Development of Methane Leak Correlations for Natural Gas Transmission and Storage Facilities

Final Report

Prepared for:

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RFP No. 20ISD002

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TRICORD Project #P2385

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95% CB	95% Confidence Band
95% PB	95% Probability Band
ANOVA	Analysis of Variance
ARB ID	Air Resources Board Identification Number
β0	y-intercept value of the regression equation
β1	slope value of the regression equation
CARB	California Air Resources Board
CF	Conversion Factor
cfm	Cubic Feet per Minute
CH_4	Methane
C_3H_8	Propane
DW Statistic	Durbin-Watson autocorrelation statistic
EPA	U.S. Environmental Protection Agency
EPA STP	EPA Standard Temperature & Pressure (25°C at 1 atmosphere)
°F	Degrees Fahrenheit
F-test	A statistical test used in the ANOVA analysis that uses the Fisher–Snedecor distribution to test the significance of the LRM model
FID	Flame Ionization Detector
ft	Feet
g/hr	Grams per Hour
HF	High Flow Sampler®
ID	Identification
inchHg	Inches of Mercury
IR	Infrared
JPEG	Joint Photographic Experts Group
K	Degrees Kelvin
kg/hr	Kilograms per Hour
l/min	Liters per minute
lbs/in^2	Pound per square inch
LDAR	Leak Detection and Repair
LLC	Limited Liability Company
LRM	Linear Regression Model – used to determine the coefficients used in the correlations
MCF	Million Cubic Feet
mg/m^3	Milligrams per Cubic Meter
mph	Miles per Hour
MSE	Mean Squared Error
NUC	Non-Uniformity Correction
°C	Degrees Celsius
OEL	Open-Ended Line
OGI	Optical Gas Imaging
pdf	Portable Document Format
PG&E	Pacific Gas and Electric
Phx 42	LDAR Tools hydrocarbon analyzer
ppmv	parts per million volume
psi	pounds per square inch
QA/QC	Quality Assurance and Quality Control
°R	Degrees Rankin
R^2	Coefficient of Simple Determination
RH%	Percent Relative Humidity
SBCF	Scale Bias Correction Factor
SoCalGas	Southern California Gas
Protocol	*Protocol for Equipment Leak Emission Estimates* (EPA-453/R-95-017, November 1995)
t-test	A statistical test used in the ANOVA analysis using the Fisher–Snedecor distribution to test the null hypothesis that the LRM model y-intercept is not significant
TRICORD	TRICORD Consulting, LLC
TVA	Toxic Vapor Analyzer
TCS	Transmission Compressor Station
UGSF	Underground Natural Gas Storage Facility
USB	Universal serial bus
VOC	Volatile Organic Compound
W	Shapiro-Wilk normality statistic

SECTION 1: EXECUTIVE SUMMARY

Tricord Consulting LLC (TRICORD) has completed a methane (CH_4) emissions study for the California Air Resources Board (CARB). The study involved testing of process equipment at three (3) natural gas transmission (TCS) and three (3) natural gas underground storage facilities (UGSF) for the purpose of determining correlations between component leak concentrations (ppmv) and their emission rates (kg/hr). Test procedures followed guidelines detailed in the U.S. Environmental Protection Agency's (EPA) Protocol for Equipment Leak Emission Estimates[1]. The results of this study are summarized in the following three (3) tables and in Section 3.0 of this report.

Table 1-1 Natural Gas TCS & UGSF Screening Value (SV) Correlations

Equipment Type	**TCS & UGSF Leak Rate / Screening Value Correlations [2]** $\boldsymbol{Leak\ rate\ \left(\frac{kg}{hr}\right) = SBCF \times (10)^{\beta_0} \times (Screening\ value)^{\beta_1}}$ (B_0 = Y-intercept, B_1 = Slope)
Valves	Leak Rate (kg/hr) = 2.5281 x $10^{-5.6854}$ x Screening Value, ppmv $^{0.6435}$
Connectors	Leak Rate (kg/hr) = 7.7258 x $10^{-6.6505}$ x Screening Value, ppmv $^{0.8706}$
Flanges	Leak Rate (kg/hr) = 10.7019 x $10^{-6.6338}$ x Screening Value, ppmv $^{1.0525}$
OELs & Others[3]	Leak Rate (kg/hr) = 3.3817 x $10^{-5.6538}$x Screening Value, ppmv $^{0.6203}$

[1] Protocol for Equipment Leak Emission Estimates, EPA-453/R-95-017, November 1995.

[2] Due to limited available data, as discussed in the project results section below, TCS and UGSF data are combined for each component type.

[3] OELs & Other were combined to avoid a low R^2 value for the group of OELs alone.

Table 1-2 Natural Gas TCS & UGSF Pegged Values

Equipment Type	Pegged Screening Values Emission Rates (kg/hr)
Valves	7.315E-02
Connectors & Flanges	2.263E-02
OELs & Other	1.542E-01

Table 1-3 Natural Gas TCS & UGSF Default Zero Values

Equipment Type	Default-Zero Emission Rates (kg/hr)
Valves	2.441E-05
Connectors & Flanges	9.131E-06
OELs & Other	2.068E-05

This report is organized into four (4) sections and has two (2) appendices:

- Section 1.0 — Executive Summary;
- Section 2.0 — Project Methodology;
- Section 3.0 — Project Results;
- Section 4.0 — Project Quality Control (QC);
- Appendix A — Calibration Data; *and*
- Appendix B — Cylinder Gas Certifications.

Three (3) supporting Excel® workbooks accompany this report:

- *CARB PROJECT RFP No 20ISD002 FIELD TEST DATA WORKBOOK*;
- *CARB PROJECT RFP No 20ISD002 CORRELATION, DEFAULT ZERO & PEGGED VALUES WORKBOOK; and*
- *CARB PROJECT RFP No 20ISD002 STATISTICS WORKBOOK.*

SECTION 2: PROJECT METHODOLOGY

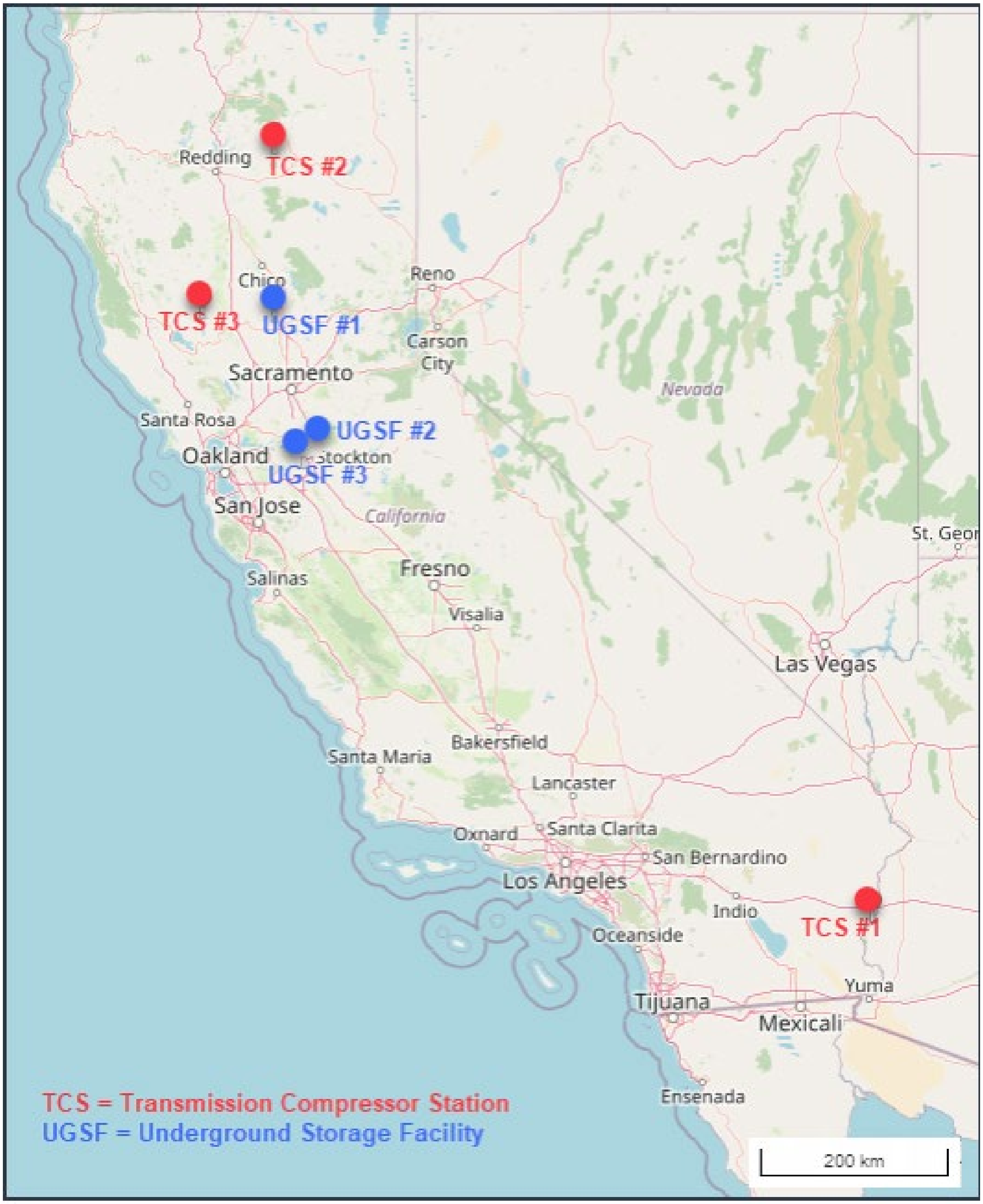
2.1 PROJECT PURPOSE

This project was conducted by TRICORD Consulting, LLC (TRICORD) for the California Air Resources Board (CARB) under contract number 20ISD002. The project's scope of work included:

- The development of a project test plan;
- Conducting leak detection surveys at three (3) natural gas transmission compressor stations (TCS) and three (3) underground natural gas storage facilities (UGSF);
- Measuring emission rates from selected leaking components;
- The development of emission rate correlation equations using methane (CH_4) screening concentrations in parts per million volume (ppmv) to estimate CH_4 mass emission rates in kilograms per hour (kg/hr); for four (4) component groups;
- Developing pegged CH_4 average emission rates for screening values greater than 100,000 ppmv for three (3) component groups;
- Developing average default zero CH_4 emission rates for screening values of zero ppmv for three (3) component groups; *and*
- The documenting of results in this report.

Following review by CARB and the participating stakeholders, TRICORD's project test plan and data report format were accepted by CARB on December 10, 2021. Field tests for the development of emission correlation equations and pegged emission factors began on January 18, 2022 and were completed on April 8, 2022. Field tests for the development of default zero emission factors were completed on July 14 and 15, 2022. Figure 2-1 indicates the locations of the three (3) TCS (in red) and the three (3) UGSF (in blue) natural gas facilities where testing was conducted.

Figure 2-1 Natural Gas Test Facility Locations



At the start of a test facility visit, TRICORD met with site operators to collect or confirm site characterization information including:

- Site owner;
- Site name;
- Site address;
- Site startup date;
- Site throughput (MCF/Day);
- Number of site wells; *and*
- Number of site compressors.

Following equipment check-outs and calibrations, leak surveys were conducted at the host facilities using both an infrared (IR) camera and a portable hydrocarbon analyzer. The TRICORD field team consisted of two individuals, both experienced in the use of the IR Camera and the hydrocarbon analyzer and the Hi Flow® Sampler.

A FLIR GF320® IR camera operated in grey-scale / enhanced mode, was used to survey areas for large leaks. Detected IR leaks were photo and video recorded. A Thermo Scientific Toxic Vapor Analyzer[4],(TVA) Model 2020 equipped with a flame ionization detector (FID) was used to detect smaller leaks within the same areas. The TVA provides a linear response up to 50,000 ppmv. For leaks above 50,000 ppmv, a diluter kit can be used to extend the TVA's linear measurement range. To avoid fatigue, approximately every thirty (30) minutes the IR camera and the analyzer operators would switch places.

A test matrix, defined in the project Test Plan, and reproduced in Table 2-1, directed the selection of components for testing. The test matrix consisted of five (5) concentration ranges for five (5) component types resulting in an array of twenty-five (25) component/concentration-range bins.

[4] A few leak surveys were conducted using an LDAR Tools PHx 42 analyzer.

A minimum of four (4) emissions tests per component type and concentration range, or one hundred (100) total emissions tests, was targeted to support the development of the ppmv to kg/hr correlation equations.

Table 2-1 Test Matrix

Natural Gas Leak Concentration Ranges → Component Type ↓	>0<100 ppmv	100<1,000 ppmv	1,000<10,000 ppmv	10,000<100,000 ppmv	≥100,000 ppmv	TOTALS
Valves	4	4	4	4	4	20
Connectors	4	4	4	4	4	20
Flanges	4	4	4	4	4	20
OELs	4	4	4	4	4	20
Others	4	4	4	4	4	20
TOTALS	**20**	**20**	**20**	**20**	**20**	**100**

Components identified by the IR camera and analyzer surveys that potentially fit within the test matrix were temporary tagged for emissions measurements. All components having leak concentrations exceeding the facility's regulatory leak threshold were verified and scheduled for repair by the site's LDAR Contractor.

2.2 EMISSIONS MEASUREMENT

Mass emissions from leaking components identified in the area surveys were measured with an intrinsically-safe (Class 1, Division 1) Bacharach High Flow® Sampler operated in its Manual 1-Stage mode. The High Flow® Sampler, which is designed specifically for natural gas leak rate measurements, uses a sufficiently large flow rate (between 5 and 10.5 cubic feet per minute) to capture the entire emission plume. Natural gas concentrations are measured by two (2), built-in sensors: a catalytic oxidation sensor for concentrations between 0% and 5% by volume of CH_4, and a thermal conductivity sensor for concentrations above 5% by volume of CH_4. During an emission test, the High Flow Sampler® also measures the component's background concentration and automatically subtracts it from the measured leak concentration.

Each High Flow® Sampler test was conducted according to the following steps:

1. A pre-test TVA reading of a component's leak concentration was made just prior to its being tested;
2. The High Flow® Sampler was powered on and its sensors re-zeroed;
3. The component's leak area was enclosed but not completely isolated, using one of the High Flow® Sampler's capture devices;
4. The enclosure device was connected to the High Flow Sampler's sample hose;
5. Typically, the TVA was positioned at the High Flow® Sampler's output to obtain a CH_4 concentration since the High Flow® Sampler's controller only displays percent concentrations and not ppmv values; if the concentration was in the percent range, then the TVA was not used, and the emission reading was taken directly from the High Flow® Sampler's controller readout;
6. Sampling continued until flow and concentration readings stabilized (typically within one (1) minute);
7. The following test data was recorded on a portable data logger (Mesa 2®):
    a. Line pressure (psig);
    b. Line temperature (^oF);
    c. Ambient barometric pressure (inHg);
    d. Ambient temperature (^oF);
    e. Sample flow rate (cfm);
    f. Background reading (CH_4 % volume);

   g. Leak reading (CH_4 % volume); *and*
   h. Leak flow rate (cfm);
8. The High Flow® Sampler was powered off, and the enclosure device removed from the component;
9. A second post-test TVA reading of the component’s leak concentration was made to verify that the leak concentration had remained stable during the emission’s test; *and*
10. The facility was notified that testing of the component had been completed, so that repairs could be scheduled, if applicable.

2.3 DATA RECORDING

An intrinsically-safe (Class 1, Division 2 certified) Juniper Systems Mesa 2® tablet was used to collect and store the site characterization details and High Flow® Sampler test data.

Field data collected on the Mesa 2® tablet was stored as an Excel® file on a removable USB drive for subsequent downloading to the project computer. Once on the project computer, the field data was automatically backed up in TRICORD’s Dropbox® account. All components tested with the High Flow® Sampler were photographed and named with the test ID number. Both IR video (MP4) and photographs (jpegs) were captured for leaks identified by the IR Camera.

Equipment Quality Check (QC) results were recorded on pre-formatted Excel® spreadsheets and ultimately saved in TRICORD’s Dropbox® account together with copies of cylinder gas certification analyses.

2.4 SUPPORT EQUIPMENT

In addition to the High Flow® Sampler, the TVA Analyzer and the Mesa2® tablet, the following support equipment was used during the field testing:

- A cylinder of commercial-grade propane gas for the IR Camera Daily Demonstration (Daily Demo) along with a gas regulator, a flow control valve and a rotameter for flow measurement;
- A laser distance finder for measurement of the IR Camera sighting distance;
- A Kestrel® hand-held weather meter for measurement of weather conditions (i.e., temperature, atmospheric pressure, wind speed, and humidity);

- Various emission capture devices (i.e., flange straps, beveled nozzle tool, capture bag, bellows tool, crevice tool, and plastic wrapping) provided with the High Flow® Sampler;
- Lecture-sized gas cylinders of 2.5% CH_4 and 100% CH_4 fitted with demand flow regulators for calibration and calibration verification of the High Flow® Sampler;
- A hot-wire anemometer to verify the High Flow® Sampler's sample flow rate;
- A cylinder of zero-grade hydrogen gas for the operation of the portable, hydrocarbon analyzer's FID;
- Cylinder gases fitted with demand flow regulators of zero-air and four (4) upscale, methane-in-air span gases (nominal concentrations of 500 ppmv, 2,000 ppmv, 10,000 ppmv, and 2.5%) for hydrocarbon analyzer calibrations and drift checks,
- A rotameter for hydrocarbon analyzer flow checks; *and*
- A variable diluter kit for the TVA to measure pegged leak concentrations.

2.5 MASS EMISSION RATE CALCULATIONS

Mass emission rates are calculated from the High Flow Sampler® test results in units of kg/hr at EPA standard temperature and pressure conditions. This is accomplished by Equations 2.1, 2.2 and 2.3. Equation 2.1 uses two (2) conversion factors to convert the High Flow Sampler's® percent leak to a mass emission.

Equation 2.1. Conversion of Leak % to mg/m^3

$$C_{std} = Leak\% \times \frac{10{,}000\ ppmv}{1\%} \times \frac{16.04}{24.45} \times \frac{\frac{mg}{m^3}}{ppmv}$$

where:

Cstd	=	Leak concentration in mg/m^3 CH_4 at EPA Standard Temperature (298.15K)
Leak%	=	Leak concentration in percent
10,000 ppmv	=	1%
16.04/24.45	=	Density of CH_4 at EPA Standard Temperature & Pressure -- 25^{o}C (298.15K) and 1 atm (29.92 inHg)
mg/m^3/ppmv	=	conversion of ppmv CH_4 to mg/m^3 CH_4 when multiplied by 16.04/24.45.

2.5.1 Converting Sample Flow Rate to EPA Standard Temperature & Pressure

The High Flow Sampler® reports sample flow rate in cubic feet per minute (cfm) at a standard temperature and pressure (STP) of 20°C and 1 atmosphere. Equation 2.2 is used to convert the High Flow® Sampler's sample flow rate to EPA STP of 25°C (298.15 Kelvin) and 1 atmosphere (29.92 inches of mercury).

Equation 2.2. Sample Flow Rate Converted to EPA STP

$$CFM_{std} = CFM_{act} \times \left(\frac{T_{std}}{T_{act}}\right)\left(\frac{P_{act}}{P_{std}}\right)$$

where:

CFM_{std}	=	Volumetric flow rate (cfm) at EPA standard conditions;
CFM_{act}	=	Actual %volumetric flow rate (cfm) as measured by the HF Sampler®
T_{std}	=	EPA Standard Temperature (298.15K)
T_{act}	=	Temperature at actual test conditions (K)
P_{act}	=	Barometric pressure at actual test conditions (inchHg); *and*
P_{std}	=	Barometric pressure at standard conditions (29.92 inchHg).

2.5.2 Calculating Standardized Mass Emission Rate (kg/hr)

Equation 2.3 combines the results of Equations 2.1 and 2.2 to calculate a mass emission rate in kg/hr at EPA STP.

Equation 2.3 Mass Emission Rate at EPA STP

$$ER_{std} = C_{std} \times CFM_{std} \times \frac{CF}{2.205}$$

where:

ER_{std}	=	Emission rate of CH_4 (kg/hr) at EPA STP;
C_{std}	=	CH_4 concentration (mg/m^3) from Equation 2.1;
CFM_{std}	=	Standardized volumetric flow rate (cfm) from Equation 3.2;
CF	=	Conversion factor 3.75E-06, = [(1m^3/35.3147 ft^3) x 60 min/hr x (1 lb/453592.37 mg)];
2.205	=	pounds per kilogram conversion factor.

2.6 CORRELATION DEVELOPMENT

The development of component-specific correlation equations for natural gas CTS and USF facilities followed the procedures described in Appendix B of the *Protocol.*[5]

The High Flow® Sampler results together with the calculations described in the previous section, produce mass emission rates which are paired with corresponding screening values. These mass emission rate/screening value data pairs were used to develop the natural gas TCS/UGSF component-specific correlations. Both data pairs were first converted into their $\log_{10}$ values. As explained in the Appendix B of the *Protocol*, "*It is necessary to perform the initial analysis in log space because the screening value and mass emission rate data typically span several orders of magnitude, and the data are not normally distributed in arithmetic space*[6]. "

The next step was to perform a linear regression in log space where the $\log_{10}$ of the mass emission rate (dependent variable Y) is regressed on the $\log_{10}$ of the screening value (independent variable X). The resulting regression line takes the form expressed in Equation 2.4:

Equation 2.4. Least Squares Regression in Log Space

$$\boldsymbol{Y_i = \beta_0 + \beta_1 x_i}$$

where:

Y_i = Logarithm (base 10) of the mass emission rate (kg/hr);
X_i = Logarithm (base 10) of the screening value (ppmv);
B_0 = Intercept of regression line; *and*
B_1 = Slope of regression line.

The slope (β_1) and intercept (β_0) values were calculated by Equations 2.5 and 2.6:

[5] Protocol for Equipment Leak Emission Estimates, Appendix B. EPA-453/R-95-017, November 1995.

[6] Ibid. Appendix B, page B-5.

Equation 2.5. Slope

$$\boldsymbol{\beta_1 = \frac{(\overline{XY}) - (\overline{X})(\overline{Y})}{\overline{X}^2 - (\overline{X})^2}}$$

Equation 2.6. Intercept

$$\boldsymbol{\beta_0 = \overline{Y} - \beta_1 \overline{X}}$$

where:

$\overline{X} = \frac{\sum X_i}{n}$
$\overline{Y} = \frac{\sum Y_i}{n}$
$\overline{XY} = \frac{\sum X_i Y_i}{n}$
$X^2 = \frac{\sum X_i^2}{n}$ *and*
n = number of screening/mass emission rate pairs.

Equation 2.7 was then used to calculate the mean squared error (MSE) of the data set to determine how closely on average the data points fit the regression line.

Equation 2.7. Mean Squared Error

$$\boldsymbol{MSE = \frac{1}{n-2} \sum_{i=1}^{n} r_i^{\,2}}$$

where:

n = number of screening/High Flow Sampler® pairs
$r_i = Y_i - \beta_0 - \beta_1 X_i$

The slope and intercept and a scale bias correction factor (SBCF) were used in the final step using Equation 2.8 to transform the regression equation from $\log_{10}$ space back to arithmetic space. This is the correlation equation:

Equation 2.8 Correlation Equation

$$\boldsymbol{Leak\ rate\ \left(\frac{kg}{hr}\right) = SBCF \times (10)^{\beta_0} \times (Screening\ value)^{\beta_1}}$$

The SBCF is a correction factor which accounts for the return from log10 space to arithmetic space. It is developed by summing a sufficient number (usually 10-15) of the terms from the infinite series expressed below in Equation 2.9:

Equation 2.9. Scale Bias Correction Factor

$$\boldsymbol{SBCF = 1 + \frac{(m-1) \times T}{m} + \frac{(m-1)^3 \times T^2}{m^2 \times 2! \times (m+1)} + \frac{(m-1)^5 \times T^3}{m^3 \times 3! \times (m+1) \times (m+3)} + \cdots}$$

where:

T	=	(MSE/2) x ((In10)^2);
MSE	=	mean square error from the regression;
In10	=	natural logarithm of 10; *and*
m	=	number of data pairs (n) – 1.

2.7 PEGGED EMISSION RATES

A pegged value is a screening result greater than 100,000 ppmv. Pegged emissions rates were developed for three (3) component groups: Valves, Connectors & Flanges, and OELs & Others. Connectors & Flanges were grouped as were OELs & Others due to an insufficient number of screening value and leak rate measurement pairs.

The first step in determining a pegged emission rate was to take the $\log_{10}$ of each of the resulting pegged mass emission rates for each component type, and then to calculate their average pegged $\log_{10}$ leak rate. The average $\log_{10}$ leak rates, variance, and scale bias correction factors were then calculated for use in Equation 2.10 to calculate the pegged leak rate.

Equation 2.10 Pegged Leak Rates

$$Pegged\ Leak\ Rate\ (kg/hr) = SBCF \times 10^{LOG:AVG}$$

where:

SBCF = Scale bias correction factor for the logs of the mass emission rates *and*
LOG:AVG = Average of the logs of the mass emission rates.

The SBCF for the pegged leak rate was determined using the same equation for the SBCF as discussed in Section 2.6, with the following two (2) exceptions:

1. The variance of the log mass emission rates was used in the "T" term, rather than the regression mean square error (MSE); *and*
2. The sample size (n) was used in the "m" term, rather than "n-1".

The variance (s^2) of the component log mass emission rates was calculated by Equation 2.11 as:

Equation 2.11 Variance of the Pegged Log$_{10}$ Mass Emission Rates

$$s^2 = \frac{1}{n-1}\sum_{i=1}^{n}(LOG{:}LEAK_i - LOG{:}AVG)^2$$

where:

LOG:LEAKi = Logarithm of leak rate from component i;
LOG:AVG = Average of the logs of the mass emission rates; and
n = Number of data points.

2.8 DEFAULT ZERO EMISSION RATES

Default zero emission rates were developed for valves, connectors, flanges, and others, that had background concentrations only. OELs were not included due to a lack of availability. The calculation procedure for developing the default zero emissions rates was the same as that used for the pegged emissions rates. Namely, mass emission rates were first calculated, converted to their log$_{10}$ values, and then the average default zero log$_{10}$ leak rates for each component type were derived. The average log$_{10}$ leak rate and a scale bias correction factor (SBCF), which accounts for the variance of the log$_{10}$ mass emission rates, were then used in Equation 2.12 to calculate the default zero leak rate for each component type:

Equation 2.12 Default Zero Leak Rates

$$Default\ Zero\ (kg/hr) = SBCF \times 10^{LOG:AVG}$$

where:

SBCF = Scale bias correction factor for the logs of the mass emission rates *and*
LOG:AVG = Average of the logs of the mass emission rates.

The SBCF for the default zero leak rate was determined using the same equation for the SBCF as discussed in Section 2.7, with the following two (2) exceptions:

1. The variance of the log mass emission rates is used in the “T” term, rather than the regression mean square error (MSE); *and*
2. The sample size (n) is used in the “m” term, rather than “n-1”.

The variance (s^2) of the component log mass emission rates was calculated using Equation 2.13:

Equation 2.13 Variance of the Default Zero Log_{10} Mass Emission Rates

$$s^2 = \frac{1}{n-1}\sum_{i=1}^{n}(LOG{:}LEAK_i - LOG{:}AVG)^2$$

where:

$LOG{:}LEAK_i$	=	Logarithm of leak rate from component i;
LOG:AVG	=	Average of the logs of the mass emission rates; *and*
n	=	Number of data points.

SECTION 3: PROJECT RESULTS

3.1 Completed Test Matrix

One hundred and fifty-seven (157) High Flow Sampler® tests were completed. Of these:

- One hundred and twenty-four (124) test results were used to develop the correlation equations;
- Nine (9) test results were used to develop pegged emission factors; *and*
- Twenty-four (24) test results were used to develop default zero emission factors.

Table 3-1 Completed Test Matrix – All Data

Component Type	Default Zero	Sample Set Counts by CH4 Screening Concentration Value Ranges, ppmv					Correlation Data Row Totals	# Pegged Screening Values > 100,000 ppmv	Grand Total
		>0 - <100	100 - <1,000	1,000 - <10,000	10,000 - <100,000	100,000 - 1,000,000			
Valve	6	6	10	7	5	4	31	1	157
Flange	6	6	6	7	2	3	24	0	
Connector	6	6	7	7	7	6	30	3	
Other	6	5	2	6	5	7	21	4	
OEL	0	6	3	6	2	2	18	1	
Column Totals	**24**	**29**	**28**	**33**	**21**	**22**	**124**	**9**	

Some TCS and UGSF data equipment type subsets did not have sufficient data to provide separate linear regression models. For this reason, as described below, the decision to merge the TCS & UGSF data subsets for each equipment type group was considered to be the most appropriate approach as appropriate.

The results of the field tests are documented in the accompanying Excel® workbook, *CARB PROJECT RFP No 20ISD002 FIELD TEST DATA WORKBOOK.*

3.2 Correlation Equation Results

Table 3-2 provides this study's component-specific correlation equations that predict CH_4 mass emissions rates from screening concentrations, excluding default zero and/or pegged results.

Table 3-2 TCF & UGSF Leak Rate / Screening Value Correlations

Component Type	Correlation $Leak\ rate\left(\frac{kg}{hr}\right) = SBCF \times (10)^{\beta_0} \times (Screening\ value)^{\beta_1}$
Valves	Leak Rate (kg/hr) = 2.5281 x $10^{-5.6854}$ x Screening Value, ppmv $^{0.6435}$
Connectors	Leak Rate (kg/hr) = 7.7258 x $10^{-6.6505}$ x Screening Value, ppmv $^{0.8706}$
Flanges	Leak Rate (kg/hr) = 10.7019 x $10^{-6.6338}$ x Screening Value, ppmv $^{1.0525}$
OELs & Others	Leak Rate (kg/hr) = 3.3817 x $10^{-5.6538}$x Screening Value, ppmv $^{0.6203}$

3.3 Results for Pegged Value Emission Factors

Emission factor results for component types with screening values >100,000 ppmv (i.e., pegged values) are provided in Table 3-3.

Table 3-3 TCF & UGSF Pegged Emission Rates

Component Type	# of Components	Pegged Emission Rate (kg/hr) = (SCBF x 10 (log10 (avg Pegged Emissions Rate, kg/hr)
Valves (using all data)	9	7.315E-02
Connectors + Flanges	3	2.263E-02
OELs + Other	5	1.542E-01

Because ANOVA test results showed that differences in variance between component groups were not significantly great, (see Section 3.5.2) the following groupings for pegged value calculations were made:

- Since there was only one (1) pegged valve, an SCBF could not be determined. Consequently, for valves, a pegged emission factor was calculated as the average of all pegged emission factors regardless of component type[7].

[7] The report figure and statistics 3rd workbook tab for Fig 3-7 show a box-whiskers plot and ANOVA test of the Log 10 emissions rate data by component group. No significant difference was found at the p = 0.05 level. Also, an inspection of Fig. 3-2 in the report and the 2nd workbook shows that the pegged values for all components plot are reasonably close to the valves' correlation line, well within the spread of the data across the line.

- There was only a single pegged value for OELs therefore the OEL and Other categories were combined to get a set of five (5) data points for calculation of a combined OELs + Other pegged emission factor.
- Connectors and Flanges were also combined since pegged data for flanges was not available.

Note that these groupings are further discussed in Section 3.5.2. The pegged values were located near the top of and close to the regression lines, with the exception of the Flanges, where they fell below the regression line, and for OELs & Other, where they were above the regression line.

3.4 Results for Default Zero Emission Factors

Table 3-4 provides the default zero emission factors.

Table 3-4 TCF & UGSF Default Zero Emission Rates

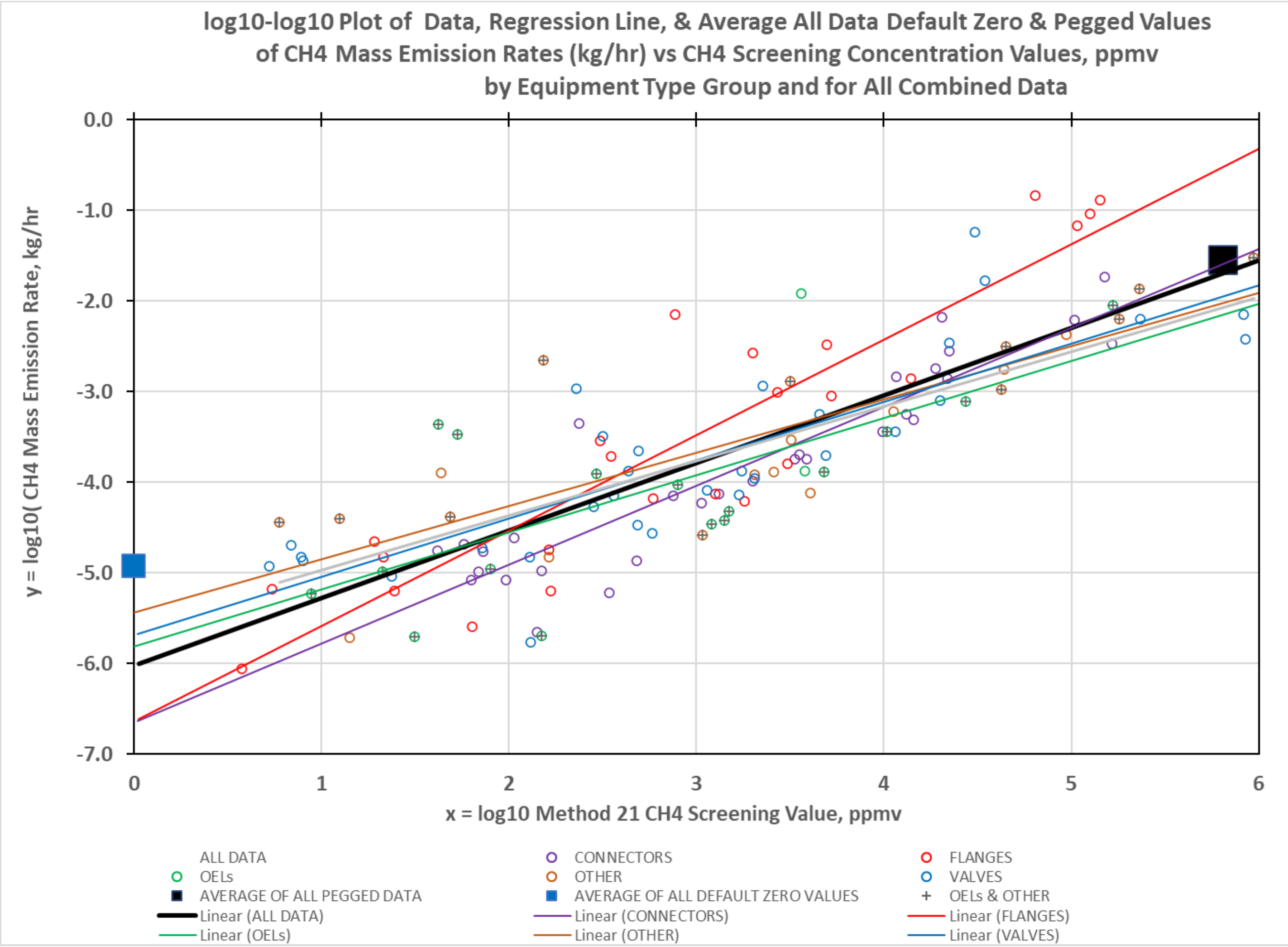
Component Type	# of Components	Default Zero Emission Rate (kg/hr) = (SCBF x 10 (avg log10 (Default Zero Emissions Rate, kg/hr)
Valves	6	2.441E-05
Connectors & Flanges	12	9.131E-06
OELs & Other	6	2.068E-05

Because ANOVA test results showed that differences in variance between component groups were not significantly great, the following groupings for default zero value calculations were made:

- Since no OELs were available to be tested for default zero emission factors, the groups OELs and Others were combined.
- Connectors and Flanges were also combined into a single default zero equipment group to provide a stronger R^2 factor.
- Valves were calculated using the available data for that component group.

Supporting details are documented in the accompanying Excel® workbook, *CARB PROJECT RFP No 20ISD002 CORRELATION, DEFAULT ZERO, & PEGGED VALUES WORKBOOK* & *CARB PROJECT RFP No 20ISD002 PROJECT STATISTICS WORKBOOK.* The following five (5) figures plot the linear regression equations and default zero and pegged value results in log_{10} space for (1) All components; (2) Valves; (3) Flanges; (4) Connectors; and (5) Other & OELs).

Figure 3-1 All Components: Log10 Regression Line, Default Zero & Pegged Data



All Types:	**y = 0.7456 x - 6.0204, R^2 = 0.69, N = 124**	**black**
Connectors:	**y = 0.8706x - 6.6505, R^2 = 0.8403, N = 30**	**purple**
Flanges:	**y = 1.0525x - 6.6338, R^2 = 0.8337, N = 24**	**red**
OELs:	**y = 0.6294x - 5.8075, R^2 = 0.4743, N = 18**	**green**
Other:	**y = 0.5887x - 5.4379, R^2 = 0.7003, N = 21**	**rust**
OELs & Other:	**y = 0.6203x - 5.6538, R^2 = 0.6138, N = 39**	**gray**
Valves:	**y = 0.6435x - 5.6854, R^2 = 0.6929, N = 31**	**blue**

Figure 3-2 Valves: Log10 Regression Line, Default Zero & Pegged Data

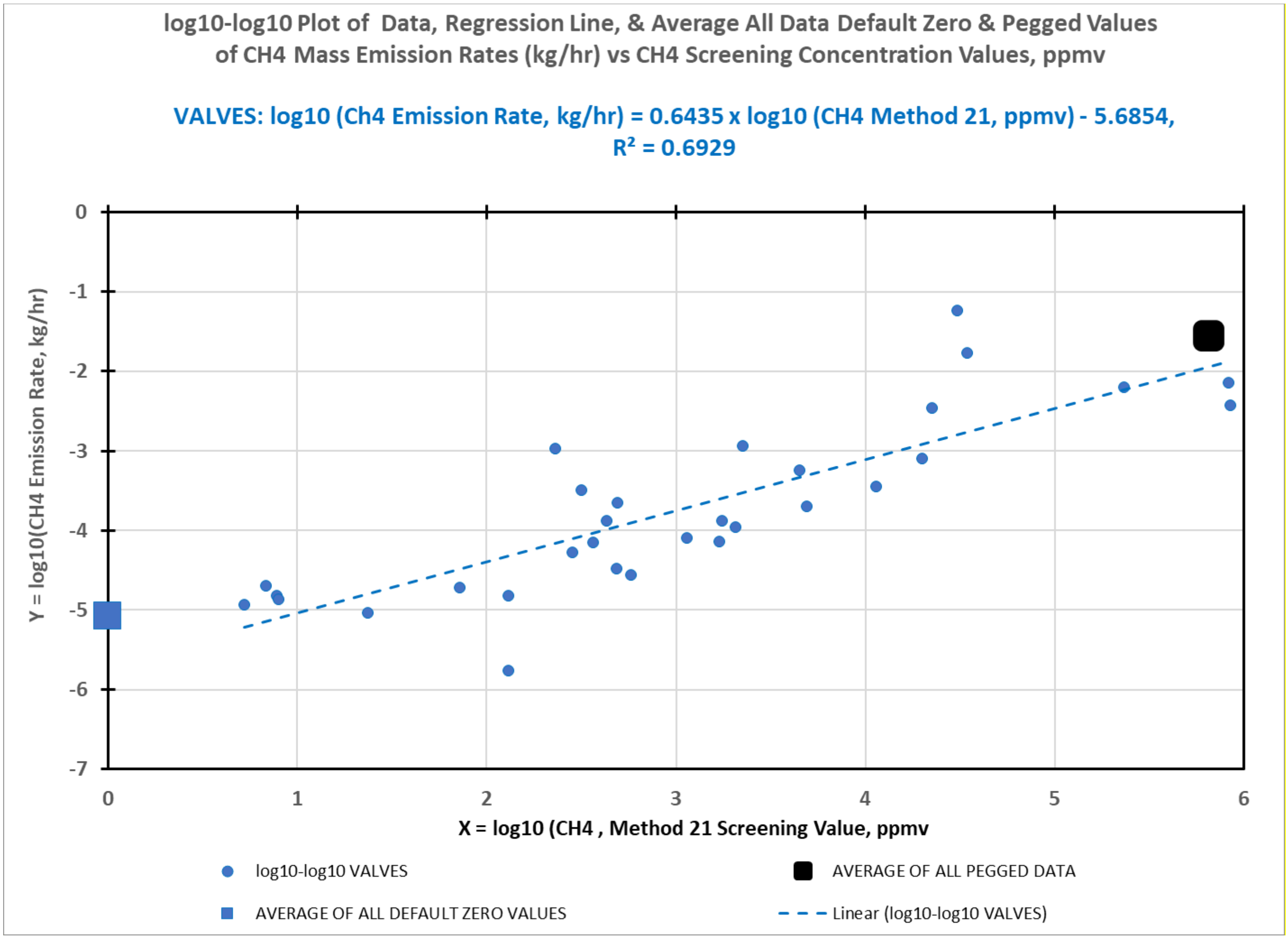


Figure 3-3: Connectors: Log10 Regression Line, Default Zero & Pegged Data

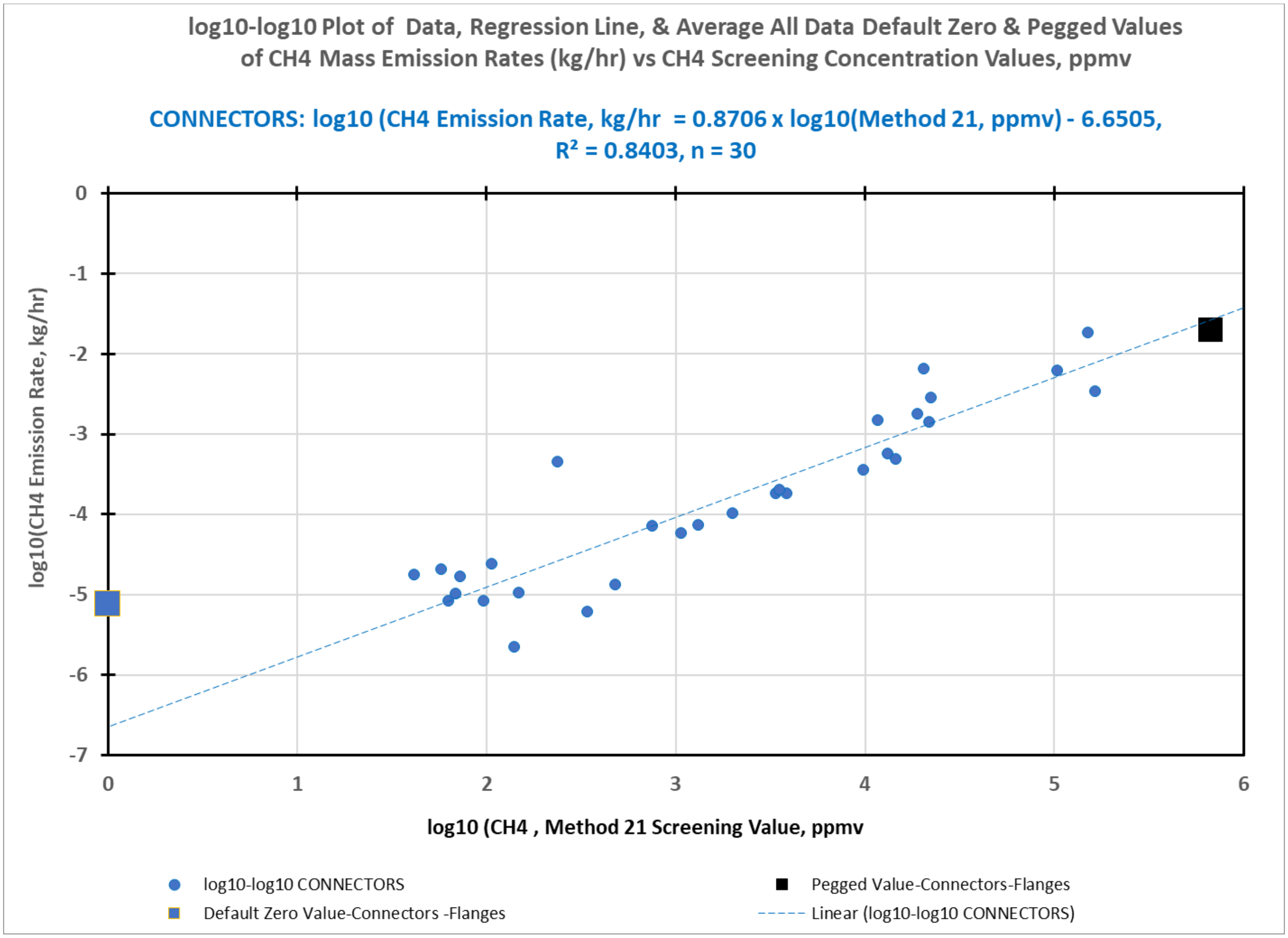


Figure 3-4: Flanges Log10 Regression Line, Default Zero & Pegged Data

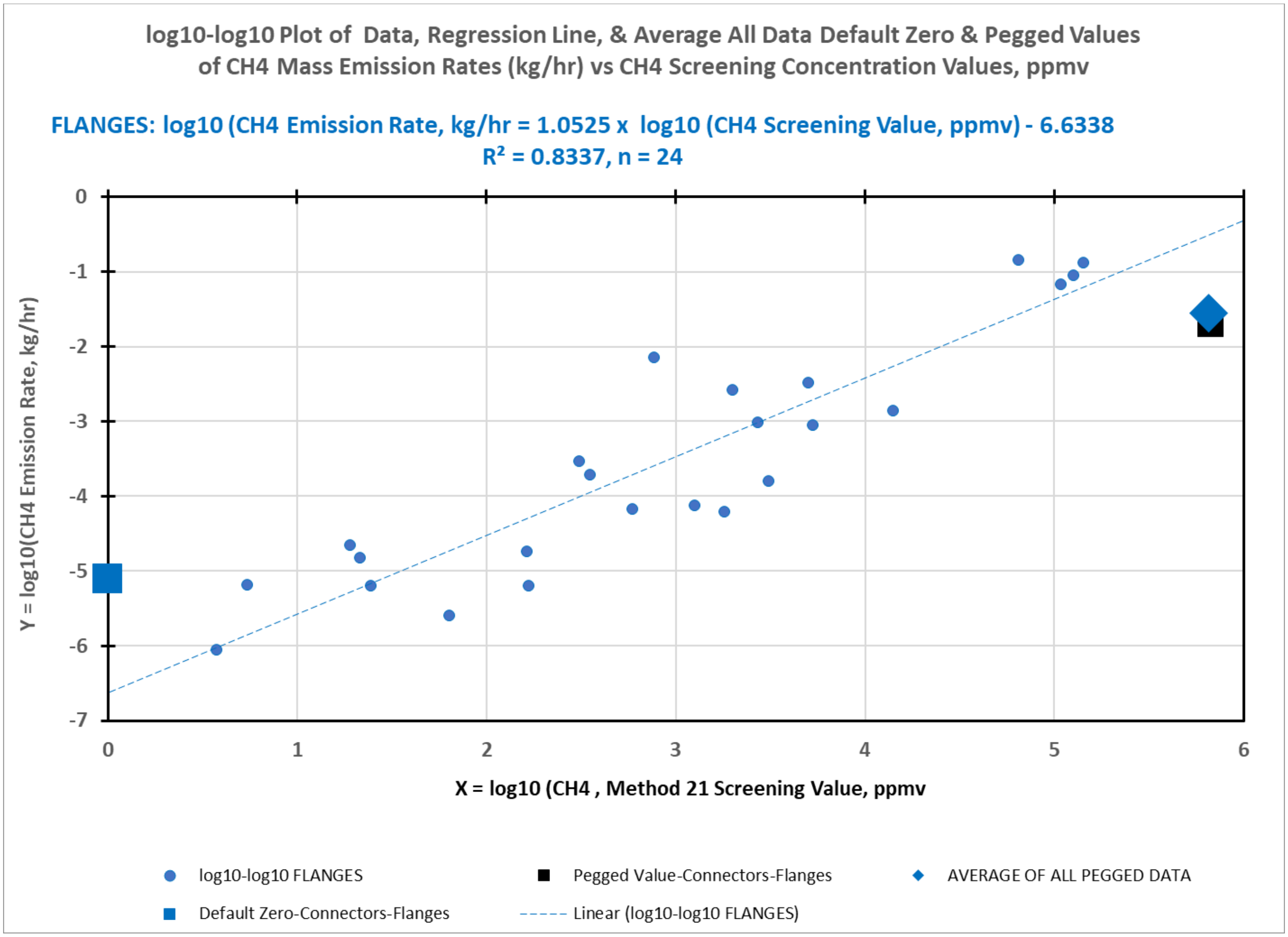
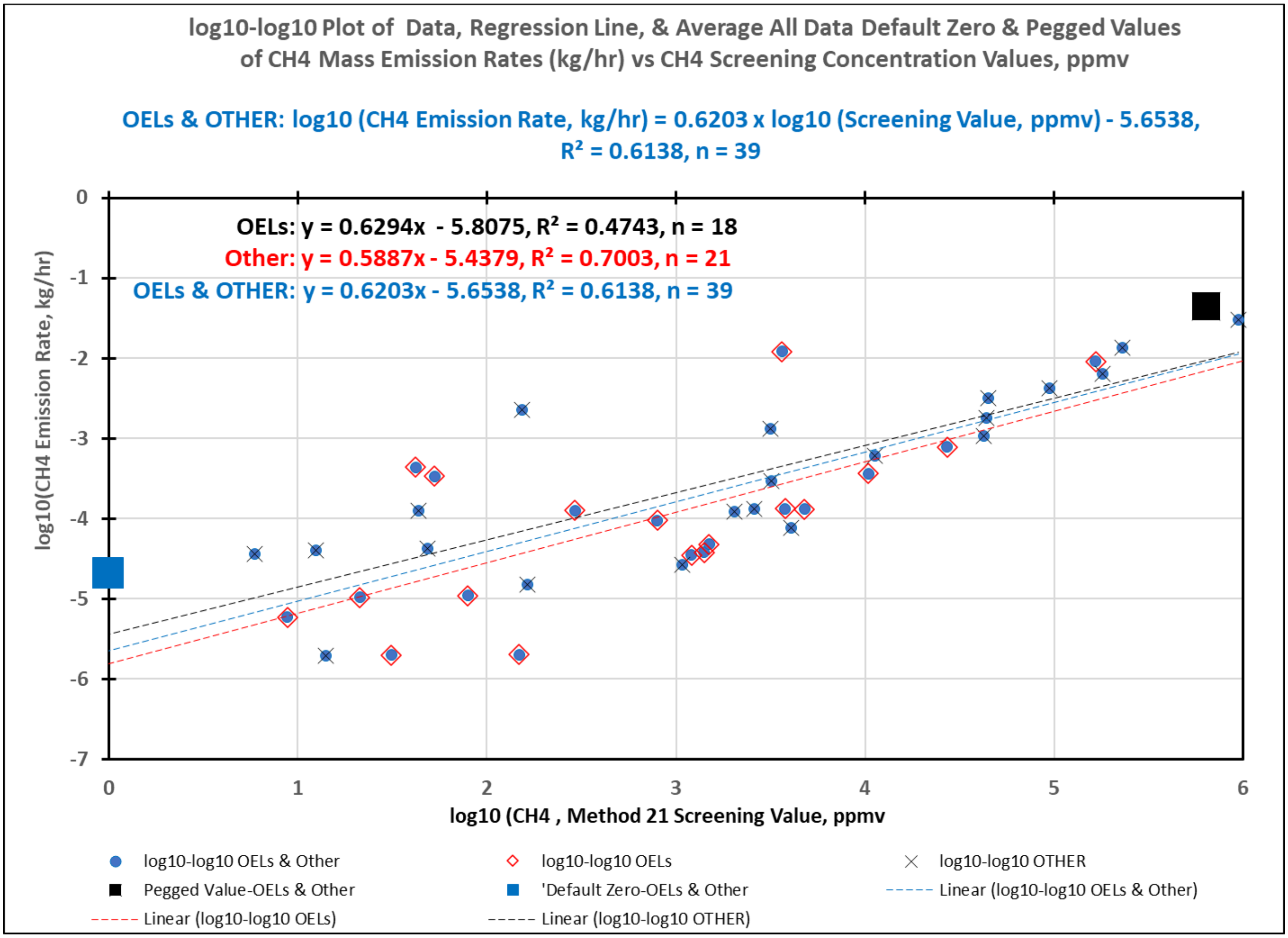


Figure 3-5: OELs & Others: Log10 Regression Line, Default Zero & Pegged Data



3.5 Statistical Analyses

The validity of the linear regression models is based upon a review of descriptive statistics, visual inspection of data plots, application of mathematical transformations as necessary, statistical significance tests of linear regression model results using Analysis of Variance (ANOVA), and an ANOVA comparison of mass emission rate values across all component type groups.

3.5.1 Descriptive Statistics

Table 3-5 summarizes the project's two (2) data sets — CH_4 ppmv and CH_4 kg/hr for each component group in terms of number of components tested (n) and the minimum, average, maximum, and range of values.

Table 3-5 Descriptive Statistics Results

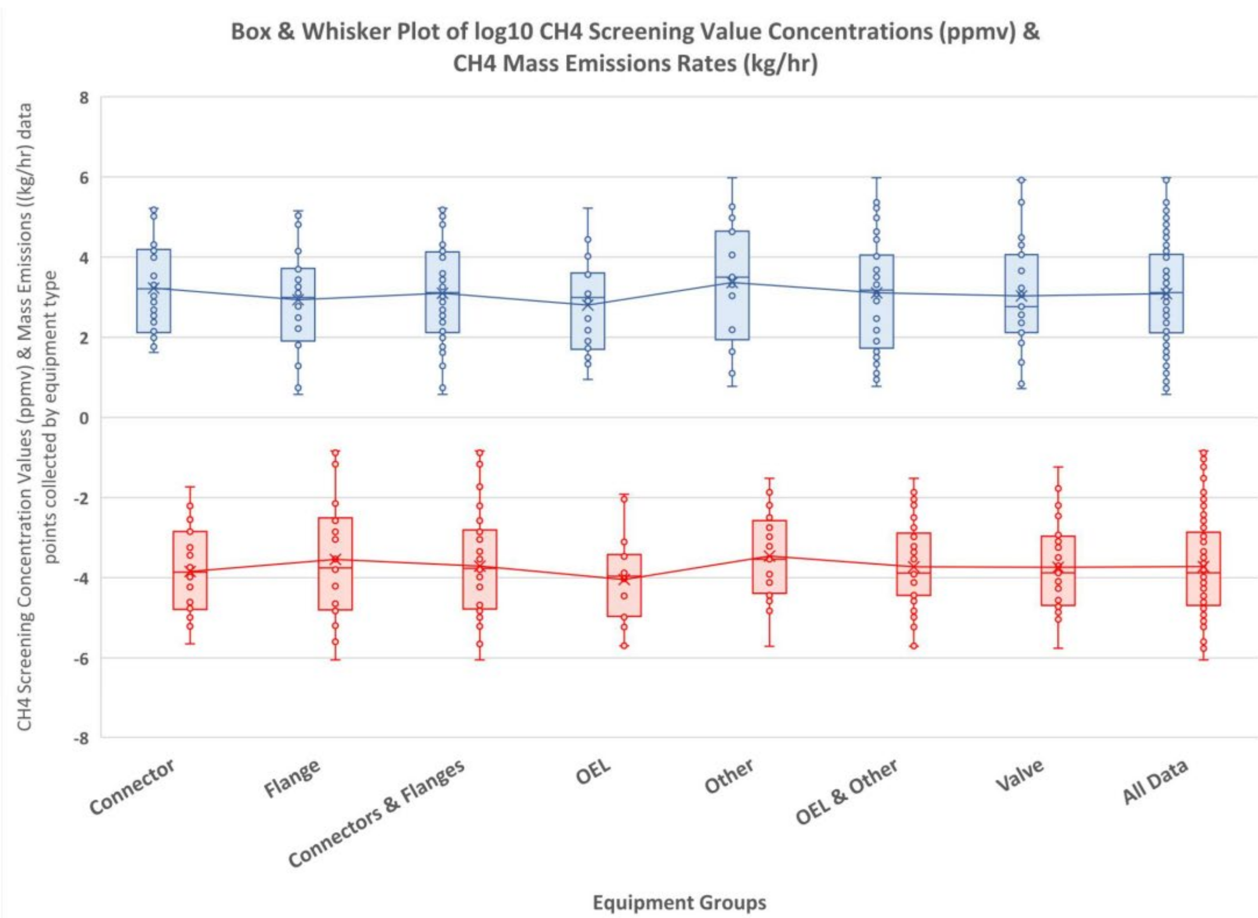
CH_4 Screening Concentration Values Data (ppmv) by Component Group					
Component Groups:	**n**	**Minimum**	**Average**	**Maximum**	**Range**
Valves	31	5	66,058	845,000	844,995
Connectors	30	42	18,936	164,000	163,958
Flanges	24	4	19,898	142,000	141,996
OELs	18	9	12,298	166,000	165,991
Others	21	6	76,354	940,000	939,994
OELs & Others	39	6	46,790	940,000	939,994
All Components	124	4	39,663	940,000	939,996

CH_4 Mass Emissions Rates Data (kg/hr) @ EPA-STP					
Component Groups:	**n**	**Minimum**	**Average**	**Maximum**	**Range**
Valves	31	1.733E-06	3.270E-03	5.824E-02	5.824E-02
Connectors	30	2.234E-06	1.502E-03	1.850E-02	1.850E-02
Flanges	24	8.872E-07	1.883E-02	1.450E-01	1.450E-01
OELs	18	1.994E-06	1.318E-03	1.209E-02	1.209E-02
Others	21	1.956E-06	3.114E-03	3.015E-02	3.015E-02
OELs & Others	39	1.956E-06	2.285E-03	3.015E-02	3.015E-02
All Components	124	8.872E-07	5.544E-03	1.450E-01	1.450E-01

Except for OELs, all component type group totals had count values greater than the minimum goal of twenty (20). The low count for OELs of eighteen (18) contributed to a relatively low R^2 correlation for that group. This was addressed, as noted previously, by combining OELs and Others for the correlation development, as well as for the pegged screening value and default zero data pairs.

The box and whisker log_{10} plot shown in Figure 3-6, provides a visual comparison of the variability and central tendency of the log_{10} hydrocarbon analyzer screening values and the log_{10} mass emissions rates across the component type groups. Each box shows a central line that is the median of each group's values, and the top and bottom of the box shows the upper and lower quartiles of the grouped data. The whiskers indicate the range of the data, and the individual datapoints are also displayed. The lines connecting the "x's" between the groups show how the $\log_{10}$ means of these groups of inputs and outputs vary across component type groups. In general, across the two sets of $\log_{10}$ data, the groups have roughly the same mean and median, and show similar variance or data spread across the group. No obvious outliers are observed.

Figure 3-6: Box & Whiskers Plot of Log10 Data of Screening Concentration Values (ppmv) & Mass Emission Rates (kg/hr) for All Component Groups



3.5.2 Evaluation of the Linear Regression Models

The simple linear regression model as described in the 1995 EPA Protocol is a method that is approved by the agency. It uses Method 21 screening concentrations from leaking equipment and corresponding hydrocarbon mass emission rates to develop a linear regression prediction model. This estimates the average emissions rate for a given screening value concentration for a given component type.

Using a statistical application package for Microsoft Excel, Analyse-It! ®, an Analysis of Variance (ANOVA) test was conducted to see if any of the equipment groups' data in log10 space, have variances that differ significantly from each other. The ANOVA test results are presented in Figure 3-7. The F-test result was 0.87 while the probability result that the equipment group populations were statistically different, was p = 0.66. The significance level for the test was set at p = 0.05. Consequently, the ANOVA test failed to reject the null hypotheses that the variabilities of the component type group datasets were different. These results support the merging of data between component groups as needed to obtain sufficient data for calculating regression models, default zero and pegged value results.

Figure 3-7: Box & Whiskers Plot of Log10 CH4 Mass Emissions Rates by Equipment Type

Compare Groups: Y: log10 (CH4 Emission Rate, kg/hr) by Component: Type

Analyse-it v6.15

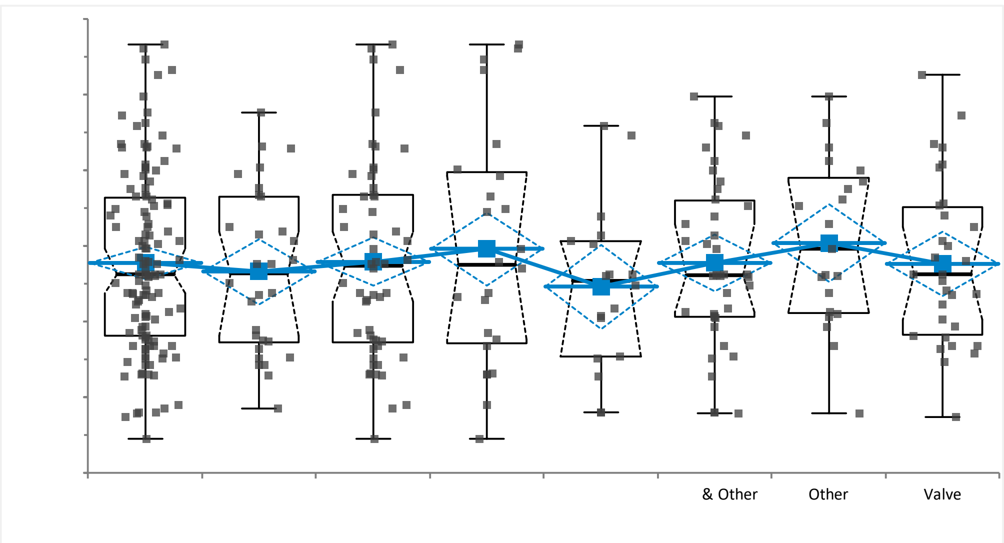
2-INPUTS-B&W & ANOVA B2:J343

Filter: No filter

Last updated 25 March 2023 at 6:52 by Mike Hebert

04/06/23

Descriptives



N	341

Y: log10 (CH4 Em. Rate, , kg/hr by Component: Type	N	Mean	95% CI*		Mean SE*	SD
All Data	124	-3.7216157	-3.93251139 to -		0.107210741	1.180631438
Connector	30	-3.84124673	-4.27001034 to -		0.217965879	1.065539702
Connectors & Flanges	54	-3.70898458	-4.02856611 to -		0.162462174	1.300497425
Flange	24	-3.5436569	-4.02302919 to -		0.243693261	1.55384364
OEL	18	-4.04358954	-4.59712098 to -		0.28139274	1.074298377
OEL & Other	39	-3.72796871	-4.10401927 to -		0.191168722	1.107481924
Other	21	-3.45743656	-3.9699071 to -		0.260519054	1.087602624
Valve	31	-3.73562581	-4.15741719 to -		0.214421482	1.08299114
Pooled	341					1.193848286

* Standard error of the mean based on the pooled sample variance.

Location

ANOVA

Source	SS	DF	MS	F	p-value
Component: Type	4.536744379	7	0.64810634	0.45	0.8667
Error	474.6161519	333	1.42527373		
Total	479.1528963	340	1.409273224		

H0: $\mu_1 = \mu_2 = \mu$…

The mean of the populations are all equal.

H1: $\mu_i \neq \mu_j$ for at least one i,j

The mean of the populations are not all equal.

[1] Do not reject the null hypothesis at the 5% significance level.

The log_{10} space linear regression model is based on a number of assumptions about the X and Y variables and their relationship:

1. The relationship between the independent and dependent variable is linear. The line of best fit is a straight line that minimizes the combined error from the distances between the regression line and the actual X|Y data points. This is accomplished using log10 transformations of X and Y values.

2. Homogeneity of variance — the range of the error in the predictions does not change significantly across the range of the independent variable, as indicated in the statistical model plots of the estimated 95% Confidence Bands (CB) and Probability Bands (PB).

3. Independence of observations — the observations in the data set were collected using statistically valid sampling methods, and there are no hidden relationships among observations. Regressions were tested for autocorrelation or indication of other hidden variables, using the Durbin-Watson (DW) statistic. The DW statistic values range from zero (0) to four (4) with 2.0 representing no autocorrelation. Values > 2.0 indicate negative autocorrelation, and values < 2.0 indicate positive autocorrelation. If significant autocorrelation or hidden variables exist, it undervalues the standard error and may cause the belief that predictors are significant when in reality they are not.

   However, guidance varies on interpretation of DW results. Two (2) rules of thumb and two (2) p-value recommendations are provided. One rule of thumb considers DW values within the range of 1.5 to 2.5 to be generally acceptable. Values outside of this range could be a cause for worry, and values less than 1 or greater than 3 are a definite concern. The DW statistics for three (3) of the four (4) regressions for Valves, Connectors and Flanges failed to detect significant indication of autocorrelation or hidden variables under the most restrictive rules of thumb and p-values guidance. Their DW statistics range from 1.55 to 2.49, with p-values ranging from 0.1620 to 0.2920. These results appear to meet both rules of thumb and are not significant at the p = 0.05 and p.001 significance levels. On the other hand, the OELs & Other group's regression show a DW statistic result of 1.32, and a p-value of 0.0399. This result meets one of the two rules of thumb, as being a potential but not definite cause for worry. It also shows significant autocorrelation at the p = 0.05 level, but not at the p = 0.01 level.

   An inspection of Figure 3-5 shows very close agreement between the OELs, Other, and OELs & Other equipment groups. A close inspection of the data and linear regression plots in Figure 3-5 of the groups OELs, Other and OELs & Other shows that the OELs group data has slightly more datapoints in the lower-left quadrant of the plot, and the Other group data has more datapoints located in the upper right quadrant of the plot. It is possible that the this may have affected the OELs and other group data’s borderline significant DW result. For these reasons it is recommended that the OELs & Other group’s borderline autocorrelation significance result, as discussed earlier in this section, is insufficient basis for rejecting the OELs & Other regression line model. Since the OELs & Other group's regression lines do not differ significantly from the other modeled regression lines, or each other, these conflicting interpretations, are not considered to be serious enough to reject the OELs & Other regression model.

4. Normality of residuals: The residuals (predicted minus actual values) are normally distributed as shown in the histograms, normal plot and Shapero-Wilk test results. All Shapiro-Wilk tests were insignificant.

5. The X values are assumed to be exact values with no errors.

Assumption #5, that the X-values (i.e., analyzer screening values) are exact values with no error cannot be met for the following reasons. The accuracy criterion of the hydrocarbon analyzers was ±10% percent agreement with the concentrations of the CH_4-in-air cylinder gases. Besides inherent calibration inaccuracies, analyzer screening concentrations could be affected by other factors, such as the variability of the leak and the operator's skill and diligence. A small leak flow rate and large screening concentration could have the same mass emissions rate as a large leak flow rate and a correspondingly small screening concentration.

However, in this particular study, the following factors limit the impact of such errors: (a) all streams were commercial pipeline quality natural gas consisting mainly of CH_4, (b) the calibration span gases were ± 2% certified CH_4 concentrations, (c) flow-controlling, demand flow gas regulators were used to perform analyzer calibrations, (d) analyzer sample flow rates were verified each test day, (e) the analyzers were drift checked each test day at mid- and end-of-day; *and* (f) the project field team were well experienced in EPA Method 21 procedures

The coefficient of variation (i.e., R^2) values for the developed linear regressions provide a common measure of how well the resulting emission rates (kg/hr) fit their corresponding screening values (ppmv). R^2 values can range from 0 to 1. A value of 0 indicates that the response variable cannot be explained by the predictor variable at all. A value of 1 indicates that the response variable can be perfectly explained without error by the predictor variable. As noted in Figures 3-1 through 3-5, the R^2 factor for the groups Valves, Connectors, Flanges and OELs & Other, ranged from 0.6138 to 0.8403. These compare well with the values reported in the 1995 EPA Protocol, which ranged from 0.19 to 0.75 across all component and service types. The R^2 values for each equipment group are at or above the levels generally considered to be indicators of a good fit of the data to a linear regression model for this type of data.

Additional evaluations of the linear regression models were conducted using the statistical application package, Analyse-It! ®. These evaluations included plotting the $\log_{10}$-$\log_{10}$ regression lines to show the regression line statistical analysis results, the extent of the 95% simultaneous confidence bands (CB) and 95% individual probability bands (PB). The CB lines are the curved inner pair of curved lines. The PB lines are the pair of dashed lines outside of the CB lines, and parallel to the linear regression model line. The CB lines indicate the area where the true population regression line model is projected to occur with a 95% probability. The PB lines show what the expected range of any individual predicted Y value would be for any given individual X value 95% of the time. These additional evaluations provide further support of the linear regression model results in the form of histograms of the predicted log10 mass emission rates along with probability and residual plots, and tests for normality and autocorrelation assumptions.

The correlation equation regression lines were tested for statistical significance for each of the four (4) component groups modeled, Valves, Connectors, Flanges, OELs & Other. T-test and F-test p-values for model fit and effect of model for each group were statistically significant being well below the 0.05 significance level.

In summary, a review of the log10-log10 data and residual plots, the R^2 values, T-Test, F-test results and corresponding p-values, and the normality and autocorrelation tests and associated p-values, indicate that for each equipment group:

- All the correlations show a good model fit;
- All correlations show that the effect of the log10 screening values on the log10 mass emissions rates is statistically significant;
- The log10-log10 data meet the general requirements of the simple linear regression model for linearity, homogeneity of variance, normality of results, *and*
- While the DW statistic result for the group OEL & Other found potential but not definite indication of autocorrelation or hidden variables, the separate plots of OELs, Other, and OELs & Other data and regression lines in Figure 3-5 show very close agreement among these three (3) groups. As explained above, the borderline potentially worrisome significance test result for group OEL & Other is not considered serious enough to reject the OELs & Other regression model.

Additional support details and results on the project statistics are provided in the accompanying Excel® workbook CARB PROJECT RFP No 20ISD002 PROJECT STATISTICS WORKBOOK.

SECTION 4: PROJECT QUALITY CONTROL

4.1 QUALITY CONTROL ACTIONS

The following quality control actions were performed by the project field team:

- IR camera daily demo;
- High Flow® Sampler daily calibration and flow verifications; *and*
- Analyzer (TVA & PHx 42) calibrations, drift checks and flow verifications.

The QC results for each are provided in Appendix A. Copies of the gas certification sheets are given in Appendix B.

4.1.1 IR Camera QC

A daily demonstration check (Daily Demo) of the IR Camera was performed prior to use to verify proper operation and to establish the sighting distance from which components could be reliably imaged for leaks. A video recording was made of each Daily Demo result. The Daily Demo QC Check included the following steps:

- The camera was turned on and allowed to cool down to its operating temperature (-321 ^{o}F)
- If needed, a non-uniformity correction (NUC) would be performed in order to produce a uniform imaging background;
- Propane gas from a commercial-grade cylinder was released to atmosphere at a controlled flow rate 0.25 liters/minute or approximately thirty (30) grams/hour;
- The maximum distance from which the propane gas flow could be reliably detected was measured (i.e., the sighting distance) with a laser distance measurer; *and*
- Along with the sighting distance, a hand-held Kestrel® weather meter was used to measure ambient temperature, wind speed, relative humidity, and barometric pressure. Observed percent cloud cover was also documented.

The Daily Demo results were recorded in a pocket notebook for later entry into a Microsoft Excel® spreadsheet. The results of the IR camera Daily Demo are provided in Appendix A.

4.1.2 Hydrocarbon Analyzer Calibrations and Drift Checks

Two (2) TVA 2020 analyzers, and on occasion a PHx42 analyzer, were used to find and measure hydrocarbon leaks. Prior to an analyzer calibration, a sample flow check was made with a rotameter to verify the analyzer's design flow rate (i.e., 1 liter/minute) and as a check for sample system leaks. The hydrocarbon analyzers were calibrated daily, before use, with vendor-certified $\pm$2% accurate gas cylinders fitted with demand flow gas regulators. Five (5) gas standards having nominal concentrations of 0, 500, 2,000, 10,000 and 2.5% methane-in-air were used for the analyzer calibrations[8]. Analyzer preparation included the following steps:

1. The analyzer's hydrogen cylinder was filled:
2. The analyzer was turned on and its flame lit;
3. The analyzer's sample flow rate was verified with a rotameter;
4. The analyzer went through a thirty (30) minute warm-up period;
5. The analyzer was entered into calibration mode and the zero and span gases were sequentially introduced to the probe via a demand flow gas regulator;
6. The analyzer was then switched to Run mode and each calibration gas was re-introduced and the results recorded in the Calibration & Drift Check spreadsheet.

Analyzer calibrations were performed at the beginning of each test day. Analyzer responses to the calibration gases required ±10% agreement with the certified gas concentration. Responses outside the acceptance criteria were addressed either by re-calibration or trouble-shooting and/or repair of the analyzer.

Mid-day and end-of-day analyzer drift checks were performed each test day. The drift check acceptance criterion required no more than -10% agreement with the certified gas concentration. Failure of a drift check required recalibration of the analyzer followed by a re-monitoring of any components that could potentially be included in the test matrix population.

In instances of analyzer flame-out, due to high concentrations, a variable dilution probe was used with the TVA to obtain a concentration reading. The dilution ratio was set using the high span gas (i.e., 2.5% CH_4) and re-checked with the same 2.5% CH_4 gas after use.

Hydrocarbon analyzer daily calibrations and drift check results are provided in Appendix A. Dilution probe ratios before and after use are recorded in the *CARB PROJECT RFP No 20ISD002 FIELD TEST DATA WORKBOOK*.

4.1.3 High Flow Sampler® QC

The High Flow Sampler's® background and gas sensors were initially calibrated at the start of testing with a 2.5% methane-in-air standard and a 100% methane standard. A calibration verification check with the same two (2) standards was repeated each test day prior to use. Both gas standards were vendor-certified ±2% accurate and were fitted with demand flow gas regulators to ensure steady and consistent flow rates. The acceptance criterion for the High Flow Sampler's® daily verification check

[8] The 2.5% CH_4 span gas was included in the analyzer calibrations on March 7, 2022.

was a response of its Gas sensor no greater than ±10% from the specified cylinder concentration. Failure to meet this criterion required a re-calibration and/or repair/maintenance.

Upon the recommendation of one of the project stake-holders, an additional High Flow Sampler® QC check was introduced. Beginning at the second test facility, the accuracy of the High Flow Sampler's® sample flow rate was verified daily prior to testing with a Model STA2 hot wire anemometer.

High Flow Sampler® daily calibrations, calibration verifications, and sample flow rate checks are provided in Appendix A.

Calibration cylinder gas certifications are provided in Appendix B.

APPENDIX A

QUALITY CONTROL DOCUMENTATION

- **IR Camera Daily Demo**
- **High Flow Sampler® Daily Calibration Verification**
- **Analyzer Calibration & Drift Checks**
    - TVA 2020 S/N 202017072507
    - TVA 2020 S/N 2020170724787
    - PHx 42 S/N 4640

Daily IR Camera Demo Results

SITE	TIMESTAMP	SIGHTING DISTANCE FEET	WIND DIRECTION	WIND SPEED	TEMP °F	RH %	BP inHg	%CLOUD COVER	RAIN
TCS #1	1/19/2022 8:18	21	Calm	0	67.2	53.0	29.88	0	0
	1/20/2022 7:45	21	Calm	1	64.0	37.4	30.1	0	0
	1/21/2022 8:00	17	Calm	0	56.0	40.7	29.8	0	0
	1/24/2022 7:40	27	Calm	0	58.0	38.1	29.8	0	0
	1/25/2022 8:08	34	Calm	0	56.0	41.0	29.7	33	0
	1/26/2022 7:47	27	Calm	0	62.0	37.0	29.98	10	0
TCS #2	3/7/2022 10:27	39	Calm	0	52.0	37.9	27.17	65	0
	3/8/2022 8:14	36	Calm	1	51.7	49.0	27.01	90	0
	3/9/2022 7:50	28	Calm	0	58.6	33.6	26.79	25	0
	3/10/2022 8:30	21	NE	4.8	37.1	42.5	26.96	0	0
TCS #3	3/15/2022 7:45	15	Calm	0	55.0	78.2	30.1	90	Misty
	3/16/2022 8:10	21	Calm	0	53.6	56.5	30.09	0	0
	3/17/2022 7:52	22	Calm	0	57.2	50.8	29.98	100	0
UGSF #1	3/21/2022 9:55	22	North	10.1	62.4	37.4	30.19	5	0
	3/22/2022 8:50	24	North	11.0	66.1	53.0	30.14	0	0
	3/23/2022 8:50	32	Calm	0.0	66.0	61.0	30.1	5	0

SITE	TIMESTAMP	SIGHTING DISTANCE FEET	WIND DIRECTION	WIND SPEED	TEMP °F	RH %	BP inHg	%CLOUD COVER	RAIN
	3/24/2022 8:45	28	North	1.1	64.7	57.3	30.03	5	0
	3/25/2022 8:40	28	South	2.1	61.3	55.8	29.99	5	0
UGSF #2	3/28/2022 12:20	28	South	7.0	63.9	59.2	29.73	90	0
	3/29/2022 7:35	24	Calm	0.0	57.9	66.0	29.92	100	Foggy
	3/30/2022 7:35	24	East	2.0	57.5	65.8	30.08	20	0
	3/31/2022 9:15	24	WNW	3.6	58.5	69.7	29.95	50	0
	4/1/2022 9:00	30	West	1.3	57.8	63.8	29.91	0	0
UGSF #3	4/4/2022 10:15	28	West	6.3	68.3	45.1	30.14	30	0
	4/5/2022 7:20	28	West	3.0	54.6	72.0	30.22	0	0
	4/6/2022 7:20	25	Calm	0.0	59.7	46.3	30.18	0	0
	4/7/2022 7:20	30	Calm	0.0	63.2	56.8	30.17	5	0
	4/8/2022 7:30	30	Calm	0.0	63.9	62.3	30.1	0	0

Notes to Daily Demo Results:

1. Propane flow rate for all tests = 0.25 liters/minute. Propane flow in grams/hour is calculated as

$$C_3H_8\frac{g}{hr} = 0.25\frac{L}{min} \times p\frac{g}{L} \times \frac{60min}{1hr} \times \frac{273.14K}{Temp_{amb}\ K} \times \frac{BP_{amb}\ mbar}{1013\ mbar}$$

Where:

C_3H_8g/hr	*Propane in grams/hour*
0.25 L/min	*Propane flow rate in liters/minute*
ρ	*Propane density in grams/liter at 0°C and 1 atmosphere*
273.14K/$Temp_{amb}$ K	*Conversion of ambient temperature to Standard Temperature*
BP_{amb} mbar/1013 mbar	*Conversion of ambient barometric pressure to Standard Barometric Pressure in millibars*

2. Sighting Distance — Maximum distance from which propane emission could be reliable seen with the IR camera
3. Temp °F — Temperature in degrees Fahrenheit
4. RH% — Percent Relative Humidity
5. % Cloud Cover — Based upon observation

High Flow Sampler® Calibration & Flow Verification S/N 1004/Hot Wire Anemometer Model STA2 S/N 21050031

Site	Timestamp	2.484% Background		2.484% Gas		99.99% Background		99.99% Gas		Flow Checks		
		%	Δ%	%	Δ%	%	Δ%	%	Δ%	Hi Flow (cfm)	Hot Wire (cfm)	Δ%
TCS #1	1/19/22 7:32	3.92	58%	2.61	5.1%	97	-3.0%	97.5	-2.5%			
	1/20/22 7:24	3.87	56%	2.69	8.3%	96.5	-3.5%	98	-2.0%			
	1/21/22 7:15	2.75	11%	2.73	9.9%	96	-4.0%	99.4	-0.6%			
	1/24/22 7:15	2.48	-0.2%	2.7	9%	96.5	-3%	99.3	-1%			
	1/26/22 7:17	2.64	6%	2.73	9.9%	96.4	-4%	99.5	0%			
TCS #2	3/7/22 9:49	2.28	-8%	2.58	3.9%	95.9	-4.1%	99.5	-0.5%	8.8	8.7	-1%
	3/8/22 7:55	2.59	4%	2.67	7.5%	94.5	-5.5%	99.3	-0.7%	9.4	9.4	0%
	3/9/22 7:31	2.67	7%	2.7	8.7%	95	-5.0%	99.3	-0.7%	9.5	9.9	4%
	3/10/22 7:52	2.8	12.7%	2.74	10%	95	-5%	98	-2%	9.5	9.8	3%
	3/11/22 7:40	2.49	0%	2.5	0.6%	95	-5%	95	-5%	9.2	9.2	0%
TCS #3	3/14/22 9:25	2.57	3%	2.56	3.1%	95.7	-4%	98	-2.0%	9.5	9.4	-1%
	3/15/22 12:55	2.67	7%	2.59	4%	95	-5%	97	-3.0%	9.8	9.5	-3%
	3/16/22 7:30	2.65	7%	2.6	5%	95	-5%	95.3	-4.7%	9.4	9.5	1%
	3/17/22 7:42	2.73	10%	2.61	5%	95.5	-4%	99.00	-1.0%	9.3	9.7	4%
	3/18/22 7:30	2.49	0%	2.63	6%	94.6	-5%	95.4	-4.6%	9.4	9.1	-3%
UGSF #1	3/22/22 8:40	2.46	-1%	2.55	3%	96.1	-4%	97.6	-2.4%	9.4	9.7	3%
	3/23/22 8:30	2.53	2%	2.57	3%	94.6	-5%	99.0	-1.0%	9.8	9.8	0%
	3/24/22 8:30	2.54	2%	2.59	4%	96.9	-3%	98.5	-1.5%	9.9	10.1	2.0%
	3/25/22 8:25	2.58	4%	2.60	5%	97.0	-3%	98.4	-2%	9.4	9.8	4.3%
UGSF #2	3/29/22 7:20	2.5	1%	2.56	3%	97.3	-3%	98.6	-1%	9.6	9.5	-1.0%
	3/30/22 7:43	2.57	3%	2.6	5%	97.1	-3%	98.5	-1%	9.4	9.6	2.1%
	3/31/22 9:25	2.48	0%	2.6	5%	98.0	-2%	99.0	-1%	9.4	9.9	5.3%
	4/1/22 8:55	2.52	1%	2.59	4%	97.6	-2%	98.0	-2%	9.4	9.7	3.2%
UGSF #3	4/6/22 7:22	2.58	4%	2.63	6%	97.6	-2%	99.0	-1%	9.4	9.7	3.2%
	4/7/22 7:15	2.58	4%	2.62	5%	96.8	-3%	98.8	-1%	9.5	9.6	1.1%
	4/8/22 7:25	2.59	4%	2.62	5%	97.2	-3%	98.1	-2%	9.8	9.8	0.0%
UGSF #1 Default Zero Tests	7/14/22 10:40	2.48	-0.8%	2.48	-0.8%	97.0	-3%	97.4	-3%	8.9	8.8	1.0%
	7/15/22 7:30	2.76	10.4%	2.48	-0.8%	96.4	-3.6%	97.0	-3%	9	9.1	1.1%

Notes to High Flow Sampler® Calibration Verification:

1. Δ% = Percent Difference between Calibration Gas Concentration and Analyzer Response calculated as:

$$\Delta\% = \left(\frac{Response - Input}{Input}\right) \times 100$$

Where:

Δ%	Percent Difference
Response	Analyzer's Response (ppmv)
Input	Calibration Gas Concentration (ppmv)

2. HiFlo (cfm) Sample flow in cubic feet/minute as displayed by the High Flow Sampler Controller
3. Hot Wire (cfm) High Flow Sampler's sample flow as measured by the Hot Wire Anemometer

TVA 2020 S/N 17072507
Calibration & Drift Check Results

Site	Gas Concentrations		0	549		1980		10,150		2.48%		Flow Check
	Timestamp	Type	ppm	ppm	Δ%	ppm	Δ%	ppm	Δ%	%	Δ%	L/Min
TCS #1	1/19/22 7:47	Cal	0.5	540	-1.6%	1,982	0.1%	10,500	3.4%			
	1/20/22 8:05	Cal	0.9	549	0.0%	1,980	0.0%	10,150	0.0%			
	1/20/22 11:02	Drift		534	-2.7%							
	1/20/22 14:45	Drift		500	-8.9%							
	1/21/22 8:10	Cal	0.4	548	-0.2%	1,977	-0.2%	10,600	4.4%			
	1/21/22 11:15	Drift		501	-8.7%							
	1/24/22 8:15	Cal	0.4	548	-0.2%	1,971	-0.5%	10,400	2.5%			
	1/24/22 11:07	Drift		507	-7.7%							
	1/24/22 11:45	Cal	0.3	550	0.2%	1,985	0.3%	10,300	1.5%			
	1/24/22 14:45	Drift		558	1.6%							
	1/26/22 7:34	Cal	0.2	552	0.5%	1,980	0.0%	10,100	-0.5%			
	1/26/22 10:33	Drift		517	-5.8%							
	1/26/22 14:26	Drift		527	-4.0%							

Notes:
Δ% = Percent Difference calculated as ((Analyzer Response - CH_4 Gas Concentration) / CH_4 Gas Concentration) x 100
ppm = parts per million volume
L/Min = Liters/Minute
TCS = Transmission Compressor Station
A 2.48% calibration gas was not included at this site
Analyzer flow checks were not conducted at this site

TVA 2020 S/N 17072507 continued…

Calibration & Drift Check Results

Site	Gas Concentrations		0	549		1980		10,150		2.48%		Flow Check
	Timestamp	Type	ppm	ppm	Δ%	ppm	Δ%	ppm	Δ%	%	Δ%	L/Min
TCS #2	3/7/22 10:39	Cal	0.9	548	-0.2%	1,980	0.0%	10,400	2.5%	2.4%	-1.8%	1.1
	3/7/22 15:24	Drift	-0.5	522	-4.9%	1,980	0.0%	10,150				
	3/8/22 8:30	Cal	-0.6	544	-0.9%	1,965	-0.8%	10,150	0.0%	2.5%	-0.2%	1.1
	3/8/22 14:15	Drift		532	-3.1%							
	3/9/22 8:05	Cal	-0.7	552	0.5%	1,971	-0.5%	10,100	-0.5%	2.5%	-0.2%	
	3/9/22 11:22	Drift		549	0.0%							
	3/9/22 11:55	Cal	-0.8	554	0.9%	1,991	0.6%	10,500	3.4%	2.5%	-0.2%	
	3/9/22 14:14	Drift		548	-0.2%							
	3/10/22 8:25	Cal	-0.1	541	-1.5%	1,953	-1.4%	10,500	3.4%	2.5%	-1.0%	1.1
	3/10/22 10:57	Drift		555	1.1%							
	3/10/22 14:17	Drift		534	-2.7%							
	3/11/22 8:11	Cal	0.9	546	-0.5%	1,985	0.3%	10,200	0.5%	2.5%	-0.2%	1.1
	3/11/22 11:34	Drift		519	-5.5%							

Notes:

Δ% = Percent Difference calculated as ((Analyzer Response - CH_4 Gas Concentration) / CH_4 Gas Concentration) x 100

ppm = parts per million volume

L/Min = Liters/Minute

TCS = Transmission Compressor Station

TVA 2020 S/N 17072507 continued…
Calibration & Drift Check Results

Site	Gas Concentrations		0	549		1980		10,150		2.48%		Flow Check
	Timestamp	Type	ppm	ppm	Δ%	ppm	Δ%	ppm	Δ%	%	Δ%	L/Min
TCS #3	3/14/22 10:30	Cal	0	545	-0.7%	1,965	-0.8%	10,200	0.5%	2.5%	-0.6%	1.1
	3/14/22 14:06	Drift		517	-5.8%							
	3/15/22 8:06	Cal	0.1	540	-1.6%	1,941	-2.0%	10,600	4.4%	2.5%	-1.4%	1.1
	3/15/22 11:04	Drift		522	-4.9%							
	3/15/22 13:24	Drift		506	-7.8%							
	3/16/22 7:49	Cal	0.6	545	-0.7%	1,961	-1.0%	10,100	-0.5%	2.5%	-0.6%	1.1
	3/16/22 11:07	Drift		546	-0.5%							
	3/16/22 13:40	Drift		554	0.9%							
	3/17/22 7:59	Cal	0.7	545	-0.7%	1,966	-0.7%	10,200	0.5%	2.5%	-0.8%	1.1
	3/17/22 11:03	Drift		514	-6.4%							
	3/17/22 14:20	Drift		507	-7.7%							
	3/18/22 8:04	Cal	0	540	-1.6%	1,951	-1.5%	10,600	4.4%	2.48%	-0.2%	1.1
	3/18/22 10:30	Drift		544	-0.9%							

Notes:
Δ% = Percent Difference calculated as ((Analyzer Response - CH_4 Gas Concentration) / CH_4 Gas Concentration) x 100
ppm = parts per million volume
L/Min = Liters/Minute
TCS = Transmission Compressor Station

TVA 2020 S/N 17072507 continued…

Calibration & Drift Check Results

Site	Gas Concentrations		0	549		1980		10,150		2.48%		Flow Check
	Timestamp	Type	ppm	ppm	Δ%	ppm	Δ%	ppm	Δ%	%	Δ%	L/Min
UGSF #1	3/21/22 10:35	Cal	0	549	0	1,945	-1.8%	10,600	4.4%	2.47%	-0.6%	1.1
	3/21/22 13:25	Drift		477	-13.1%							
	3/22/22 9:10	Cal	0	544	-0.9%	1,965	-0.8%	10,050	-1.0%	2.46%	-1.0%	1.0
	3/22/22 11:25	Drift		522	-4.9%							
	3/22/22 14:30	Drift		525	-4.4%							
	3/23/22 9:00	Cal	0.1	553	0.7%	1,995	0.8%	10,600	4.4%	2.47%	-0.6%	1.0
	3/23/22 14:50	Drift		505	-8.0%							
	3/24/22 9:00	Cal	0	550	0.2%	1,984	0.2%	10,400	2.5%	2.43%	-2.2%	1.0
	3/24/22 11:20	Drift		512	-6.7%							
	3/24/22 12:15	Drift		508	-7.5%							
	3/25/22 9:05	Cal	0	544	-0.9%	1,953	-1.4%	10,300	1.5%	2.47%	-0.6%	1.0
	3/25/22 11:00	Drift		503	-8.4%							
	3/25/22 12:15	Drift		505	-8.0%							

Notes:

Δ% = Percent Difference calculated as ((Analyzer Response - CH_4 Gas Concentration) / CH_4 Gas Concentration) x 100

ppm = parts per million volume

L/Min = Liters/Minute

UGSF = Underground Storage Facility

TVA 2020 S/N 17072507 continued…

Calibration & Drift Check Results

Site	Gas Concentrations		0	549		1980		10,150		2.48%		Flow Check
	Timestamp	Type	ppm	ppm	Δ%	ppm	Δ%	ppm	Δ%	%	Δ%	L/Min
UGSF #2	3/28/22 12:50	Cal	0	546	-0.5%	1,950	-1.5%	10,400	2.5%	2.45%	-1.4%	1.0
	3/29/22 8:15	Cal	0	550	0.2%	1,950	-1.5%	10,600	4.4%	2.44%	-1.8%	1.0
	3/29/22 11:15	Drift		542	-1.3%							
	3/29/22 13:35	Drift		552	0.5%							
	3/30/22 8:00	Cal	0.2	545	-0.7%	1,972	-0.4%	10,400	2.5%	2.47%	-0.6%	1.0
	3/30/22 10:35	Drift		515	-6.2%							
	3/31/22 9:40	Cal	0	543	-1.1%	1,972	-0.4%	10,100	-0.5%	2.43%	-2.2%	1.0
	3/31/22 13:50	Drift		515	-6.2%							
	4/1/22 8:25	Cal	0.1	544	-0.9%	1,971	-0.5%	10,100	-0.5%	2.45%	-1.4%	1.0
	4/1/22 11:25	Drift		515	-6.2%							
	4/1/22 13:50	Drift		520	-5.3%							

Notes:

Δ% = Percent Difference calculated as ((Analyzer Response - CH_4 Gas Concentration) / CH_4 Gas Concentration) x 100

ppm = parts per million volume

L/Min = Liters/Minute

UGSF = Underground Storage Facility

TVA 2020 S/N 17072507 continued…

Calibration & Drift Check Results

Site	Gas Concentrations		0	549		1980		10,150		2.48%		Flow Check
	Timestamp	Type	ppm	ppm	Δ%	ppm	Δ%	ppm	Δ%	%	Δ%	L/Min
UGSF #3	4/4/22 10:45	Cal	0	544	-0.9%	1,950	-1.5%	10,200	0.5%	2.47%	-0.6%	1.0
	4/4/22 13:30	Drift		522	-4.9%							
	4/5/22 8:00	Cal	0.2	553	0.7%	1,982	0.1%	10,700	5.4%	2.45%	-1.4%	1.0
	4/5/22 10:30	Drift		522	-4.9%							
	4/5/22 13:07	Drift		525	-4.4%							
	4/6/22 7:45	Cal	0.2	547	-0.4%	1,970	-0.5%	10,200	0.5%	2.45%	-1.4%	1.1
	4/6/22 11:00	Drift		516	-6.0%							
	4/6/22 13:40	Drift		515	-6.2%							
	4/7/22 7:40	Cal	0.1	546	-0.5%	1,974	-0.3%	10,200	0.5%	2.46%	-1.0%	1.0
	4/7/22 11:01	Drift		526	-4.2%							
	4/7/22 13:12	Drift		520	-5.3%							
	4/8/22 7:50	Cal	0.2	557	1.5%	2,011	1.6%	10,200	0.5%	2.52%	1.4%	1.0
	4/8/22 11:15	Drift		520	-5.3%							

<u>Notes:</u>

Δ% = Percent Difference calculated as ((Analyzer Response - CH_4 Gas Concentration) / CH_4 Gas Concentration) x 100

ppm = parts per million volume

L/Min = Liters/Minute

UGSF = Underground Storage Facility

TVA 2020 S/N 17072507 continued…

Calibration & Drift Check Results

Site	Gas Concentrations		0	549		1,980		10,150		Flow Check
	Timestamp	Type	ppm	ppm	Δ%	ppm	Δ%	ppm	Δ%	L/Min
UGSF #1 Default Zero Test	7/14/2022 11:11	Cal	0	529	-3.6%	1,908	-3.6%	10,200	-0.5%	1.0
	7/14/2022 14:56	Drift		474	-13.7%					
	7/15/2022 08:20	Cal	0.7	549	0.0%	1,970	0.5%	10,070	0.8%	1.0
	7/15/2022 11:15	Drift		518	5.6%					

Notes:

Δ% = Percent Difference calculated as ((Analyzer Response - CH_4 Gas Concentration) / CH_4 Gas Concentration) x 100

ppm = parts per million volume

L/Min = Liters/Minute

UGSF = Underground Storage Facility

TVA 2020 S/N 170724787
Calibration & Drift Check Results

Site	Timestamp	Type	0	549		1980		10,150		2.48%		Flow Check
			ppm	ppm	Δ%	ppm	Δ%	ppm	Δ%	%	Δ%	L/Min
TCS #1	3/21/22 10:51	Cal	0.0	548	-0.2%	1967	-0.7%	10200	0.5%	2.42%	-2.6%	1.1
	3/22/22 9:20	Cal	0.0	544	-0.9%	1941	-2.0%	10050	-1.0%	2.46%	-1.0%	1.0
	3/22/22 14:25	Drift		568	3.5%							
	3/23/22 8:55	Cal	0.0	544	-0.9%	1966	-0.7%	10400	2.5%	2.47%	-0.6%	1.0
	3/23/22 11:15	Drift		498	-9.3%							
	3/23/22 14:50	Drift		505	-8.0%							
	3/25/22 8:55	Cal	0.0	546	-0.5%	1961	-1.0%	10100	-0.5%	2.46%	-1.0%	1.0
	3/25/22 11:00	Drift		503	-8.4%							
UGSF #1	3/28/22 12:40	Cal	0	544	-0.9%	1957	-1.2%	10200	0.5%	2.46%	-1.0%	1.0
	3/28/22 14:10	Drift		513	-6.6%							
	3/29/22 8:00	Cal	0.1	531	-3.3%	1920	-3.0%	10000	-1.5%	2.41%	-3.0%	1.0
	3/29/22 11:10	Drift		514	-6.4%							
	3/29/22 13:30	Drift		510	-7.1%							
	3/30/22 7:50	Cal	0.2	545	-0.7%	1972	-0.4%	10400	2.5%	2.47%	-0.6%	1.0
	3/30/22 10:35	Drift		515	-6.2%							
	3/31/22 9:30	Cal	0.2	510	-7.1%	1970	-0.5%	10200	0.5%	2.51%	1.0%	1.0
	3/31/22 13:55	Drift		510	-7.1%							
	4/1/22 8:15	Cal	0	539	-1.8%	1966	-0.7%	10400	2.5%	2.45%	-1.4%	1.0
	4/1/22 11:20	Drift		505	-8.0%							
	4/1/22 13:45	Drift		502	-8.6%							

Notes:
Δ% = Percent Difference calculated as ((Analyzer Response - CH_4 Gas Concentration) / CH_4 Gas Concentration) x 100
ppm = parts per million by volume
L/Min = Liters/Minute
TCS = Transmission Compressor Station
UGSF = Underground Storage Facility

TVA 2020 S/N 170724787 continued…
Calibration & Drift Check Results

Site	Timestamp	Type	0	549		1980		10,150		2.48%		Flow Check
			ppm	ppm	Δ%	ppm	Δ%	ppm	Δ%	%	Δ%	L/Min
UGSF #3	4/4/22 10:35	Cal	0	547	-0.4%	1978	-0.1%	10500	3.4%	2.46%	-1.0%	1.0
	4/4/22 13:35	Drift		550	0.2%							
	4/5/22 7:50	Cal	0.2	550	0.2%	1999	1.0%	10700	5.4%	2.46%	-1.0%	1.0
	4/5/22 10:30	Drift		515	-6.2%							
	4/5/22 13:05	Drift		510	-7.1%							
	4/6/22 7:35	Cal	0.1	550	0.2%	1990	0.5%	10300	1.5%	2.51%	1.0%	1.0
	4/6/22 11:05	Drift		510	-7.1%							
	4/6/22 13:35	Drift		508	-7.5%							
	4/7/22 7:30	Cal	0.2	546	-0.5%	1966	-0.7%	10600	4.4%	2.49%	0.2%	1.0
	4/7/22 11:00	Drift		515	-6.2%							
	4/7/22 13:10	Drift		511	-6.9%							
	4/8/22 7:40	Cal	0.2	551	0.4%	1991	0.6%	10700	5.4%	2.45%	-1.4%	1.0
	4/8/22 11:10	Drift		514	-6.4%							

Notes:
Δ% = Percent Difference calculated as ((Analyzer Response - CH_4 Gas Concentration) / CH_4 Gas Concentration) x 100
ppm = parts per million by volume
L/Min = Liters/Minute
UGSF = Underground Storage Facility

PHX 42 S/N 4640 Daily Calibration & Drift Check

Site			0	549		1980		10,150		2.48%		Flow Check
	Timestamp	Type	ppm	ppm	Δ%	ppm	Δ%	ppm	Δ%	%	Δ%	L/Min
TCF #2	3/8/22 8:30	Cal	0.3	551	0.4%	1982	0.1%	10192	0.4%	2.48%	-0.2%	0.30
	3/8/22 10:55	Drift		543	-1.1%							
	3/9/22 8:05	Cal	0	556	1.3%	1983	0.2%	10,208	0.6%	2.48%	-0.2%	
	3/9/22 11:12	Drift		509	-7.3%							
	3/9/22 11:55	Cal	0.8	554	0.9%	1991	0.6%	10500	3.4%	2.48%	-0.2%	
	3/10/22 8:02	Cal	0.1	560	2.0%	1987	0.4%	10169	0.2%	2.47%	-0.6%	
	3/10/22 10:56	Drift		587	6.9%							
	3/10/22 14:17	Drift		572	4.2%							
TCF #3	3/14/22 10:22	Cal	0.8	556	1.3%	1998	0.9%	10207	0.6%	2.5%	0.2%	
	3/14/22 14:06	Drift		541	-1.5%							
	3/15/22 7:57	Cal	0	577	5.1%	2030	2.5%	10670	5.1%	2.5%	1.0%	0.30
	3/15/22 11:04	Drift		571	4.0%							
	3/15/22 13:29	Drift		568	3.5%							
	3/16/22 8:10	Cal	0	547	-0.4%	1972	-0.4%	10154	0.0%	2.5%	0.2%	
	3/16/22 11:06	Drift		540	-1.6%							
	3/16/22 13:40	Drift		550	0.2%							
	3/17/22 8:14	Cal	0.3	550	0.2%	1984	0.2%	10126	-0.2%	2.5%	-0.2%	0.30
	3/17/22 11:03	Drift		539	-1.8%							
	3/17/22 14:20	Drift		522	-4.9%							
	3/18/22 8:07	Cal	0.5	549	0.0%	1968	-0.6%	10141	-0.1%	2.5%	-0.2%	0.30
	3/18/22 10:30	Drift		544	-0.9%							

Notes:
Δ% = Percent Difference calculated as (($Analyzer Response - CH_4$ Gas Concentration) / CH_4 Gas Concentration) x 100
ppm = parts per million by volume
L/Min = Liters/Minute
TCF = Transmission Compressor Station

APPENDIX B

CALIBRATION GAS CERTIFICATIONS

- Hydrogen (12/16/21)
- Zero Air (12/16/21)
- 549 ppmv Methane-in-Air (12/16/21)
- 1,980 ppmv Methane-in-Air (12/16/21)
- 1,960 ppmv Methane-in-Air (3/15/22)
- 10,150 ppm Methane-in-Air (12/16/21)
- 2.484% Methane-in-Air (12/16/21)
- 2.491% Methane-in-Air (3/15/22)
- 99.99% Methane-in-Air (12/16/21)

Hydrogen Gas

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Oldsmar, FL 34677
(800) 910-0051
fax: (866) 755-8920
www.gascogas.com

CERTIFICATE OF ANALYSIS

Date: December 16, 2021
Order Number: 3365
Lot Number: 304-402305503-1

Customer: Gases 101

Use Before: 12/20/2025

Component	Specification	THC < 0.5 PPM
Hydrogen	99.999% vol.	99.999% vol.

Cylinder Size: 21 Cu. Ft.
Contents: 600 Liter

Valve: CGA 350
Pressure: 2000 psig

Impurities verified against analytical standards traceable to NIST by weight and/or analysis.

Analyst:

Glenn Velez

Zero Gas

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CERTIFICATE OF ANALYSIS

Date: December 16, 2021
Order Number: 3365
Lot Number: 304-402300736-1

Customer: Gases 101

Use Before: 12/20/2025

Component	Requested Concentration	Analytical Result
Oxygen	20-22% vol.	20.9% vol. THC <0.1 PPM

Cylinder Size: 3.70 Cu. Ft.
Contents: 105 Liter

Valve: 5/8"-18 UNF
Pressure: 1200 psig

Impurities verified against analytical standards traceable to NIST by weight and/or analysis.

Analyst:

Glenn Velez

549 ppm CH_4 in Air

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CERTIFICATE OF ANALYSIS

Date: December 16, 2021
Order Number: 3365
Lot Number: 304-402287502-1

Customer: Gases 101
Use Before: 12/20/2025

Component	Requested Concentration	Analytical Result (+/- 2%)
Methane	500 PPM	549 PPM
Air	Balance	Balance

Cylinder Size: 3.70 Cu. Ft.
Contents: 105 Liter

Valve: 5/8"-18 UNF
Pressure: 1200 psig

Product composition verified by direct comparison to calibration standards traceable to N.I.S.T. weights and/ or N.I.S.T. Gas Mixture reference materials.

Analyst:

Glenn Velez

1,980 ppm CH_4 in Air

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CERTIFICATE OF ANALYSIS

Date: December 16, 2021
Order Number: 3365
Lot Number: 304-402305504-1

Customer: Gases 101

Use Before: 12/20/2025

Component	Requested Concentration	Analytical Result (+/- 2%)
Methane	2000 PPM	1980 PPM
Air	Balance	Balance

Cylinder Size: 3.70 Cu. Ft.
Contents: 105 Liter

Valve: 5/8"-18 UNF
Pressure: 1200 psig

Product composition verified by direct comparison to calibration standards traceable to N.I.S.T. weights and/ or N.I.S.T. Gas Mixture reference materials.

Analyst:

Glenn Velez

1,960 ppm CH_4 in Air

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CERTIFICATE OF ANALYSIS

Date: March 15, 2022
Order Number: 3429-REV1
Lot Number: 304-402390972-1

Customer: Gases 101

Use Before: 3/15/2026

Component	Requested Concentration	Analytical Result (+/- 2%)
Methane	2000 PPM	1960 PPM
Air	Balance	Balance

Cylinder Size: 3.70 Cu. Ft.
Contents: 105 Liter

Valve: 5/8"-18 UNF
Pressure: 1200 psig

Product composition verified by direct comparison to calibration standards traceable to N.I.S.T. weights and/ or N.I.S.T. Gas Mixture reference materials.

Analyst:

Nicholas Raymond

10,150 ppm CH_4 in Air

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CERTIFICATE OF ANALYSIS

Date: December 16, 2021
Order Number: 3365
Lot Number: 304-402305505-1

Customer: Gases 101

Use Before: 12/20/2025

Component	Requested Concentration	Analytical Result (+/- 2%)
Methane	1% vol.	1.015% vol.
Air	Balance	Balance

Cylinder Size: 3.70 Cu. Ft.
Contents: 105 Liter

Valve: 5/8"-18 UNF
Pressure: 1200 psig

Product composition verified by direct comparison to calibration standards traceable to N.I.S.T. weights and/ or N.I.S.T. Gas Mixture reference materials.

Analyst:

Glenn Velez

2.484% vol. CH_4 in Air

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CERTIFICATE OF ANALYSIS

Date: December 16, 2021
Order Number: 3365
Lot Number: 304-402312179-1

Customer: Gases 101

Use Before: 12/20/2025

Component	Requested Concentration	Analytical Result (+/- 2%)
Methane	2.5% vol. (50% LEL)	2.484% vol.
Air	Balance	Balance

Cylinder Size: 3.70 Cu. Ft.
Contents: 105 Liter

Valve: 5/8"-18 UNF
Pressure: 1200 psig

Product composition verified by direct comparison to calibration standards traceable to N.I.S.T. weights and/ or N.I.S.T. Gas Mixture reference materials.

Analyst:

Glenn Velez

2.491% CH_4 in Air

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CERTIFICATE OF ANALYSIS

Date: March 15, 2022
Order Number: 3429-REV1
Lot Number: 304-402313985-1

Customer: Gases 101

Use Before: 03/15/2026

Component	Requested Concentration	Analytical Result (+/- 2%)
Methane	2.5% vol. (50% LEL)	2.491% vol.
Air	Balance	Balance

Cylinder Size: 3.70 Cu. Ft.
Contents: 105 Liter

Valve: 5/8"-18 UNF
Pressure: 1200 psig

Product composition verified by direct comparison to calibration standards traceable to N.I.S.T. weights and/ or N.I.S.T. Gas Mixture reference materials.

Analyst:

Nicholas Raymond

99.99% CH_4 in Air

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CERTIFICATE OF ANALYSIS

Date: December 16, 2021
Order Number: 3365
Lot Number: 304-402305506-1

Customer: Gases 101

Use Before: 12/20/2025

Component	Specification	THC < 0.5 PPM
Methane	99.999% vol.	99.99% vol.

Cylinder Size: 3.70 Cu. Ft.
Contents: 105 Liter

Valve: 5/8"-18 UNF
Pressure: 1200 psig

Impurities verified against analytical standards traceable to NIST by weight and/or analysis.

Analyst:

Glenn Velez