively large minimum detection limit of the High-Flow samplers. It should be noted that the correlation equations in this study only used data from the natural gas industry and those of the 1996 EPA/GRI and the 1999 CAPCOA studies came from a variety of operations and services.

(8) Component-level average emission factors for different component types were also derived. The emission factors are either smaller than, comparable to, or larger than the corresponding ones in the 1996 EPA/GRI study.

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# APPENDIX A:
# Component Leakage Rate Histograms

## A.1 Introduction

The figures in this section show the leakage rate histograms for flanges, manual valves, open-ended lines, "others", pressure relief valves, regulators, seals, and threaded connections. Individual component leakage rate histograms are shown to offer a comparison among different types of components. All emission rates were plotted unless noted below the figures. The histograms were utilized in Appendix B to determine a general trend for the probability distribution function.

**Figure A.1.1 – Flanges**

Statistics:

No Leaks = 10,047

Leaks = 54

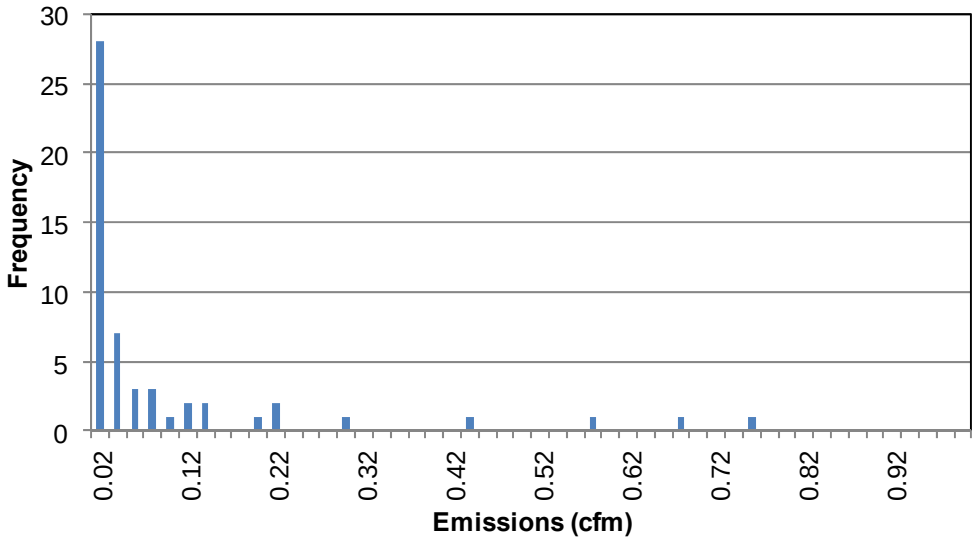



**Figure A.1.2 - Manual Valves**

Statistics:

No Leaks = 10,702

Leaks = 63

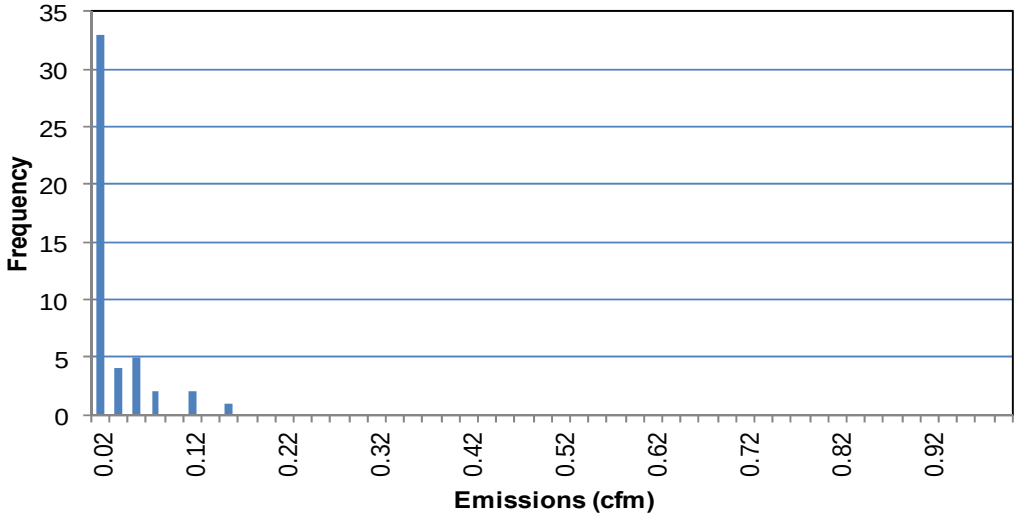
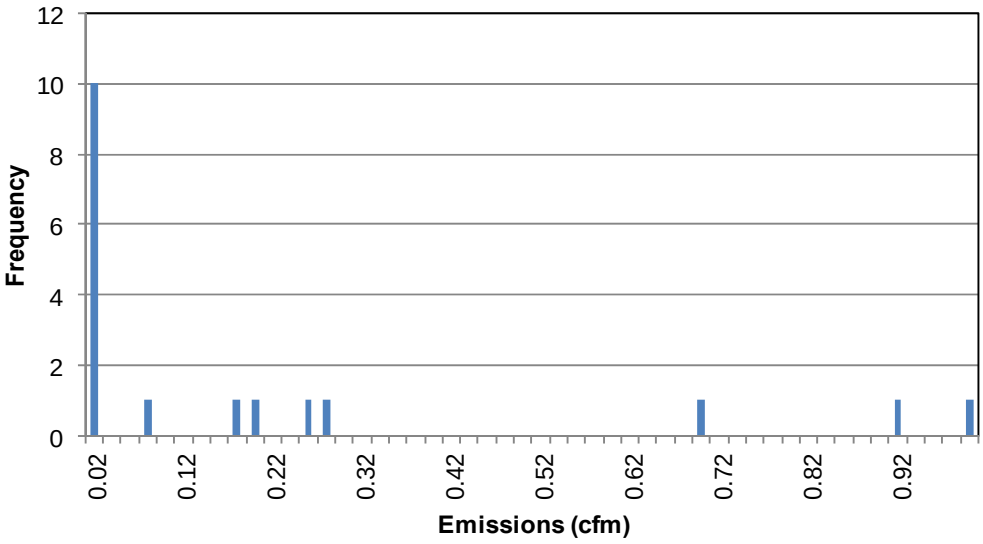



**Figure A.1.3 - Open-Ended Lines**

Statistics:

No Leaks = 362

Leaks = 22



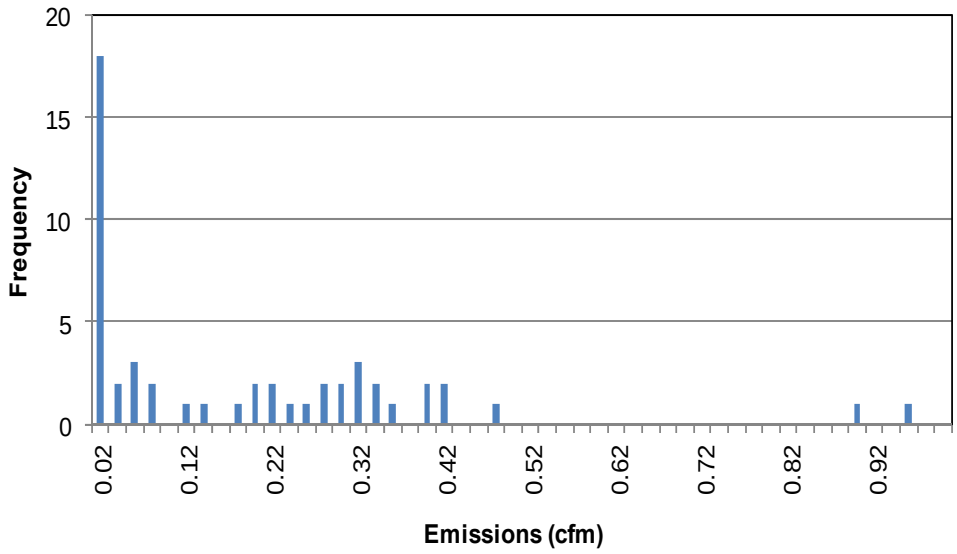

Note: The range of emissions of Figure A.1.3 is between 0.005 and 1.0 cfm and therefore, the following leakage rates were left out: 1.08, 1.69, 4.12, and 8.85 cfm. However, these exclusions do not change the general trend of the histogram.

**Figure A.1.4 – Others**

Statistics:

No Leaks = 86

Leaks = 52




Note: The range of emissions of Figure A.1.4 is between 0.005 and 1.0 cfm and therefore, a leakage rate of 3.18 cfm was left out. This exclusion does not change the general trend of the histogram.

**Figure A.1.5 - Pressure Relief Valves**

Statistics:

No Leaks = 352

Leaks = 6

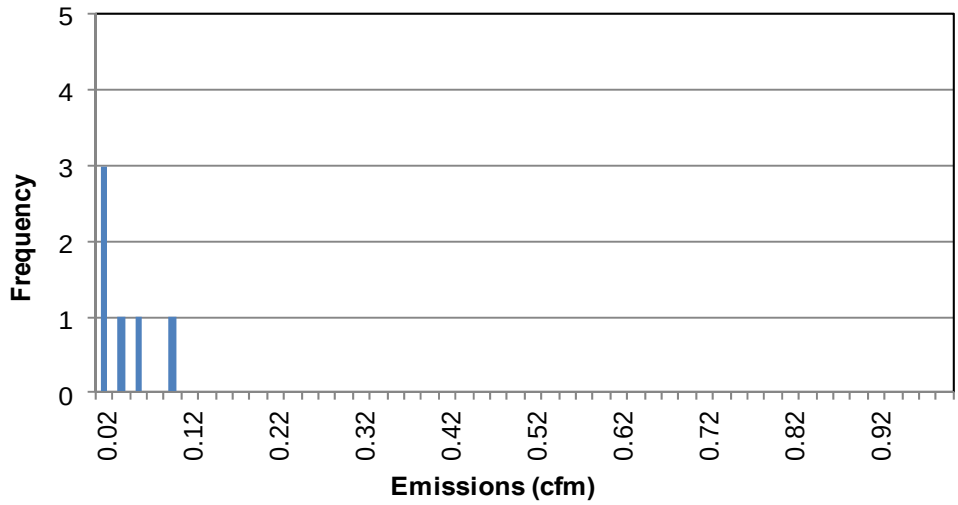



**Figure A.1.6 – Regulators**

Statistics:

No Leaks = 918

Leaks = 11

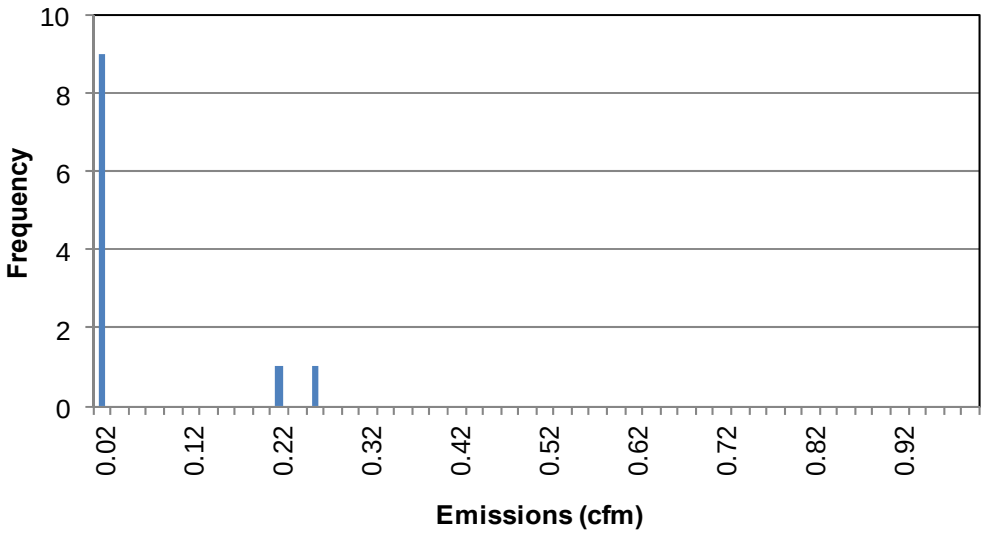



**Figure A.1.7 – Seals**

Statistics:

No Leaks = 133

Leaks = 13

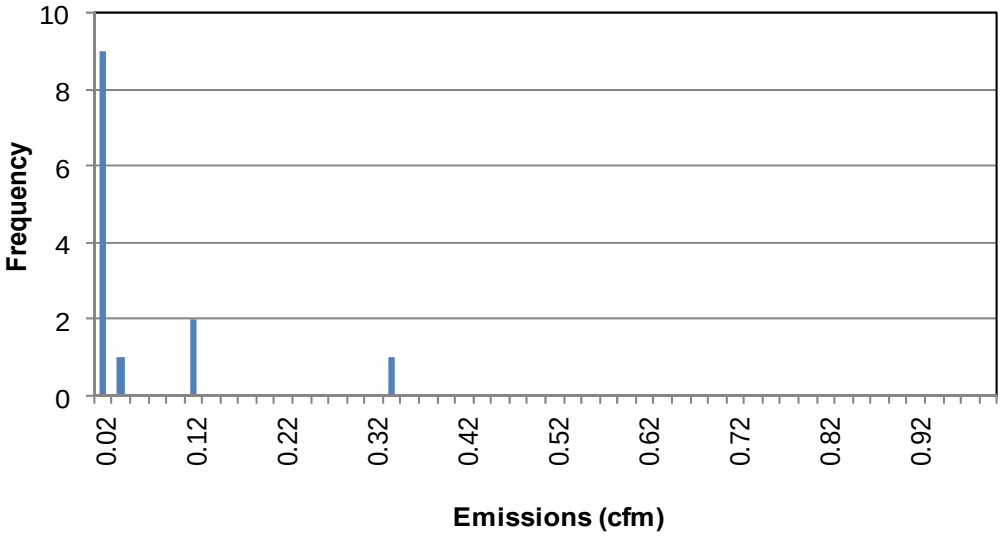
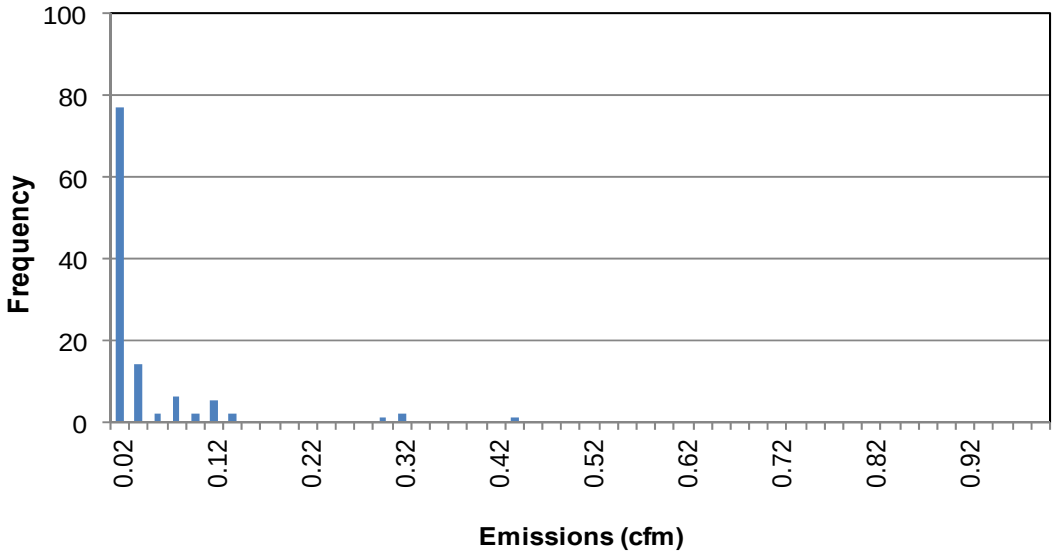



**Figure A.1.8 - Threaded Connections**

Statistics:

No Leaks = 56,938

Leaks = 123




Note: The range of emissions of Figure A.1.8 is between 0.005 and 1.0 cfm and therefore, a leakage rate of 1.23 cfm was left out. This exclusion does not change the general trend of the histogram.

## A.2 Conclusion

All the leakage rate histograms appeared to have the same trend. The majority of leakage rates were within the range of 0 to 0.02 cfm. For leakage rates greater than 0.02 cfm, the frequency at which the leakages occurred decreased as the leakage rate increased.

# APPENDIX B:
# Geometric Mean Justification

Appendix B is to justify using the geometric mean in favor of the arithmetic mean for derivation of emission factors by evaluating all the component leakage rate histograms in Appendix A utilizing a probability distribution function and a cumulative distribution function.

## B.1 Weibull Probability Distribution Function (PDF)

A probability distribution function (PDF) can be used to calculate the probability that a variable is contained within a range of values. PDFs are useful for determining the probability that a leakage rate will occur within a specific range in this study. The Weibull PDF is a continuous probability distribution. It is relevant for non-negative values and can be used to determine the probability that a value lies within a specified range.

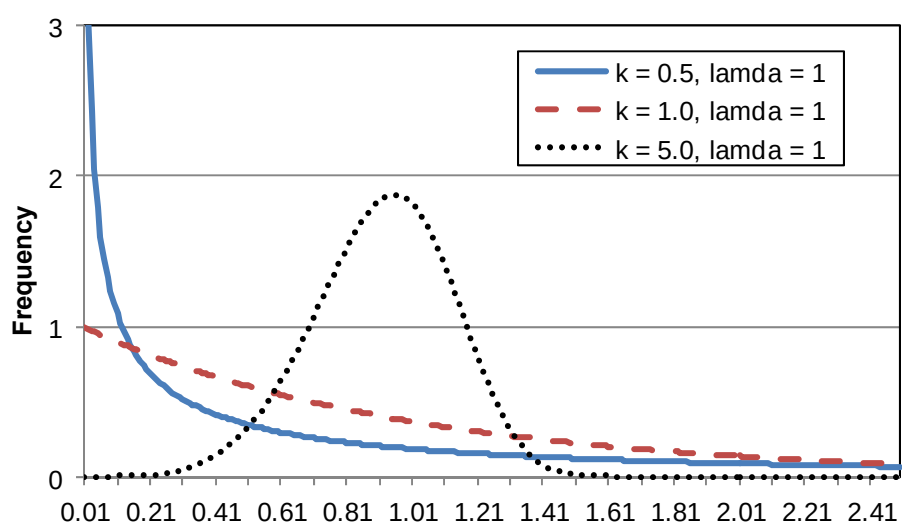
The Weibull Probability Distribution Function can be expressed as:

$$P\left(x\in(a,b)\right)=\int_a^b \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-(x/\lambda)^k}=-e^{-\left(\frac{x}{\lambda}\right)^k} \text{ for } x=(a,b)$$

The Weibull PDF is dependent on the shape parameter, k, and the scale parameter, $\lambda$. Any increase or decrease in the shape parameter affects the general shape of the Weibull PDF. On the other hand, the larger the scale parameter, the more spread out the distribution.

Figure B.1.1 illustrates the Weibull PDFs with k = 0.5, 1.0, and 5.0 for $\lambda$ = 1. As shown in Figure B.1.1, for the Weibull PDF curve with k = 0.5, the frequency approaches infinity as the leakage rate approaches 0 and the frequency decreases as the leakage rate increases. The shape of this curve is very similar to the leakage rate histograms of all components in Appendix A. Therefore, a k value of 0.5 was used in all the subsequent analyses using the Weibull PDF.

**Figure B.1.1 – Weibull Distribution Curve**



The following example illustrates how to calculate the probability of a leakage rate falling between the range of 0.002 and 0.0038 cfm with k = 0.5 and λ = 0.05.

<u>EXAMPLE – PROBABILITY DISTRIBUTION METHOD</u>

Calculate the probability that a leakage rate from a seal is between 0.002 and 0.0038 cfm. Use k = 0.5 and λ = 0.05.

$$P\left(x\in(0.002, 0.0038)\right)= -e^{-\frac{x^k}{\lambda}} \text{ for } x=(0.002, 0.0038)$$

$$P\left(x\in(0.002, 0.0038)\right)=\left(-e^{-\left(\frac{0.0038}{0.05}\right)^{0.5}}\right)-\left(-e^{-\left(\frac{0.002}{0.05}\right)^{0.5}}\right)$$

$$P\left(x\in(0.002, 0.0038)\right)=-(0.7591)-(-0.9387)$$

$$P\left(x\in(0.002, 0.0038)\right)=0.1796$$

The probability that a leakage rate between 0.002 and 0.0038 cfm for a seal is 0.1796.

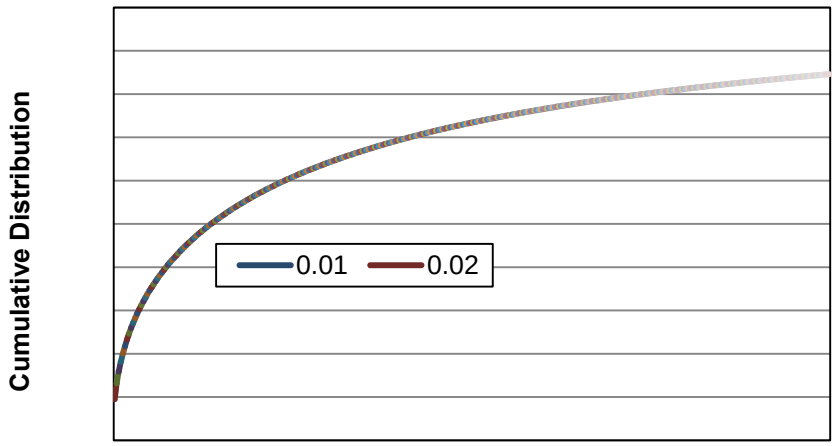
## B.2 Weibull Cumulative Distribution Function (CDF)

A cumulative distribution function (CDF) calculates the probability that a leakage rate will be located between 0 and a random leakage rate, x. The Weibull Cumulative Distribution Function can be expressed as:

$$P(y < x)= F(x; k, \lambda)=1- e^{-(x/\lambda)^k}$$

The Weibull CDF equation was derived by setting the range in the Weibull PDF from 0 to a random leakage rate, x for calculating the probability a leakage rate will be less than or greater than a random leakage rate. The cumulative probability for leak rates from 0 cfm to infinite will be equal to unity. Similar to the PDF, the CDF is dependent on the shape parameter, k, and the scale parameter, λ. Figure B.2.1 illustrates the Weibull Cumulative Distribution Curve for k = 0.5 and λ = 1. As the leakage rate increases, the probability of a leakage between 0 and that leakage rate will increase. Whenever P(y < x) = 0.50, the Weibull CDF will assume x to be the median, or value where 50 percent of all possible leakage rates are less than x, and 50 percent of all possible leakage rates are greater than x. Whenever P(y < x) = 0.50, the total values in the CDF will have the most equal distribution.

**Figure B.2.1 - Weibull Cumulative Distribution Curve**




In this study, a value of 0.5 was assigned to the shape parameter (k) because of the similarity between the Weibull Probability Distribution Curve in Figure B.1.1 and all of the component leakage rate histograms in Appendix A. Since the scale parameter ($\lambda$) was different for each component, the value of $\lambda$ was determined separately for each component type using the equation below. The $\lambda$ value equation was derived by setting the PDF equal to 0.5 with the range equals to (0, x), where x is the median leakage rate for that component type, and then solving for $\lambda$.

$$\lambda = e^{\left(\frac{x}{\frac{\ln(\ln 2)}{k}}\right)}$$

The following example illustrates how to calculate the probability of a leakage rate of a threaded connection in the screening value range of 1,000 – 49,999 ppmV is contained in (1) the range between 0 and the geometric mean (0.0143 cfm) and (2) the range between 0 and the arithmetic mean (0.033 cfm) with k = 0.5. The value of $\lambda$ was first calculated to be 0.0208 with k = 0.5 and the median leakage rate of 0.010 cfm. As shown, the cumulative probability for a leakage rate falls in the range between 0 and the geometric mean is 56.35 percent, while that falls in the range between 0 and the arithmetic mean is 71.61 percent.

<u>EXAMPLE – CUMULATIVE DISTRIBUTION EQUATION METHOD</u>

Calculate the probability of a leakage rate of a threaded connection in the screening value range of 1,000 – 49,999 ppmV is contained in (1) the range between 0 and the geometric mean (0.0143 cfm) and (2) the range between 0 and the arithmetic mean (0.033 cfm). Use k = 0.5 and the median leakage rate = 0.010 cfm.

$$P\big(x\in(a, b)\big) = \int_a^b \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-(x/\lambda)^k} = -e^{-\frac{x^k}{\lambda}} \text{ for } x=(0, b)$$

Value of $\lambda$:

$$\lambda = e^{\left(\frac{x}{\frac{\ln(\ln 2)}{k}}\right)} = e^{\left(\frac{0.010}{\frac{\ln(\ln 2)}{0.5}}\right)} = 0.0208$$

Geometric mean:

$$P\big(x\in(0, 0.0143)\big) = -e^{-\frac{x^k}{\lambda}} \text{ for } x=(0, 0.0143)$$

$$P\big(x\in(0, 0.0143)\big) = \left(-e^{\left(\frac{0.0143}{0.0208}\right)^{0.5}}\right)-\left(-e^{\left(\frac{0}{0.0208}\right)^{0.5}}\right)$$

$$P\big(x\in(0, 0.0143)\big) = -(0.4365)-(-1)$$

$$P\big(x\in(0, 0.0143)\big) = 0.5635$$

Arithmetic Mean:

$$P\big(x\in(0, 0.033)\big) = -e^{-\frac{x^k}{\lambda}} \text{ for } x=(0, 0.033)$$

$$P\big(x\in(0, 0.033)\big) = \left(-e^{\left(\frac{0.033}{0.0208}\right)^{0.5}}\right)-\left(-e^{\left(\frac{0}{0.0208}\right)^{0.5}}\right)$$

$$P\big(x\in(0, 0.033)\big) = -(0.2839)-(-1)$$

$$P\big(x\in(0, 0.033)\big) = 0.7161$$

**Table B.2.1 Cumulative Distribution Function on Geometric Mean and Arithmetic Mean Calculations (k = 0.5)**

| | Flanges | | Manual Valves | | Open Ended Lines | | Others | | Seals | | Threaded Connections | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 10,000 – 49,999 ppmV | ≥50,000 ppmV | 10,000 – 49,999 ppmV | ≥50,000 ppmV | 10,000 – 49,999 ppmV | ≥50,000 ppmV | 10,000 – 49,999 ppmV | ≥50,000 ppmV | 10,000 – 49,999 ppmV | ≥50,000 ppmV | 10,000 – 49,999 ppmV | ≥50,000 ppmV |
| Geometric mean (cfm) | 0.0293 | 0.0747 | 0.0136 | 0.0197 | 0.005 | 0.2874 | 0.0691 | 0.1157 | 0.1217 | 0.3907 | 0.0143 | 0.0168 |
| Arithmetic Mean (cfm) | 0.052 | 0.206 | 0.034 | 0.034 | 0.005 | 1.748 | 0.241 | 0.328 | 0.405 | 0.996 | 0.033 | 0.043 |
| Median Leakage (cfm) | 0.040 | 0.110 | 0.005 | 0.020 | 0.005 | 0.485 | 0.080 | 0.200 | 0.530 | 0.370 | 0.010 | 0.010 |
| Scale parameter ($\lambda$) | 0.0833 | 0.2290 | 0.0104 | 0.0416 | 0.0104 | 3.6382 | 0.1665 | 0.4163 | 1.1031 | 0.7701 | 0.0208 | 0.0208 |
| CDF for Geometric Mean* | 44.75% | 43.52% | 68.12% | 49.74% | 50.00% | 24.50% | 47.49% | 40.97% | 28.26% | 50.95% | 56.35% | 59.28% |
| CDF for Arithmetic Mean** | 54.63% | 61.27% | 83.59% | 59.50% | 50.00% | 50.00% | 69.97% | 58.84% | 45.44% | 67.93% | 71.61% | 76.24% |

NOTE: * = Boundary range (0, geometric mean)
** = Boundary range (0, arithmetic mean)

## B.3 Conclusion

As shown in Table B.2.1, for a leaking flange in this study with a screening value in the 50,000+ ppmV, its leakage rate has a 43.52 percent probability of being less than the calculated geometric mean of 0.0747 cfm and a 56.48 percent (=100 percent - 43.52 percent ) probability of being greater than the calculated geometric mean. On the other hand, for a leaking flange in this study with a screening value in the 50,000+ ppmV, its leakage rate has a 61.27 percent probability of being less than the calculated arithmetic mean of 0.206 cfm and a 38.73 percent (=100 percent - 61.27 percent ) probability of being greater than the calculated arithmetic mean. The closer the cumulative probability is to 50 percent, the more evenly distributed the range.

The results tabulated in Table B.2.1 indicate that using the geometric mean yields a cumulative probability typically closer to 50 percent than that using the arithmetic mean for the majority of the component types and for both screening value ranges. It implies that the geometric mean is a better indicator than the arithmetic mean as the mean for each range of leakage rates found in this study. Consequently, the geometric means, instead of arithmetic means were used to derive the emission factors in this study.

# APPENDIX C:
# Raw Leakage Rate Data

## C.1: Emissions Data

In some cases, component counts were not taken during the survey. Therefore, the data used for the emissions calculations shown in Section 5.4 was limited by data associated with component counts. The following tables present the raw data separated by equipment and by industry sector.

Equipment Designations are as follows:

| | |
|---|---|
| Wellheads | (WE) |
| Separators | (SE) |
| Dehydrators | (DH) |
| Piping Segments | (PI) |
| Reciprocating Compressors | (RC) |
| Centrifugal Compressors | (CC) |
| Rotary Compressors | (RO) |
| Pneumatic Actuators | (PA) |
| Pneumatic Valves | (PV) |
| M&R Stations | (MR) |
| Hatches | (HT) |
| Pumps | (PU) |
| Customer Meters | (CM) |
| Compressor Vents | (VE) |

Industry Sector Designations are as follows:

| | |
|---|---|
| Production and Processing | (P) |
| Storage | (S) |
| Transmission | (T) |
| Distribution | (D) |

### Table C.1.1 – Wellheads

| ID | Component | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|---|
| WE-P1 | Flange | 50000 | 0.1 |
| WE-P2 | | | |
| WE-P3 | Flange | 650 | 0.005 |
| WE-P3 | Flange | 27000 | 0.01 |
| WE-P4 | | | |
| WE-P5 | | | |
| WE-P6 | | | |
| WE-P7 | | | |
| WE-P8 | | | |
| WE-P9 | | | |
| WE-P10 | | | |
| WE-P11 | | | |
| WE-P12 | | | |
| WE-P13 | | | |
| WE-P14 | | | |
| WE-P15 | | | |
| WE-P16 | | | |
| WE-P17 | | | |
| WE-P18 | | | |
| WE-P19 | | | |
| WE-P20 | | | |
| WE-P21 | | | |
| WE-P22 | Seal | 6150 | 0.04 |
| WE-P23 | Seal | 48000 | 0.08 |
| WE-P24 | | | |
| WE-P25 | | | |
| WE-P26 | | | |
| WE-P27 | | | |
| WE-P28 | | | |
| WE-P29 | | | |
| WE-P30 | | | |
| WE-P31 | | | |
| WE-P32 | | | |
| WE-P33 | | | |
| WE-P34 | | | |
| WE-P35 | | | |
| WE-P36 | Seal | 60 | 0.005 |
| WE-P37 | | | |
| WE-P38 | | | |

| ID | Component | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|---|
| WE-P42 | | | |
| WE-P43 | | | |
| WE-P44 | | | |
| WE-P45 | | | |
| WE-P46 | | | |
| WE-P47 | | | |
| WE-P48 | | | |
| WE-P49 | | | |
| WE-P50 | | | |
| WE-P51 | | | |
| WE-P52 | | | |
| WE-P53 | | | |
| WE-P54 | | | |
| WE-P55 | | | |
| WE-P56 | Threaded Connection | 13000 | 0.005 |
| WE-P57 | | | |
| WE-P58 | | | |
| WE-P59 | | | |
| WE-P60 | | | |
| WE-P61 | | | |
| WE-P62 | | | |
| WE-P63 | | | |
| WE-P64 | | | |
| WE-P65 | | | |
| WE-P66 | | | |
| WE-P67 | | | |
| WE-P68 | | | |
| WE-P69 | | | |
| WE-P70 | | | |
| WE-P71 | | | |
| WE-P72 | | | |
| WE-P73 | | | |
| WE-P74 | | | |
| WE-P75 | | | |
| WE-P76 | | | |
| WE-P77 | | | |
| WE-P78 | | | |
| WE-P79 | | | |
| WE-P80 | | | |

| | | | |
|---|---|---|---|
| WE-P39 | | | |
| WE-P40 | | | |
| WE-P41 | | | |
| WE-P84 | | | |
| WE-P85 | | | |
| WE-P86 | | | |
| WE-P87 | | | |
| WE-P88 | | | |
| WE-P89 | | | |
| WE-P90 | | | |
| WE-P91 | | | |
| WE-P92 | | | |
| WE-P93 | | | |
| WE-P94 | | | |
| WE-P95 | | | |
| WE-P96 | | | |
| WE-P97 | | | |
| WE-P98 | | | |
| WE-P99 | | | |
| WE-P100 | | | |
| WE-P101 | | | |
| WE-P102 | | | |
| WE-P103 | | | |
| WE-P104 | Threaded Connection | 50000 | 0.11 |
| WE-P105 | | | |
| WE-P106 | Threaded Connection | 50000 | 0.03 |
| WE-P107 | | | |
| WE-P108 | | | |
| WE-P109 | Threaded Connection | 3000 | 0.005 |
| WE-P110 | | | |
| WE-P111 | | | |
| WE-P112 | | | |
| WE-P113 | Threaded Connection | 50000 | 0.03 |
| WE-P114 | | | |
| WE-P115 | | | |

| | | | |
|---|---|---|---|
| WE-P81 | | | |
| WE-P82 | | | |
| WE-P83 | | | |
| WE-P126 | | | |
| WE-P127 | | | |
| WE-P128 | | | |
| WE-S1 | Manual Valve | | 0.02 |
| WE-S1 | Manual Valve | | 0.12 |
| WE-S1 | Manual Valve | | 0.04 |
| WE-S1 | Manual Valve | | 0.07 |
| WE-S1 | Manual Valve | | 0.05 |
| WE-S2 | Manual Valve | | 0.3 |
| WE-S2 | Manual Valve | | 0.13 |
| WE-S2 | Manual Valve | | 0.08 |
| WE-S2 | Manual Valve | | 0.35 |
| WE-S3 | OEL | | 0.08 |
| WE-S3 | OEL | | 0.25 |
| WE-S3 | OEL | | 0.02 |
| WE-S3 | OEL | | 0.12 |
| WE-S3 | OEL | | 0.5 |
| WE-S4 | OEL | | 1.35 |
| WE-S5 | OEL | | 0.15 |
| WE-S6 | OEL | | 0.18 |
| WE-S6 | OEL | | 0.22 |
| WE-S7 | Threaded Connection | | 1.23 |
| WE-S7 | Threaded Connection | | 0.24 |
| WE-S7 | Threaded Connection | | 0.06 |
| WE-S8 | Threaded Connection | | |
| WE-S9 | Threaded Connection | 28000 | 0.005 |
| WE-S10 | Threaded Connection | 7200 | 0.005 |
| WE-S11 | Threaded Connection | 450 | 0.005 |
| WE-S11 | Threaded Connection | 6250 | 0.005 |
| WE-S11 | Threaded Connection | 18500 | 0.028 |
| WE-S12 | Threaded Connection | 65 | 0.005 |
| WE-S13 | Threaded | 1600 | 0.005 |

| | | | |
|---|---|---|---|
| | | | |
| WE-P116 | | | |
| WE-P117 | | | |
| WE-P118 | | | |
| WE-P119 | | | |
| WE-P120 | Threaded Connection | 50000 | 0.16 |
| WE-P121 | | | |
| WE-P122 | | | |
| WE-P123 | | | |
| WE-P124 | Valve | 33000 | 0.02 |
| WE-P125 | | | |
| WE-S24 | | | |
| WE-S25 | Valve | 5800 | 0.005 |
| WE-S26 | | | |
| WE-S27 | Valve | 50000 | 0.26 |
| WE-S28 | Valve | 1000 | 0.005 |
| WE-S29 | | | |
| WE-S30 | | | |
| WE-S31 | | | |
| WE-S32 | Valve | 47000 | 0.005 |
| WE-S33 | Valve | 50000 | 0.17 |
| WE-S33 | Valve | 5000 | 0.005 |
| WE-S34 | | | |

| | | | |
|---|---|---|---|
| | Connection | | |
| WE-S14 | Threaded Connection | 50000 | 0.005 |
| WE-S15 | | | |
| WE-S16 | Threaded Connection | 7600 | 0.005 |
| WE-S17 | Threaded Connection | 5000 | 0.005 |
| WE-S18 | | | |
| WE-S19 | | | |
| WE-S20 | Threaded Connection | 50000 | 0.13 |
| WE-S21 | Valve | 14500 | 0.005 |
| WE-S22 | | | |
| WE-S23 | Valve | 50000 | 0.01 |
| WE-S35 | Valve | 50000 | 0.08 |
| WE-S35 | Valve | 50000 | 0.08 |
| WE-S36 | | | |
| WE-S37 | | | |
| WE-S38 | Valve | 50000 | 0.2 |
| WE-S38 | Valve | 1450 | 0.005 |
| WE-S39 | Valve | 50000 | 0.07 |
| WE-S40 | Valve | 16500 | 0.04 |
| WE-S41 | Valve | 50000 | 0.005 |
| WE-S42 | | | |
| WE-S43 | Valve | 50000 | 0.005 |
| WE-S44 | Valve | 50000 | 0.005 |

### Table C.1.2 – Separators

| ID | Component | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|---|
| SE-P1 | | | |
| SE-P2 | | | |
| SE-P3 | | | |
| SE-P4 | Flange | 750 | 0.005 |
| SE-P4 | Flange | 1100 | 0.005 |
| SE-P5 | | | |
| SE-P6 | | | |
| SE-P7 | | | |
| SE-P8 | Flange | 1200 | 0.005 |
| SE-P9 | | | |
| SE-P10 | | | |
| SE-P11 | | | |

| ID | Component | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|---|
| SE-P24 | Flange | 5250 | 0.21 |
| SE-P24 | Flange | 9850 | 0.005 |
| SE-P25 | | | |
| SE-P26 | | | |
| SE-P27 | | | |
| SE-P28 | | | |
| SE-P29 | | | |
| SE-P30 | | | |
| SE-P31 | | | |
| SE-P32 | | | |
| SE-P33 | | | |
| SE-P34 | | | |

| | | | |
|---|---|---|---|
| SE-P12 | | | |
| SE-P13 | | | |
| SE-P14 | | | |
| SE-P15 | | | |
| SE-P16 | | | |
| SE-P17 | | | |
| SE-P18 | | | |
| SE-P19 | | | |
| SE-P20 | | | |
| SE-P21 | | | |
| SE-P22 | | | |
| SE-P23 | | | |
| SE-P46 | | | |
| SE-P47 | | | |
| SE-P48 | | | |
| SE-P49 | | | |
| SE-P50 | | | |
| SE-P51 | | | |
| SE-P52 | | | |
| SE-P53 | | | |
| SE-P54 | | | |
| SE-P55 | | | |
| SE-P56 | | | |
| SE-P57 | | | |
| SE-P58 | | | |
| SE-P59 | | | |
| SE-P60 | | | |
| SE-P61 | | | |
| SE-P62 | | | |
| SE-P63 | | | |
| SE-P64 | | | |
| SE-P65 | Regulator | 40000 | 0.005 |
| SE-P65 | Threaded Connection | 50000 | 0.005 |
| SE-P66 | | | |
| SE-P67 | | | |
| SE-P68 | | | |
| SE-P69 | | | |
| SE-P70 | | | |
| SE-P71 | | | |
| SE-P72 | | | |
| SE-P73 | Threaded | 50000 | 0.02 |

| | | | |
|---|---|---|---|
| SE-P35 | | | |
| SE-P36 | | | |
| SE-P37 | | | |
| SE-P38 | | | |
| SE-P39 | | | |
| SE-P40 | Manual Valve | 25500 | 0.005 |
| SE-P41 | | | |
| SE-P42 | Manual Valve | 50000 | 0.03 |
| SE-P42 | Other | 50000 | 0.02 |
| SE-P43 | Other | 10750 | 0.005 |
| SE-P44 | PRV | 7400 | 0.02 |
| SE-P45 | Regulator | 50000 | 0.12 |
| SE-P86 | Valve | 2700 | 0.005 |
| SE-P87 | | | |
| SE-P88 | | | |
| SE-P89 | | | |
| SE-P90 | | | |
| SE-P91 | | | |
| SE-P92 | | | |
| SE-P93 | | | |
| SE-P94 | | | |
| SE-P95 | | | |
| SE-P96 | Valve | 890 | 0.005 |
| SE-P97 | | | |
| SE-P98 | | | |
| SE-P99 | | | |
| SE-P100 | | | |
| SE-P101 | | | |
| SE-P102 | | | |
| SE-P103 | | | |
| SE-P104 | | | |
| SE-P105 | | | |
| SE-P106 | | | |
| SE-P107 | | | |
| SE-P108 | | | |
| SE-P109 | | | |
| SE-P110 | | | |
| SE-P111 | | | |
| SE-P112 | | | |
| SE-P113 | | | |
| SE-P114 | | | |

| | | | |
|---|---|---|---|
| | Connection | | |
| SE-P73 | Threaded Connection | 16000 | 0.02 |
| SE-P73 | Threaded Connection | 15500 | 0.005 |
| SE-P74 | | | |
| SE-P75 | Threaded Connection | 8350 | 0.005 |
| SE-P76 | | | |
| SE-P77 | | | |
| SE-P78 | Threaded Connection | 8900 | 0.005 |
| SE-P79 | | | |
| SE-P80 | | | |
| SE-P81 | | | |
| SE-P82 | | | |
| SE-P83 | | | |
| SE-P84 | | | |
| SE-P85 | | | |
| SE-S11 | | | |
| SE-S12 | | | |
| SE-S13 | | | |

| | | | |
|---|---|---|---|
| | | | |
| SE-P115 | Valve | 50000 | 0.01 |
| SE-S1 | | | |
| SE-S2 | | | |
| SE-S3 | | | |
| SE-S4 | | | |
| SE-S5 | | | |
| SE-S6 | | | |
| SE-S7 | OEL | 46000 | 0.005 |
| SE-S8 | | | |
| SE-S9 | | | |
| SE-S10 | OEL | 9000 | 0.005 |
| SE-S10 | Other | 1000 | 0.005 |
| SE-S10 | Other | 11250 | 0.005 |
| SE-S10 | Threaded Connection | 3100 | 0.005 |
| SE-S14 | | | |
| SE-T1 | | | |
| SE-T2 | | | |

### Table C.1.3 – Dehydrators

| ID | Component | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|---|
| DH-P1 | Flange | 10500 | 0.03 |
| DH-P1 | Regulator | 50000 | 0.26 |
| DH-P1 | Threaded connection | 16075 | 0.02 |
| DH-P2 | | | |
| DH-P3 | | | |
| DH-P4 | | | |
| DH-P5 | | | |
| DH-P6 | Threaded connection | 15750 | 0.03 |
| DH-P7 | Threaded connection | 10500 | 0.03 |
| DH-P8 | | | |

| ID | Component | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|---|
| DH-S1 | | | |
| DH-S2 | | | |
| DH-S3 | | | |
| DH-S4 | | | |
| DH-S5 | | | |
| DH-S6 | | | |
| DH-S7 | | | |
| DH-S8 | | | |
| DH-S9 | | | |

### Table C.1.4 – Piping Segments

| ID | Component | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|---|
| PI-P1 | Flange | 23000 | 0.005 |

| ID | Component | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|---|
| PI-P23 | | | |

| | | | |
|---|---|---|---|
| PI-P2 | | | |
| PI-P3 | | | |
| PI-P4 | | | |
| PI-P5 | | | |
| PI-P6 | | | |
| PI-P7 | | | |
| PI-P8 | Manual Valve | 50000 | 0.01 |
| PI-P9 | | | |
| PI-P10 | | | |
| PI-P11 | | | |
| PI-P12 | | | |
| PI-P13 | | | |
| PI-P14 | | | |
| PI-P15 | | | |
| PI-P16 | | | |
| PI-P17 | Other | 17000 | 0.06 |
| PI-P18 | | | |
| PI-P19 | | | |
| PI-P20 | | | |
| PI-P21 | | | |
| PI-P22 | | | |
| PI-P44 | | | |
| PI-P45 | | | |
| PI-P46 | Threaded Connection | 50000 | 0.06 |
| PI-P47 | Valve | 50000 | 0.01 |
| PI-P47 | Valve | 16000 | 0.005 |
| PI-P48 | | | |
| PI-P49 | | | |
| PI-P50 | | | |
| PI-P51 | | | |
| PI-P52 | | | |
| PI-P53 | | | |
| PI-P54 | | | |
| PI-P55 | | | |
| PI-P56 | | | |
| PI-P57 | | | |
| PI-P58 | | | |
| PI-P59 | | | |

| | | | |
|---|---|---|---|
| PI-P24 | | | |
| PI-P25 | | | |
| PI-P26 | Other | 50000 | 0.01 |
| PI-P27 | | | |
| PI-P28 | | | |
| PI-P29 | | | |
| PI-P30 | | | |
| PI-P31 | | | |
| PI-P32 | | | |
| PI-P33 | | | |
| PI-P34 | Regulator | 6500 | 0.02 |
| PI-P34 | Regulator | 11000 | 0.01 |
| PI-P35 | | | |
| PI-P36 | | | |
| PI-P37 | | | |
| PI-P38 | | | |
| PI-P39 | | | |
| PI-P40 | | | |
| PI-P41 | Threaded Connection | 40000 | 0.005 |
| PI-P42 | | | |
| PI-P43 | | | |
| PI-S17 | | | |
| PI-S18 | Threaded Connection | 14000 | 0.02 |
| PI-S18 | Threaded Connection | 1000 | 0.005 |
| PI-S19 | | | |
| PI-S20 | | | |
| PI-S21 | Threaded Connection | 4200 | 0.005 |
| PI-S21 | Threaded Connection | 50000 | 0.11 |
| PI-S21 | Valve | 50000 | 0.02 |
| PI-S21 | Valve | 1100 | 0.04 |
| PI-T1 | Other | 4500 | 0.01 |
| PI-T1 | Flange | 44750 | 0.01 |
| PI-T2 | Flange | 50000 | 0.04 |
| PI-T2 | Manual Valve | 16500 | 0.05 |
| PI-T2 | Manual Valve | 11000 | 0.02 |
| PI-T2 | Manual Valve | 11750 | 0.04 |
| PI-T3 | OEL | 50000 | 1.69 |
| PI-T3 | OEL | 50000 | 0.69 |

| | | | |
|---|---|---|---|
| PI-P60 | | | |
| PI-P61 | | | |
| PI-P62 | | | |
| PI-P63 | | | |
| PI-P64 | | | |
| PI-S1 | | | |
| PI-S2 | | | |
| PI-S3 | Flange | 47000 | 0.1 |
| PI-S3 | Flange | 7500 | 0.12 |
| PI-S4 | | | |
| PI-S5 | | | |
| PI-S6 | | | |
| PI-S7 | | | |
| PI-S8 | OEL | 6000 | 0.005 |
| PI-S9 | | | |
| PI-S10 | | | |
| PI-S11 | | | |
| PI-S12 | OEL | 50000 | 1.02 |
| PI-S12 | Pressure Relief Valve | 36750 | 0.04 |
| PI-S12 | PRV | 50000 | 0.06 |
| PI-S12 | Regulator | 17000 | 0.08 |
| PI-S13 | Threaded Connection | 1250 | 0.005 |
| PI-S13 | Threaded Connection | 2400 | 0.005 |
| PI-S14 | | | |
| PI-S15 | Threaded Connection | 19000 | 0.005 |
| PI-S16 | | | |
| PI-T16 | Threaded Connection | 1100 | 0.005 |
| PI-T17 | | | |
| PI-T18 | | | |
| PI-T19 | | | |
| PI-T20 | | | |
| PI-T21 | | | |

| | | | |
|---|---|---|---|
| PI-T3 | OEL | 50000 | 8.85 |
| PI-T3 | OEL | 50000 | 4.12 |
| PI-T3 | OEL | 50000 | 1 |
| PI-T3 | OEL | 50000 | 0.28 |
| PI-T4 | Threaded Connection | 50000 | 0.01 |
| PI-T4 | Threaded Connection | 10750 | 0.005 |
| PI-T4 | Threaded Connection | 40000 | 0.005 |
| PI-T4 | Threaded Connection | 6700 | 0.005 |
| PI-T4 | Threaded Connection | 7350 | 0.005 |
| PI-T4 | Threaded Connection | 10750 | 0.005 |
| PI-T4 | Threaded Connection | 7450 | 0.005 |
| PI-T4 | Threaded Connection | 7650 | 0.005 |
| PI-T4 | Threaded Connection | 50000 | 0.03 |
| PI-T5 | | | |
| PI-T6 | | | |
| PI-T7 | | | |
| PI-T8 | | | |
| PI-T9 | Threaded Connection | 50000 | 0.01 |
| PI-T10 | Threaded Connection | 17250 | 0.11 |
| PI-T11 | | | |
| PI-T12 | | | |
| PI-T13 | Threaded Connection | 1200 | 0.005 |
| PI-T13 | Threaded Connection | 1200 | 0.005 |
| PI-T14 | | | |
| PI-T15 | Threaded Connection | 5650 | 0.005 |
| PI-T16 | Threaded Connection | 1400 | 0.005 |
| PI-D15 | Manual Valve | 7450 | 0.005 |
| PI-D15 | Manual Valve | 19500 | 0.005 |
| PI-D15 | Manual Valve | 50000 | 0.01 |
| PI-D15 | Manual Valve | 9950 | 0.005 |
| PI-D16 | | | |
| PI-D17 | | | |

| | | | |
|---|---|---|---|
| PI-T22 | Valve | 3800 | 0.005 |
| PI-T23 | | | |
| PI-T24 | | | |
| PI-T25 | | | |
| PI-T26 | | | |
| PI-T27 | Valve | 5900 | 0.005 |
| PI-T28 | | | |
| PI-D1 | Other | 50000 | 0.05 |
| PI-D2 | | | |
| PI-D3 | | | |
| PI-D4 | | | |
| PI-D5 | | | |
| PI-D6 | | | |
| PI-D7 | | | |
| PI-D8 | | | |
| PI-D9 | | | |
| PI-D10 | | | |
| PI-D11 | | | |
| PI-D12 | | | |
| PI-D13 | | | |
| PI-D14 | Manual Valve | 1000 | 0.005 |

| | | | |
|---|---|---|---|
| PI-D18 | Manual Valve | 38000 | 0.005 |
| PI-D18 | Manual Valve | 50000 | 0.02 |
| PI-D18 | Manual Valve | 28750 | 0.005 |
| PI-D18 | Manual Valve | 50000 | 0.005 |
| PI-D18 | Manual Valve | 1000 | 0.005 |
| PI-D19 | Threaded Connection | 1250 | 0.005 |
| PI-D19 | Threaded Connection | 50000 | 0.01 |
| PI-D20 | | | |
| PI-D21 | Threaded Connection | 27250 | 0.005 |
| PI-D22 | | | |
| PI-D23 | | | |
| PI-D24 | Threaded Connection | 6200 | 0.005 |
| PI-D24 | Threaded Connection | 33000 | 0.005 |
| PI-D25 | | | |
| PI-D26 | | | |
| PI-D27 | | | |
| PI-D28 | Threaded Connection | 8700 | 0.005 |
| PI-D29 | Threaded Connection | 6350 | 0.005 |
| PI-D30 | Threaded Connection | 3100 | 0.005 |
| PI-D31 | | | |
| PI-D32 | | | |

### Table C.1.5 – Reciprocating Compressors

| ID | Component | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|---|
| RC-P1 | Flange | 2550 | 0.005 |
| RC-P2 | Flange | 50000 | 0.11 |
| RC-P2 | Flange | 2650 | 0.005 |
| RC-P2 | Flange | 300 | 0.005 |
| RC-P3 | | | |
| RC-P4 | Flange | 300 | 0.005 |
| RC-P4 | Flange | 1300 | 0.005 |
| RC-P5 | Flange | 35750 | 0.01 |
| RC-P6 | Flange | 1450 | 0.005 |
| RC-P7 | Flange | 50000 | 0.06 |
| RC-P16 | | | |
| RC-P17 | Regulator | 2400 | 0.005 |

| ID | Component | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|---|
| RC-P8 | Flange | 37000 | 0.03 |
| RC-P9 | Flange | 9800 | 0.01 |
| RC-P10 | OEL | 50000 | 0.08 |
| RC-P11 | | | |
| RC-P12 | | | |
| RC-P13 | | | |
| RC-P14 | OEL | 6000 | 0.005 |
| RC-P14 | Regulator | 5700 | 0.005 |
| RC-P14 | Regulator | 50000 | 0.02 |
| RC-P15 | | | |
| RC-S5 | | | |
| RC-S6 | | | |

| | | | |
|---|---|---|---|
| RC-P18 | Regulator | 50000 | 0.43 |
| RC-P19 | Regulator | 2100 | 0.005 |
| RC-P19 | Threaded Connection | 2150 | 0.005 |
| RC-P19 | Threaded Connection | 50000 | 0.005 |
| RC-P19 | Threaded Connection | 1200 | 0.005 |
| RC-P20 | | | |
| RC-P21 | | | |
| RC-P22 | | | |
| RC-P23 | Threaded Connection | 1000 | 0.005 |
| RC-P23 | Threaded Connection | 50000 | 0.32 |
| RC-P23 | Threaded Connection | 50000 | 0.04 |
| RC-P23 | Threaded Connection | 4000 | 0.005 |
| RC-P24 | Threaded Connection | 16250 | 0.005 |
| RC-P24 | Threaded Connection | 10000 | 0.02 |
| RC-P24 | Threaded Connection | 6000 | 0.005 |
| RC-P25 | Threaded Connection | 15000 | 0.31 |
| RC-P25 | Threaded Connection | 50000 | 1.08 |
| RC-P25 | Threaded Connection | 50000 | 0.04 |
| RC-P26 | Threaded Connection | 1600 | 0.005 |
| RC-P26 | Threaded Connection | 3700 | 0.005 |
| RC-P27 | | | |
| RC-P28 | Threaded Connection | 50000 | 0.005 |
| RC-P29 | | | |
| RC-P30 | | | |
| RC-P31 | Threaded Connection | 15000 | 0.005 |
| RC-P31 | Threaded Connection | 11250 | 0.005 |
| RC-P31 | Threaded Connection | 50000 | 0.01 |
| RC-P31 | Threaded Connection | 16250 | 0.21 |

| | | | |
|---|---|---|---|
| RC-S7 | | | |
| RC-T1 | Flange | 25000 | 0.05 |
| RC-T1 | Flange | 24200 | 0.15 |
| RC-T1 | Flange | 50000 | 1.42 |
| RC-T1 | Flange | 50000 | 0.55 |
| RC-T1 | Flange | 50000 | 0.13 |
| RC-T1 | Flange | 50000 | 0.44 |
| RC-T1 | Flange | 24250 | 0.04 |
| RC-T1 | Flange | 50000 | 0.75 |
| RC-T1 | Flange | 50000 | 0.14 |
| RC-T1 | Flange | 50000 | 0.68 |
| RC-T1 | Flange | 12000 | 0.07 |
| RC-T1 | Flange | 29250 | 0.02 |
| RC-T1 | Seal | 50000 | 0.19 |
| RC-T1 | Seal | 49500 | 0.1 |
| RC-T2 | Seal | 12500 | 0.005 |
| RC-T2 | Threaded Connection | 8500 | 0.005 |
| RC-T2 | Threaded Connection | 4500 | 0.005 |
| RC-T2 | Threaded Connection | 8800 | 0.005 |
| RC-T3 | | | |
| RC-T4 | Threaded Connection | 50000 | 0.01 |
| RC-T4 | Threaded Connection | 50000 | 0.005 |
| RC-T4 | Threaded Connection | 50000 | 0.01 |
| RC-T4 | Threaded Connection | 50000 | 0.01 |
| RC-T4 | Threaded Connection | 50000 | 0.04 |
| RC-T4 | Threaded Connection | 50000 | 0.01 |
| RC-T4 | Threaded Connection | 50000 | 0.01 |
| RC-T5 | | | |

| | | | |
|---|---|---|---|
| RC-P32 | Threaded Connection | 18000 | 0.01 |
| RC-P32 | Threaded Connection | 50000 | 0.005 |
| RC-P32 | Threaded Connection | 49000 | 0.05 |
| RC-P33 | Valve | 50000 | 0.58 |
| RC-P34 | | | |
| RC-P35 | | | |
| RC-P36 | | | |
| RC-S1 | Valve | | 0.04 |
| RC-S2 | | | |
| RC-S3 | | | |
| RC-S4 | | | |

| | | | |
|---|---|---|---|
| RC-T6 | | | |
| RC-T7 | Threaded Connection | 50000 | 0.005 |
| RC-T7 | Threaded Connection | 50000 | 0.005 |
| RC-T7 | Threaded Connection | 50000 | 0.01 |
| RC-T7 | Threaded Connection | 34000 | 0.01 |
| RC-T7 | Threaded Connection | 50000 | 0.005 |
| RC-T7 | Threaded Connection | 50000 | 0.01 |
| RC-T7 | Threaded Connection | 29500 | 0.005 |
| RC-T7 | Threaded Connection | 43750 | 0.12 |
| RC-T7 | Valve | 29000 | 0.005 |
| RC-T8 | | | |

### Table C.1.6 – Centrifugal Compressors

| ID | Component | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|---|
| CC-P1 | | | |
| CC-P2 | Seal | 50000 | 0.02 |
| CC-P3 | | | |
| CC-P4 | Threaded Connection | 920 | 0.005 |
| CC-P4 | Threaded Connection | 900 | 0.005 |
| CC-S1 | Threaded Connection | | 0.08 |
| CC-S1 | Threaded Connection | | 0.11 |
| CC-S1 | Valve | | 0.03 |
| CC-S2 | Valve | | 0.04 |
| CC-S2 | Valve | | 0.05 |

| ID | Component | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|---|
| CC-S3 | Threaded Connection | | |
| CC-S3 | Valve | | 0.02 |
| CC-S3 | Valve | | 0.04 |
| CC-T1 | Flange | 1800 | 0.005 |
| CC-T1 | Flange | 2000 | 0.005 |
| CC-T1 | Flange | 3000 | 0.005 |
| CC-T1 | Flange | 3400 | 0.005 |
| CC-T1 | Seal | 50000 | 0.12 |
| CC-T2 | | | |

### Table C.1.7 – Rotary Compressors

| ID | Component | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|---|
| RO-P1 | | | |
| RO-P2 | | | |
| RO-P3 | | | |

| ID | Component | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|---|
| RO-P4 | | | |
| RO-P5 | | | |
| RO-P6 | | | |

### Table C.1.8 – Pneumatic Actuators

| ID | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|
| PA-P1 | | |
| PA-P2 | | |
| PA-P3 | | |
| PA-P4 | | |
| PA-P5 | | |
| PA-P6 | | |
| PA-P7 | | |
| PA-P8 | | |
| PA-P9 | | |
| PA-P10 | | |
| PA-P11 | | |
| PA-P12 | | |
| PA-P13 | | |
| PA-P14 | | |
| PA-P15 | | |
| PA-P16 | | |
| PA-P17 | | |
| PA-P52 | | |
| PA-P53 | | |
| PA-P54 | | |
| PA-P55 | 50000 | 0.31 |
| PA-P56 | 50000 | 0.3 |
| PA-P57 | | |
| PA-P58 | 50000 | 0.005 |
| PA-P59 | 40000 | 0.04 |
| PA-P60 | 1500 | 0.005 |
| PA-P61 | | |
| PA-P62 | | |
| PA-P63 | 50000 | 0.05 |
| PA-P64 | 4050 | 0.005 |
| PA-P65 | | |
| PA-P66 | | |
| PA-P67 | | |
| PA-P68 | 50000 | 0.22 |
| PA-P69 | | |
| PA-P70 | | |
| PA-P71 | | |
| PA-P72 | | |
| PA-P73 | | |

| ID | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|
| PA-P18 | | |
| PA-P19 | | |
| PA-P20 | | |
| PA-P21 | | |
| PA-P22 | | |
| PA-P23 | | |
| PA-P24 | | |
| PA-P25 | 50000 | 0.47 |
| PA-P26 | 50000 | 0.9 |
| PA-P27 | 25000 | 0.05 |
| PA-P28 | 50000 | 0.21 |
| PA-P29 | 8250 | 0.19 |
| PA-P30 | 50000 | 0.25 |
| PA-P31 | 29950 | 0.01 |
| PA-P32 | 50000 | 0.28 |
| PA-P33 | 50000 | 0.95 |
| PA-P34 | 50000 | 0.4 |
| PA-P95 | | |
| PA-P96 | | |
| PA-P97 | | |
| PA-P98 | | |
| PA-P99 | | |
| PA-P100 | | |
| PA-P101 | | |
| PA-P102 | | |
| PA-P103 | | |
| PA-P104 | | |
| PA-P105 | | |
| PA-P106 | | |
| PA-P107 | | |
| PA-P108 | | |
| PA-P109 | | |
| PA-P110 | | |
| PA-P111 | | |
| PA-P112 | | |
| PA-P113 | | |
| PA-P114 | | |
| PA-P115 | | |
| PA-S1 | | |

| ID | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|
| PA-P35 | 50000 | 0.33 |
| PA-P36 | 50000 | 0.31 |
| PA-P37 | 50000 | 0.24 |
| PA-P38 | 24000 | 0.02 |
| PA-P39 | 22000 | 0.005 |
| PA-P40 | 50000 | 0.04 |
| PA-P41 | 50000 | 0.01 |
| PA-P42 | 50000 | 0.27 |
| PA-P43 | 50000 | 0.29 |
| PA-P44 | 50000 | 0.31 |
| PA-P45 | | |
| PA-P46 | | |
| PA-P47 | | |
| PA-P48 | | |
| PA-P49 | | |
| PA-P50 | | |
| PA-P51 | | |
| PA-S23 | | |
| PA-S24 | | |
| PA-S25 | | |
| PA-S26 | | |
| PA-S27 | | |
| PA-S28 | | |
| PA-S29 | | |
| PA-S30 | | |
| PA-S31 | | |
| PA-S32 | | |
| PA-S33 | | |
| PA-S34 | 26250 | 0.005 |
| PA-S35 | | |
| PA-S36 | 50000 | 0.005 |
| PA-S37 | | |
| PA-S38 | | |
| PA-S39 | | |
| PA-S40 | | |
| PA-S41 | | |
| PA-S42 | | |
| PA-S43 | | |
| PA-S44 | | |

| | | |
|---|---|---|
| PA-P74 | | |
| PA-P75 | 14000 | 0.11 |
| PA-P76 | | |
| PA-P77 | | |
| PA-P78 | 32000 | 0.02 |
| PA-P79 | | |
| PA-P80 | | |
| PA-P81 | 8200 | 0.41 |
| PA-P82 | 50000 | 0.07 |
| PA-P83 | 35000 | 0.17 |
| PA-P84 | | |
| PA-P85 | 6950 | 0.2 |
| PA-P86 | 7600 | 0.12 |
| PA-P87 | | |
| PA-P88 | | |
| PA-P89 | | |
| PA-P90 | 50000 | 0.4 |
| PA-P91 | | |
| PA-P92 | | |
| PA-P93 | 50000 | 0.41 |
| PA-P94 | | |
| PA-D1 | | |
| PA-D2 | | |
| PA-D3 | | |
| PA-D4 | | |
| PA-D5 | | |
| PA-D6 | | |

| | | |
|---|---|---|
| PA-S2 | | |
| PA-S3 | | |
| PA-S4 | | |
| PA-S5 | | |
| PA-S6 | | |
| PA-S7 | | |
| PA-S8 | | |
| PA-S9 | | |
| PA-S10 | | |
| PA-S11 | | |
| PA-S12 | | |
| PA-S13 | | |
| PA-S14 | | |
| PA-S15 | | |
| PA-S16 | | |
| PA-S17 | | |
| PA-S18 | | |
| PA-S19 | | |
| PA-S20 | | |
| PA-S21 | | |
| PA-S22 | | |
| PA-D7 | | |
| PA-D8 | | |
| PA-D9 | | |
| PA-D10 | | |
| PA-D11 | | |
| PA-D12 | | |

| | | |
|---|---|---|
| PA-S45 | | |
| PA-S46 | | |
| PA-S47 | | |
| PA-S48 | | |
| PA-S49 | | |
| PA-S50 | | |
| PA-S51 | | |
| PA-S52 | 14000 | 0.02 |
| PA-T1 | | |
| PA-T2 | | |
| PA-T3 | | |
| PA-T4 | 50000 | 0.01 |
| PA-T5 | | |
| PA-T6 | | |
| PA-T7 | | |
| PA-T8 | | |
| PA-T9 | | |
| PA-T10 | | |
| PA-T11 | | |
| PA-T12 | | |
| PA-T13 | 50000 | 0.01 |
| PA-D13 | | |
| PA-D14 | | |
| PA-D15 | | |
| PA-D16 | | |
| | | |
| | | |

### Table C.1.9 – Pneumatic Valves

| ID | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|
| PV-P1 | | |
| PV-P2 | | |
| PV-P3 | | |
| PV-P4 | | |
| PV-P5 | | |
| PV-P6 | | |
| PV-P7 | | |
| PV-P8 | | |
| PV-P9 | | |
| PV-P10 | | |

| ID | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|
| PV-P34 | 50000 | 0.18 |
| PV-P35 | 50000 | 0.28 |
| PV-P36 | 21000 | 0.32 |
| PV-P37 | 50000 | 0.15 |
| PV-P38 | 50000 | 0.09 |
| PV-P39 | 50000 | 0.16 |
| PV-P40 | 50000 | 0.35 |
| PV-P41 | 50000 | 0.23 |
| PV-P42 | 35000 | 0.24 |
| PV-P43 | 50000 | 0.18 |

| ID | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|
| PV-P67 | | |
| PV-P68 | | |
| PV-P69 | | |
| PV-P70 | | |
| PV-P71 | 50000 | 0.15 |
| PV-P72 | | |
| PV-P73 | | |
| PV-P74 | | |
| PV-P75 | | |
| PV-P76 | | |

| | | |
|---|---|---|
| PV-P11 | | |
| PV-P12 | | |
| PV-P13 | | |
| PV-P14 | | |
| PV-P15 | | |
| PV-P16 | | |
| PV-P17 | | |
| PV-P18 | | |
| PV-P19 | | |
| PV-P20 | | |
| PV-P21 | | |
| PV-P22 | 12000 | 0.2 |
| PV-P23 | 18000 | 0.01 |
| PV-P24 | 50000 | 0.3 |
| PV-P25 | 50000 | 0.2 |
| PV-P26 | 50000 | 0.31 |
| PV-P27 | 50000 | 0.24 |
| PV-P28 | 50000 | 0.14 |
| PV-P29 | 50000 | 0.26 |
| PV-P30 | 50000 | 0.27 |
| PV-P31 | 22050 | 0.01 |
| PV-P32 | 50000 | 0.17 |
| PV-P33 | 50000 | 0.22 |
| PV-P100 | | |
| PV-P101 | | |
| PV-P102 | | |
| PV-P103 | 50000 | 0.01 |
| PV-P104 | | |
| PV-P105 | | |
| PV-P106 | 50000 | 0.3 |
| PV-P107 | | |
| PV-P108 | 50000 | 0.3 |
| PV-P109 | | |
| PV-P110 | 50000 | 0.33 |
| PV-P111 | | |
| PV-P112 | 50000 | 0.53 |
| PV-P113 | | |
| PV-P114 | | |
| PV-P115 | 45250 | 0.04 |
| PV-P116 | | |
| PV-P117 | | |

| | | |
|---|---|---|
| PV-P44 | 50000 | 0.03 |
| PV-P45 | 25500 | 0.005 |
| PV-P46 | 50000 | 0.25 |
| PV-P47 | 5000 | 0.24 |
| PV-P48 | 34500 | 0.06 |
| PV-P49 | 50000 | 0.26 |
| PV-P50 | 28750 | 0.22 |
| PV-P51 | | |
| PV-P52 | | |
| PV-P53 | | |
| PV-P54 | | |
| PV-P55 | | |
| PV-P56 | | |
| PV-P57 | | |
| PV-P58 | | |
| PV-P59 | | |
| PV-P60 | 50000 | 0.005 |
| PV-P61 | 50000 | 0.02 |
| PV-P62 | | |
| PV-P63 | | |
| PV-P64 | | |
| PV-P65 | 40000 | 0.17 |
| PV-P66 | | |
| PV-P127 | 24000 | 0.12 |
| PV-P128 | | |
| PV-P129 | | |
| PV-P130 | 50000 | 0.01 |
| PV-P131 | | |
| PV-P132 | 19000 | 0.14 |
| PV-P133 | 50000 | 0.84 |
| PV-P134 | | |
| PV-P135 | | |
| PV-P136 | 50000 | 0.07 |
| PV-P137 | 3600 | 0.005 |
| PV-P138 | 50000 | 0.005 |
| PV-P139 | 15000 | 1.64 |
| PV-P140 | | |
| PV-P141 | | |
| PV-P142 | 50000 | 0.005 |
| PV-P143 | | |
| PV-P144 | | |

| | | |
|---|---|---|
| PV-P77 | | |
| PV-P78 | | |
| PV-P79 | | |
| PV-P80 | | |
| PV-P81 | | |
| PV-P82 | 50000 | 0.22 |
| PV-P83 | | |
| PV-P84 | | |
| PV-P85 | | |
| PV-P86 | 50000 | 0.02 |
| PV-P87 | | |
| PV-P88 | 50000 | 0.15 |
| PV-P89 | | |
| PV-P90 | | |
| PV-P91 | 17000 | 0.03 |
| PV-P92 | 50000 | 0.31 |
| PV-P93 | | |
| PV-P94 | | |
| PV-P95 | | |
| PV-P96 | | |
| PV-P97 | | |
| PV-P98 | | |
| PV-P99 | | |
| PV-P154 | | |
| PV-P155 | | |
| PV-P156 | | |
| PV-P157 | | |
| PV-P158 | | |
| PV-P159 | | |
| PV-P160 | | |
| PV-P161 | | |
| PV-P162 | | |
| PV-P163 | | |
| PV-P164 | | |
| PV-P165 | | |
| PV-P166 | | |
| PV-P167 | | |
| PV-P168 | | |
| PV-P169 | | |
| PV-P170 | | |
| PV-P171 | | |

| | | |
|---|---|---|
| PV-P118 | | |
| PV-P119 | | |
| PV-P120 | 46000 | 0.22 |
| PV-P121 | | |
| PV-P122 | 50000 | 0.18 |
| PV-P123 | | |
| PV-P124 | | |
| PV-P125 | | |
| PV-P126 | | |

| | | |
|---|---|---|
| PV-P145 | | |
| PV-P146 | | |
| PV-P147 | | |
| PV-P148 | | |
| PV-P149 | | |
| PV-P150 | | |
| PV-P151 | | |
| PV-P152 | | |
| PV-P153 | | |

| | | |
|---|---|---|
| PV-P172 | | |
| PV-P173 | | |
| PV-P174 | | |
| PV-P175 | | |
| PV-P176 | | |
| PV-P177 | | |
| PV-S1 | | |

### Table C.1.10 – M&R Stations

| ID | Component | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|---|
| MR-T1 | | | |
| MR-T2 | | | |
| MR-T3 | | | |
| MR-D1 | Flange | 4000 | 0.005 |
| MR-D2 | | | |
| MR-D3 | | | |
| MR-D4 | | | |
| MR-D5 | | | |
| MR-D6 | | | |

| ID | Component | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|---|
| MR-D7 | Flange | 1500 | 0.005 |
| MR-D8 | Manual Valve | 500 | 0.005 |
| MR-D9 | | | |
| MR-D10 | | | |
| MR-D11 | | | |
| MR-D12 | | | |
| MR-D13 | | | |
| MR-D14 | | | |
| MR-D15 | | | |

### Table C.1.11 – Hatches

| ID | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|
| HT-P1 | | |
| HT-P2 | | |
| HT-P3 | | |
| HT-P4 | | |
| HT-P5 | | |
| HT-P6 | | |
| HT-P7 | | |
| HT-P8 | 50000 | 3.18 |
| HT-P9 | 3000 | 0.005 |
| HT-P10 | | |
| HT-P11 | | |
| HT-P12 | | |

| ID | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|
| HT-P13 | | |
| HT-P14 | | |
| HT-P15 | | |
| HT-P16 | | |
| HT-P17 | 50000 | 0.34 |
| HT-P18 | 50000 | 0.35 |
| HT-P19 | | |
| HT-P20 | | |
| HT-P21 | | |
| HT-P22 | 50000 | 0.91 |
| HT-P23 | 6000 | 0.34 |
| HT-P24 | 4950 | 0.14 |

| ID | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|
| HT-P25 | | |
| HT-P26 | 1200 | 0.005 |
| HT-P27 | 1200 | 0.005 |
| HT-P28 | | |
| HT-P29 | | |
| HT-P30 | 2800 | 0.005 |
| HT-P31 | | |
| HT-P32 | | |
| HT-P33 | | |
| HT-P34 | | |

### Table C.1.12 – Pumps

| ID | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|
| PU-P1 | | |
| PU-P2 | | |

### Table C.1.13 – Customer Meters

| ID | Component | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|---|
| CM-T1 | | | |
| CM-T2 | | | |
| CM-D1 | | | |
| CM-D2 | | | |
| CM-D3 | | | |
| CM-D4 | | | |

| ID | Component | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|---|
| CM-D5 | | | |
| CM-D6 | | | |
| CM-D7 | | | |
| CM-D8 | | | |
| CM-D9 | Flange | 5100 | 0.005 |
| CM-D10 | Flange | 5750 | 0.005 |

### Table C.1.14 – Vents

| ID | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|
| VE1 | 50000 | 3.78 |
| VE2 | 50000 | 0.04 |
| VE3 | 50000 | 0.61 |
| VE4 | 50000 | 0.08 |
| VE5 | 50000 | 0.23 |
| VE6 | 50000 | 0.29 |
| VE7 | 50000 | 0.2 |
| VE8 | 50000 | 1.5 |
| VE9 | 50000 | 1 |
| VE10 | 50000 | 0.14 |
| VE11 | 50000 | 0.3 |

| ID | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|
| VE12 | 50000 | 0.37 |
| VE13 | 50000 | 0.005 |
| VE14 | 50000 | 2.51 |
| VE15 | 50000 | 0.37 |
| VE16 | 50000 | 5.41 |
| VE17 | 50000 | 1.28 |
| VE18 | 50000 | 1.28 |
| VE19 | 50000 | 1.85 |
| VE20 | 50000 | 1.26 |
| VE21 | 3200 | 0.03 |
| VE22 | 1750 | 0.1 |

## C.2: Correlation and Screening Values Data

The following tables give the data used in the ppmV and cfm correlations in Sections 5.2 and 5.3. This was a separate data set that was not limited by component counting, but was limited by readings where leaks were found with the screening device in ppmV, but not with the Hi-Flow in cfm.

### Table C.2.1 – Flanges

| SV (ppmV) | $CH_4$ (cfm) |
|---|---|
| 750 | 0.01 |
| 890 | 0.01 |

| SV (ppmV) | $CH_4$ (cfm) |
|---|---|
| 3,000 | 0.01 |
| 3,400 | 0.01 |

| SV (ppmV) | $CH_4$ (cfm) |
|---|---|
| 18,000 | 0.01 |
| 18,000 | 0.01 |

| SV (ppmV) | $CH_4$ (cfm) |
|---|---|
| 50,000 | 0.01 |
| 50,000 | 0.03 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1,000 | 0.01 | 4,000 | 0.01 | 24,250 | 0.04 | 50,000 | 0.05 |
| 1,100 | 0.01 | 4,050 | 0.01 | 25,000 | 0.05 | 50,000 | 0.06 |
| 1,100 | 0.01 | 4,500 | 0.01 | 27,000 | 0.01 | 50,000 | 0.11 |
| 1,300 | 0.01 | 6,100 | 0.04 | 27,000 | 0.07 | 50,000 | 0.14 |
| 1,400 | 0.01 | 6,350 | 0.21 | 29,250 | 0.02 | 50,000 | 0.14 |
| 1,450 | 0.01 | 8,350 | 0.01 | 31,000 | 0.04 | 50,000 | 0.19 |
| 1,500 | 0.01 | 10,500 | 0.03 | 36,750 | 0.08 | 50,000 | 0.29 |
| 1,800 | 0.01 | 11,250 | 0.01 | 37,000 | 0.03 | 50,000 | 0.44 |
| 2,000 | 0.01 | 12,000 | 0.07 | 49,500 | 0.10 | 50,000 | 0.58 |
| 2,150 | 0.01 | 14,000 | 0.12 | 50,000 | 0.01 | 50,000 | 0.68 |
| 2,700 | 0.01 | 16,000 | 0.01 | 50,000 | 0.01 | 50,000 | 0.75 |
| 3,000 | 0.01 | 16,250 | 0.21 | 50,000 | 0.01 | 50,000 | 0.01 |

### Table C.2.2 – Manual Valves

| SV (ppmV) | $CH_4$ (cfm) | SV (ppmV) | $CH_4$ (cfm) | SV (ppmV) | $CH_4$ (cfm) | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|---|---|---|---|---|
| 500 | 0.01 | 6,200 | 0.01 | 26,000 | 0.01 | 50,000 | 0.01 |
| 1,200 | 0.01 | 6,350 | 0.01 | 27,250 | 0.01 | 50,000 | 0.01 |
| 1,200 | 0.01 | 7,600 | 0.01 | 28,750 | 0.01 | 50,000 | 0.01 |
| 1,200 | 0.01 | 8,100 | 0.01 | 38,000 | 0.01 | 50,000 | 0.02 |
| 1,250 | 0.01 | 8,700 | 0.01 | 40,000 | 0.01 | 50,000 | 0.08 |
| 1,450 | 0.01 | 11,750 | 0.04 | 50,000 | 0.01 | 50,000 | 0.16 |
| 1,600 | 0.01 | 15,500 | 0.01 | 50,000 | 0.01 | 50,000 | 0.01 |
| 2,100 | 0.01 | 16,000 | 0.01 | 50,000 | 0.02 | 50,000 | 0.01 |
| 2,400 | 0.01 | 16,500 | 0.04 | 50,000 | 0.02 | 50,000 | 0.01 |
| 3,100 | 0.01 | 16,500 | 0.05 | 50,000 | 0.03 | 50,000 | 0.05 |
| 5,000 | 0.01 | 19,000 | 0.12 | 50,000 | 0.05 | | |
| 5,000 | 0.01 | 23,000 | 0.01 | 50,000 | 0.06 | | |
| 5,800 | 0.01 | 24,200 | 0.15 | 50,000 | 0.07 | | |

### Table C.2.3 – Open-Ended Lines

| SV (ppmV) | $CH_4$ (cfm) | SV (ppmV) | $CH_4$ (cfm) | SV (ppmV) | $CH_4$ (cfm) | SV (ppmV) | $CH_4$ (cfm) |
|---|---|---|---|---|---|---|---|
| 1,000 | 0.01 | 47,000 | 0.01 | 50,000 | 0.91 | 50,000 | 0.01 |
| 1,250 | 0.01 | 50,000 | 0.08 | 50,000 | 1.00 | 50,000 | 4.6 |
| 5,000 | 0.01 | 50,000 | 0.17 | 50,000 | 1.08 | 50,000 | 7.522 |
| 11,250 | 0.01 | 50,000 | 0.2 | 50,000 | 1.69 | 50,000 | 0.01 |
| 12,500 | 0.01 | 50,000 | 0.26 | 50,000 | 4.12 | 50,000 | 0.01 |
| 19,000 | 0.01 | 50,000 | 0.28 | 50,000 | 8.85 | | |
| 46,000 | 0.01 | 50,000 | 0.69 | 50,000 | 0.01 | | |

### Table C.2.4 – Pressure Relief Valves

| SV (ppmV) | $CH_4$ (cfm) |
|---|---|
| 1,000 | 0.01 |
| 5,250 | 0.01 |

| SV (ppmV) | $CH_4$ (cfm) |
|---|---|
| 5,400 | 0.01 |
| 36,750 | 0.04 |

| SV (ppmV) | $CH_4$ (cfm) |
|---|---|
| 50,000 | 0.06 |
| 50,000 | 0.12 |

### Table C.2.5 – Regulators

| SV (ppmV) | $CH_4$ (cfm) |
|---|---|
| 1,200 | 0.01 |
| 1,600 | 0.01 |
| 5,250 | 0.21 |
| 5,700 | 0.01 |

| SV (ppmV) | $CH_4$ (cfm) |
|---|---|
| 6,500 | 0.02 |
| 10,000 | 0.02 |
| 12,000 | 0.2 |
| 16,250 | 0.01 |

| SV (ppmV) | $CH_4$ (cfm) |
|---|---|
| 50,000 | 0.01 |
| 50,000 | 0.26 |
| 50,000 | 1.02 |
| 50,000 | 0.01 |

| SV (ppmV) | $CH_4$ (cfm) |
|---|---|
| 50,000 | 0.24 |

### Table C.2.6 – Seals

| SV (ppmV) | $CH_4$ (cfm) |
|---|---|
| 200 | 0.01 |
| 200 | 0.01 |
| 250 | 0.01 |
| 300 | 0.01 |
| 500 | 0.01 |
| 650 | 0.01 |
| 700 | 0.01 |
| 900 | 0.01 |
| 1,750 | 0.1 |
| 3,200 | 0.03 |
| 4,200 | 0.03 |
| 4,750 | 0.02 |
| 6,000 | 0.34 |
| 6,150 | 0.02 |
| 7,500 | 0.15 |
| 24,750 | 0.68 |

| SV (ppmV) | $CH_4$ (cfm) |
|---|---|
| 25,790 | 0.53 |
| 30,000 | 0.01 |
| 47,000 | 0.01 |
| 50,000 | 0.04 |
| 50,000 | 0.08 |
| 50,000 | 0.11 |
| 50,000 | 0.12 |
| 50,000 | 0.13 |
| 50,000 | 0.14 |
| 50,000 | 0.17 |
| 50,000 | 0.2 |
| 50,000 | 0.21 |
| 50,000 | 0.21 |
| 50,000 | 0.22 |
| 50,000 | 0.23 |
| 50,000 | 0.29 |

| SV (ppmV) | $CH_4$ (cfm) |
|---|---|
| 50,000 | 0.29 |
| 50,000 | 0.3 |
| 50,000 | 0.36 |
| 50,000 | 0.37 |
| 50,000 | 0.37 |
| 50,000 | 0.38 |
| 50,000 | 0.49 |
| 50,000 | 0.54 |
| 50,000 | 0.55 |
| 50,000 | 0.60 |
| 50,000 | 0.61 |
| 50,000 | 0.85 |
| 50,000 | 1.00 |
| 50,000 | 1.12 |
| 50,000 | 1.26 |
| 50,000 | 1.28 |

| SV (ppmV) | $CH_4$ (cfm) |
|---|---|
| 50,000 | 1.28 |
| 50,000 | 1.31 |
| 50,000 | 1.42 |
| 50,000 | 1.5 |
| 50,000 | 1.85 |
| 50,000 | 2.22 |
| 50,000 | 2.48 |
| 50,000 | 2.51 |
| 50,000 | 3.78 |
| 50,000 | 5.41 |
| 50,000 | 8.22 |
| 50,000 | 0.01 |
| 50,000 | 0.11 |

### Table C.2.7 – Threaded Connections

| SV (ppmV) | $CH_4$ (cfm) |
|---|---|
| 300 | 0.01 |
| 300 | 0.01 |
| 450 | 0.01 |
| 490 | 0.01 |
| 920 | 0.01 |

| SV (ppmV) | $CH_4$ (cfm) |
|---|---|
| 7,400 | 0.02 |
| 7,450 | 0.01 |
| 7,450 | 0.01 |
| 7,500 | 0.01 |
| 7,500 | 0.12 |

| SV (ppmV) | $CH_4$ (cfm) |
|---|---|
| 17,000 | 0.08 |
| 17,250 | 0.11 |
| 17,500 | 0.01 |
| 18,000 | 0.01 |
| 18,500 | 0.028 |

| SV (ppmV) | $CH_4$ (cfm) |
|---|---|
| 50,000 | 0.01 |
| 50,000 | 0.01 |
| 50,000 | 0.01 |
| 50,000 | 0.01 |
| 50,000 | 0.01 |

| | |
|---|---|
| 1,000 | 0.01 |
| 1,000 | 0.01 |
| 1,100 | 0.04 |
| 1,500 | 0.01 |
| 2,400 | 0.01 |
| 2,500 | 0.01 |
| 2,550 | 0.01 |
| 2,650 | 0.01 |
| 3,100 | 0.01 |
| 3,700 | 0.01 |
| 3,800 | 0.01 |
| 3,950 | 0.01 |
| 4,000 | 0.01 |
| 4,200 | 0.01 |
| 4,500 | 0.01 |
| 5,090 | 0.01 |
| 5,650 | 0.01 |
| 6,000 | 0.01 |
| 6,000 | 0.01 |
| 6,000 | 0.01 |
| 6,150 | 0.04 |
| 6,250 | 0.01 |
| 6,300 | 0.01 |
| 6,700 | 0.01 |
| 7,200 | 0.01 |
| 7,350 | 0.01 |

| | |
|---|---|
| 7,650 | 0.01 |
| 8,500 | 0.01 |
| 8,800 | 0.01 |
| 8,900 | 0.01 |
| 9,800 | 0.01 |
| 9,850 | 0.01 |
| 9,950 | 0.01 |
| 10,250 | 0.01 |
| 10,500 | 0.03 |
| 10,750 | 0.01 |
| 10,750 | 0.01 |
| 10,750 | 0.01 |
| 11,000 | 0.01 |
| 11,000 | 0.02 |
| 12,500 | 0.01 |
| 13,000 | 0.01 |
| 14,000 | 0.02 |
| 14,000 | 0.02 |
| 14,000 | 0.11 |
| 14,500 | 0.01 |
| 15,000 | 0.01 |
| 15,000 | 0.31 |
| 15,000 | 0.01 |
| 15,750 | 0.03 |
| 16,075 | 0.02 |
| 17,000 | 0.06 |

| | |
|---|---|
| 19,500 | 0.01 |
| 25,500 | 0.01 |
| 28,000 | 0.01 |
| 29,000 | 0.01 |
| 29,500 | 0.01 |
| 31,250 | 0.01 |
| 33,000 | 0.02 |
| 33,000 | 0.01 |
| 34,000 | 0.01 |
| 35,750 | 0.01 |
| 40,000 | 0.01 |
| 41,250 | 0.01 |
| 43,750 | 0.12 |
| 44,750 | 0.01 |
| 47,000 | 0.1 |
| 48,000 | 0.08 |
| 49,000 | 0.05 |
| 50,000 | 0.01 |
| 50,000 | 0.01 |
| 50,000 | 0.01 |
| 50,000 | 0.01 |
| 50,000 | 0.01 |
| 50,000 | 0.01 |
| 50,000 | 0.01 |
| 50,000 | 0.01 |
| 50,000 | 0.01 |

| | |
|---|---|
| 50,000 | 0.01 |
| 50,000 | 0.02 |
| 50,000 | 0.02 |
| 50,000 | 0.03 |
| 50,000 | 0.03 |
| 50,000 | 0.04 |
| 50,000 | 0.04 |
| 50,000 | 0.04 |
| 50,000 | 0.04 |
| 50,000 | 0.04 |
| 50,000 | 0.08 |
| 50,000 | 0.13 |
| 50,000 | 0.32 |
| 50,000 | 0.43 |
| 50,000 | 0.01 |
| 50,000 | 0.01 |
| 50,000 | 0.01 |
| 50,000 | 0.01 |
| 50,000 | 0.01 |
| 50,000 | 0.01 |
| 50,000 | 0.01 |
| 50,000 | 0.1 |
| 50,000 | 0.11 |
| 50,000 | 0.01 |