THESIS

EVALUATION OF COMMERCIALLY AVAILABLE ON-LINE ANALYZERS FOR MEASUREMENT OF NATURAL GAS CONTAMINANTS

Submitted by

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ABSTRACT

EVALUATION OF COMMERCIALLY AVAILABLE ON-LINE ANALYZERS FOR MEASUREMENT OF NATURAL GAS CONTAMINANTS

The proliferation of natural gas usage and extraction has led to never-before-seen levels of demand across the United States in several industries. Because of this increased demand for quality processed natural gas, a need has arisen to streamline its processing and distribution for faster and more efficient delivery to customers. One method to achieve this is by consolidating natural gas contaminant analyzers at processing and distribution sites; current sites typically operate with multiple separate gas analyzers, each dedicated to measuring one individual contaminant species.

Recent developments in laser-based gas composition analysis (in particular Tunable Diode Laser Absorption Spectroscopy or TDLAS) as well as advances in gas chromatograph (GC) technology have given rise to commercially-available analyzing instruments which are capable of detecting and measuring multiple gas contaminants simultaneously. In order to verify the effectiveness and reliability of these new technologies, three specific gas analyzing instruments (herein referred to as Instruments A, B, and C) were selected for in-depth laboratory and field testing. The main objective of this research is to quantify the accuracy, precision and uncertainty of these new multi-species gas analyzers and compare their performance with existing gas analyzers currently in use by natural gas processing and distribution organizations.

Four natural gas contaminant species were specified for evaluation of the natural gas contaminant analyzers; these are water (H_2O), hydrogen sulfide (H_2S), oxygen (O_2) and carbon dioxide (CO_2). Laboratory testing was performed first by sampling existing natural gas from three separate sources then by custom gas mixtures blended in-house from pure component gases to simulate four levels of contaminants (Low, two Mid-range blends, and High). For results verification a sample of each gas mixture (both source natural gas and custom blends) was submitted to EMPACT Analytical Inc. for composition analysis. Following laboratory testing, two instruments were selected for ongoing (through February 2022) field testing to simulate "real-world" conditions and their results are compared with those of existing on-site gas contaminant analyzers.

It was concluded that Instrument A (TDLAS-based) was the most accurate and reliable of the three analyzers under test and required the least amount of user intervention to maintain satisfactory operation. Instrument B (also TDLAS-based) ranked a close second-place, having slightly less accuracy than Instrument A in measuring gas concentrations and falling short by its inability to detect O_2; it also experienced multiple failures which required user intervention and/or shipping the instrument back to the manufacturer for repair and reconfiguration. Instrument C (GC-based) performed the poorest of the three analyzers with very low accuracy in measuring O_2 and H_2O to the point of being essentially non-detected species; it also required in-depth user intervention for initial setup and on multiple occasions during operation which was determined to be inappropriate for the intended application.

ACKNOWLEDGMENTS

The experience of working toward a Master of Science degree from Colorado State University is one I will surely remember for the rest of my life. Returning to higher education after a four-year lapse from a not-so-positive undergrad experience proved to be difficult but also immensely rewarding. Being able to engage in research at the Powerhouse Energy Institute with the kind of thoughtful, intelligent and motivated staff, faculty and students there was truly a privilege. The people I met and the experiences I shared with them have motivated and shaped me for the better and I feel that I have grown immensely as a human overall in the past two and a half years.

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Most of all I must thank my parents, in particular my father, for providing relentless support and motivation in the endeavor to raise my level of education and improve my future. My father has always led by example, himself attaining a Ph.D in Civil Engineering when I was a child which greatly motivated me to also pursue an engineering degree. Without my parents' constant push for me to realize my potential I would surely not have made it to this point in my education and career. The sacrifices (both financial and otherwise) my parents made to ensure my future cannot go unappreciated and I will forever be in their debt. I am also thankful for their constant motivation in upholding the noble values and teachings of my Islamic faith which was a key motivating factor in my pursuing higher education. Finally, I must give praise to God for blessing me with these opportunities to improve myself as a human being since education has not only increased my knowledge but challenged me to raise my perseverance and self-discipline to levels I did not think I would be able to achieve.

TABLE OF CONTENTS

ABSTRACT ii
ACKNOWLEDGEMENTS iii
DEFINITION OF TERMS vii
CHAPTER 1 – INTRODUCTION 1
1.1 Background 1
1.2 Natural Gas Contaminant Quantification 7
1.3 Scope Overview 11
CHAPTER 2 – METHODS AND MATERIALS 14
2.1 Test Approach 14
2.2 Utility/Field Natural Gas Testing 17
2.3 Selected Analyzer Operation 18
2.4 Testing System Layout 20
2.5 Molar Concentration Analysis 26
2.6 Data Acquisition Program 28
2.7 Test Plan and Procedure 29
2.8 Uncertainty Calculation Methods 35
CHAPTER 3 – COMPARISON OF CONTAMINANT ANALYZERS 39
3.1 Initial Analyzer Start-Up 39
3.2 Analyzer Source Natural Gas Contaminant Results 41
3.3 Analyzer Contaminant Custom Blend Results 45
3.4 Analyzer Performance Evaluation 56
CHAPTER 4 – FIELD TESTING OF CONTAMINANT ANALYZERS 60
4.1 Field Test Site 60
4.2 On-Site Gas Analyzers 64
4.3 Field Test Experimental Setup 68
4.4 Initial Field Test Results 72
CHAPTER 5 – CONCLUSION AND ONGOING WORK 78
5.1 Laboratory Testing Evaluation 78
5.2 Field Testing 81
5.3 Ongoing Work 81
REFERENCES 82
APPENDIX A: OTHER SPECIES RESULTS 86
APPENDIX B: THIRD-PARTY LABORATORY RESULTS 98
APPENDIX C: UNCERTAINTY CALCULATIONS 113
APPENDIX D: CIG NATURAL GAS TARIFF 118

DEFINITION OF TERMS

FERC – U.S. Federal Energy Regulatory Commission

CIG – Colorado Interstate Gas company

GC – Gas Chromatograph

TCD – Thermal Conductivity Detector

TDLAS – Tunable Diode Laser Absorption Spectroscopy

CSU – Colorado State University

MEMS – Micro Electro-Mechanical System

LGR – Los Gatos Research

ICOS – Integrated-Cavity Output Spectroscopy

OFCEAS – Optical Feedback Cavity Enhanced Absorption Spectroscopy

EECL – Engines and Energy Conversion Labs

BPR – Back-Pressure Regulator

SCFM – Standard Cubic Feet per Minute

LPS – Low Pressure Sampling

GPA – Gas Processors Association

DAQ – Data Acquisition

ASTM – American Society for Testing and Materials

LOD – Limit of Detection

GUI – Graphical User Interface

CHAPTER 1 – INTRODUCTION

1.1 Background

From the middle of the 20th Century to today natural gas has seen a steady rise in usage for various applications ranging from stationary power generation to transportation and industrial chemical production [1]. The trend of natural gas consumption vs. time from 1950 to present is shown in Figure 1-1.

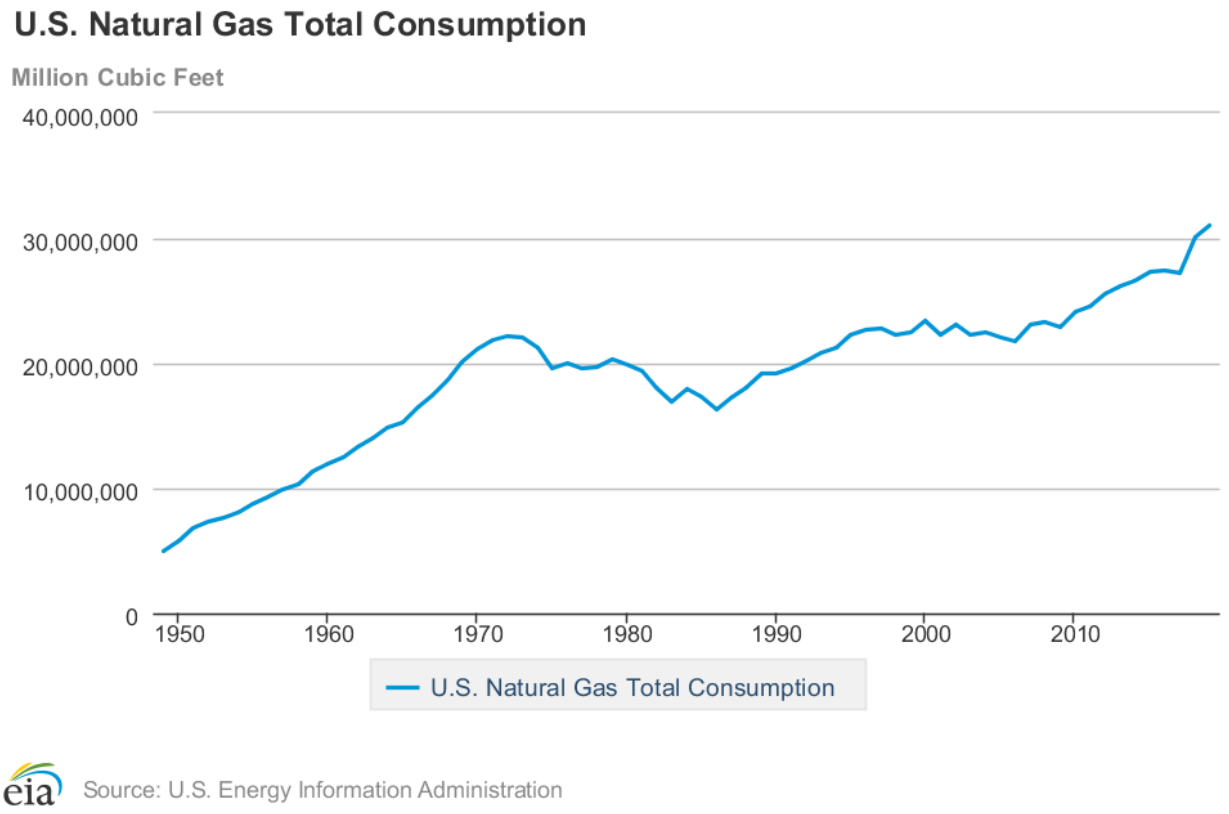


Figure 1-1. United States Natural Gas Consumption trend over time [1].

As can be seen in Figure 1-1 the consumption of natural gas has been increasing since the mid-1980s following a slight decrease between 1970 and 1985. The ongoing trend of increased natural gas demand and the subsequent rise in its production have made standardization of its composition an ever-growing need. This increasing need has led to a response by the commercial

gas analyzer industry to develop and release on-line analyzers capable of measuring multiple gas components simultaneously, as opposed to individual analyzers for each gas component which is the current convention in natural gas processing and transportation. These on-line, rapid-analysis devices allow for a streamlined analysis process and reduced time required to attain accurate gas composition data. Accurate analysis of not only the energy content but also the gas composition with regards to unwanted contaminants is a high priority among regulatory bodies, refinement facilities and trading organizations [2].

Natural gas composition (referred to as quality) is regulated through tariff agreements between pipeline owners which are filed with the United States Federal Energy Regulatory Commission (FERC). Figure 1-2 shows an asset map of pipelines and sites owned by Kinder Morgan, one of the major conglomerates overseeing natural gas production in the United States.

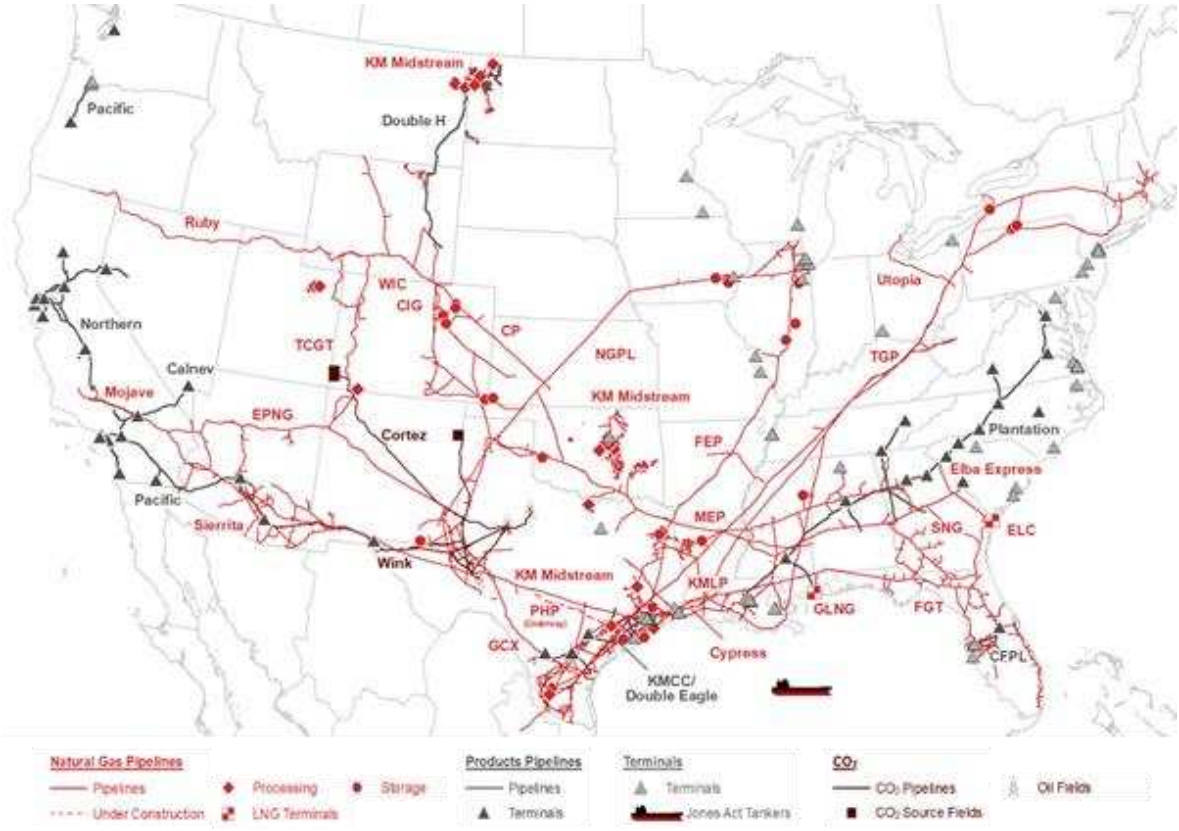


Figure 1-2. Kinder Morgan United States asset map; Natural Gas in red [3].

One company within the Kinder Morgan network is Colorado Interstate Gas (CIG). It is responsible for the transport of natural gas from production areas in the Rocky Mountains to Colorado, Wyoming and indirectly to much of the western half of the continental United States. Among the details of its tariff, which include statements of transport and storage rates, definitions of terms and conditions and forms of service agreements, are specifications for gas quality. The CIG Tariff of 2013 states: "At a pressure of 14.73 psia and a temperature of 60°F, such Gas shall not contain more than: (i) 0.25 grain of hydrogen sulphide per 100 cubic feet, (ii) 5 grains of total Sulphur per 100 cubic feet, (iii) 10 parts per million (0.001 percent) by volume of oxygen, (iv) 3.0 percent by volume of carbon dioxide, (v) 7 pounds of water vapor per million cubic feet in Kansas, Oklahoma and Texas and 5 pounds of water vapor per million cubic feet in all other states." It also specifies Gross Heating Value must fall between 968 and 1,235 Btu/SCF [4]. In situations where a natural gas site detects contaminants over the allowable limit, the site will "shut-in" meaning it stops the transfer of pipeline gas to the next site until the cause of the contaminant increase is found and fixed. This typically entails a thorough analysis of the pipeline and processing equipment to check for leaks and additional analysis of the gas composition to verify the level of contaminants. If no issue is found at the site where the contaminated gas was detected, the previous natural gas site just upstream in the pipeline is contacted and is required to perform similar checks to its measurement, pipeline and processing equipment until the natural gas contaminants are reduced back to acceptable levels.

Depending on the location and method of extraction (crude oil wells, gas wells or condensate wells), raw natural gas can vary widely in composition of unwanted contaminants and energy content [2]. Current industry conventions classify natural gas based on its origin and

chemical composition in two main categories: conventional and unconventional gas. Conventional gas occurs in deep reservoirs and can either be associated or non-associated with crude oil. Unconventional gas is found in other forms based on its source which can be shale rock, coalbeds, deep aquifers or crystalline gas hydrate (essentially natural gas trapped in ice) [2]. Having accurate knowledge of energy content is crucial in determining the monetary value of natural gas; energy content is determined by the ratio of reactive species (hydrocarbons) to non-reactive (carbon dioxide, helium, nitrogen) ones that make up the gas mixture. The non-reactive species which reduce the heating value are referred to as "diluents". Contaminants are other gas species which may reduce the energy content of a natural gas mixture but more importantly are harmful to the environment and/or corrosive and can cause damage to transport piping and equipment over time. Contaminant composition is important in determining how much and what type of processing will be required to make the gas suitable for transportation and ultimately for use by the consumer [2].

Hydrogen sulfide is one such component of raw unrefined natural gas found in almost every natural gas source to some degree; source natural gas is referred to as "sweet" if there is little to no H2S content or "sour" if levels of H2S are above acceptable quantities. Some reported sources can be as high as 2 percent or 20,000 ppm of the total gas mixture [5]. This is considered an exceedingly high amount in the context of public safety as hydrogen sulfide has deadly effects on the human respiratory system. Exposure to concentrations near 100 ppm over prolonged duration (30 minutes or more) causes breathing difficulty, noncardiogenic pulmonary edema, cyanosis and ultimately coma or death [6]. According to the National Institute for Occupational Safety and Health, exposure to only 500 ppm can be deadly over prolonged periods (30-60

minutes) and levels over 1000 ppm can cause near-instant death [7]. Although it does have a strong odor one particularly dangerous side-effect is fatigue of the olfactory nerves at 100 ppm concentrations which renders a human unable to detect the gas's presence by smell [7]. Hydrogen sulfide is also highly corrosive and readily combusts with air in a wide range of concentrations from as little as 4.5 percent to as high as 45 percent (45,000 to 450,000 ppm) often with explosive effects [8]. Its corrosive effects on steel, a common material used in natural gas processing and transportation, have been widely investigated and are determined to result from mixtures of water and hydrogen sulfide present in the natural gas being transported. When the steel corrodes in the presence of these two substances hydrogen is released and rapidly absorbed by the metal causing internal cracking and structural degradation [9]. Figure 1-3 shows samples of pipe steel exposed to a hydrogen sulfide-water solution and the effect of hydrogen absorption into the metal.

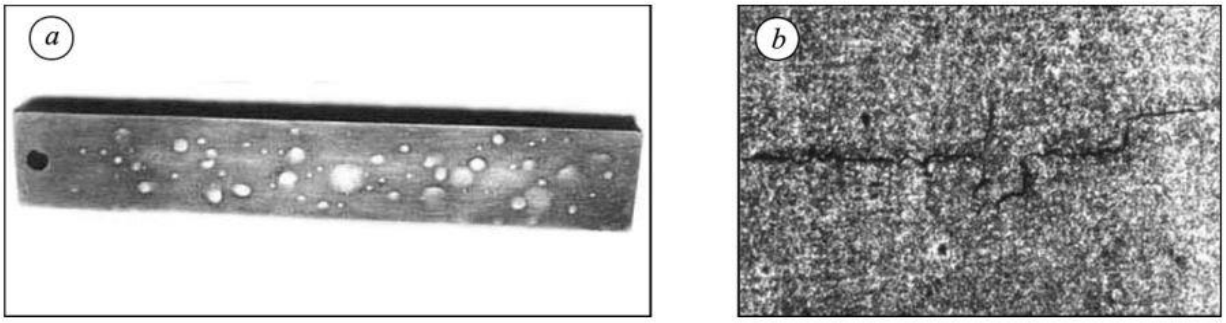


Figure 1-3. Surface blisters (a) and hydrogen-induced cracking (b) formed in pipe steel tested for 96 hours in a hydrogen-sulfide solution in the absence of external stresses [9].

These corrosion issues also affect wear in natural gas compressor engines. Water is a product of the natural gas combustion reaction with air; piston rings in internal combustion engines rarely provide a perfect seal between the combustion chamber and crankcase so some intake and combustion gases inevitably escape past the rings into the engine crankcase. Over time the

engine oil in the crankcase accumulates hydrogen sulfide and water which react with the engine oil and form acids. These acids corrode and cause accelerated wear of critical internal engine components such as crankshaft bearings and piston rings, reducing the longevity of natural gas engines and requiring shortened maintenance intervals and additional specialized equipment and procedures to combat the negative effects of hydrogen sulfide [10].

Other common contaminants like water and oxygen do not pose the same environmental and public health risks but still negatively impact natural gas value. The presence of water causes oxidation reactions with materials in transport equipment accelerating corrosion and wear and at low temperatures can cause damage to equipment from freezing. Oxygen is not found naturally in raw natural gas but migrates into the mixture from outside air through leaks in transport equipment and causes significant amounts of corrosion after reacting with other component gases [2].

In order to achieve required natural gas quality the raw product must be processed, oftentimes in multiple phases. Each phase addresses the removal of unwanted components such as heavy hydrocarbons, nitrogen, water and acid gases. Natural gas processing plants must be designed based on the types of phases and degree to which each phase must alter the gas's composition. Much of the technologies employed in the construction and operation of processing plants depends on the composition of the raw gas to be processed. Heavy hydrocarbon components of raw natural gas such as butane and propane can be separated, recovered and fractionated to be sold individually or blended as liquefied petroleum gas. Heavy components can be separated by cooling, oil absorption, adsorption or membrane processes. Water in liquid form can be separated relatively simply by cooling of the gas mixture. Water in

vapor form, however, requires more complex processes such as absorption by a chemical reaction, adsorption into a desiccant-type substance, or at low pressures a gas permeation process using membranes. The most common method for water removal is by using glycol separators, a type of liquid desiccant [2]. Nitrogen is removed by cryogenic distillation, pressure swing adsorption or membrane separation. Helium is also a component of natural gas in varying amounts and is a valuable commodity in other industries. Its concentration in a raw natural gas mixture determines whether the additional cost of helium extraction is justified and is typically done through nitrogen injection. Oxygen at low concentrations is removed by non-regenerative scavengers and at high concentrations by a catalytic reaction to produce water which can then be taken out in the dehydration process [2]. The presence of both carbon dioxide and hydrogen sulfide can cause weak acids to form when also present with water. Both carbon dioxide and hydrogen sulfide can be removed in the same process, usually involving washing the gas mixture with amine compounds, potassium carbonate or a caustic solution based on a sodium hydroxide compound [2]. They can also be removed by adsorbent processes such as molecular sieves or membranes although membrane processes are limited to carbon dioxide removal due to mechanical weaknesses of the membranes in high-pressure, high-temperature conditions which are required for hydrogen sulfide processing [2].

1.2 Natural Gas Contaminant Quantification

As of calendar year 2020 the majority of natural gas composition analysis has been performed using multiple individual instruments, each dedicated to a limited number of gas species. The MEAS-9-01 committee of the Pipeline Research Council International (PRCI) has identified the

need to evaluate on-line instruments capable of detecting multiple natural gas contaminants in real time; these instruments have become commercially available only in recent years due to proliferation of laser-based gas analysis. It has been realized that if current multiple-instrument setups can be replaced or supplemented with one instrument to detect a range of contaminant species, operating and maintenance costs can be reduced while simultaneously enhancing measurement and detection capabilities. Current commercially available natural gas analyzing devices use one of two main methods for determining gas composition: gas chromatography and laser spectroscopy. Gas chromatography has existed much longer than laser spectroscopy with its beginnings dating back to the 1940s [11]. Gas chromatography (GC) involves physically separating the gas mixture into its individual components which are then fed into a detector and analyzed. Physical separation of the gas components is accomplished by injecting the sample gas into a carrier gas stream which then travels through a column typically made of a long tube wound in a spiral with a small internal diameter and maintained at a specified temperature. The GC column has a stationary phase (either liquid or solid) coating the inside of the tubing; this stationary phase can be made of one of multiple possible structures. The structure and composition of the stationary phase depends on the expected compounds to be analyzed (polar, nonpolar or hydrogen-bond) and multiple GC columns can be combined into a single unit to broaden the number of detectable compounds in a mixture sample [12]. Figure 1-4 shows a simplified diagram of a typical gas chromatography system. Depending on the affinity of the different components of the gas mixture to absorb into the stationary phase each component will reach the detector in varying concentrations by the time it has traveled completely through the GC column. The analog signal produced by the detector is then processed into a digital plot

of the gas composition called a Chromatogram [13]. Figure 1-5 shows an example chromatogram with the signal peaks corresponding to the retention time of each analyte component in the sample. The signal peaks indicate the chemical compounds detected and are categorized by pre-calculated retention times in the specific GC column being used.

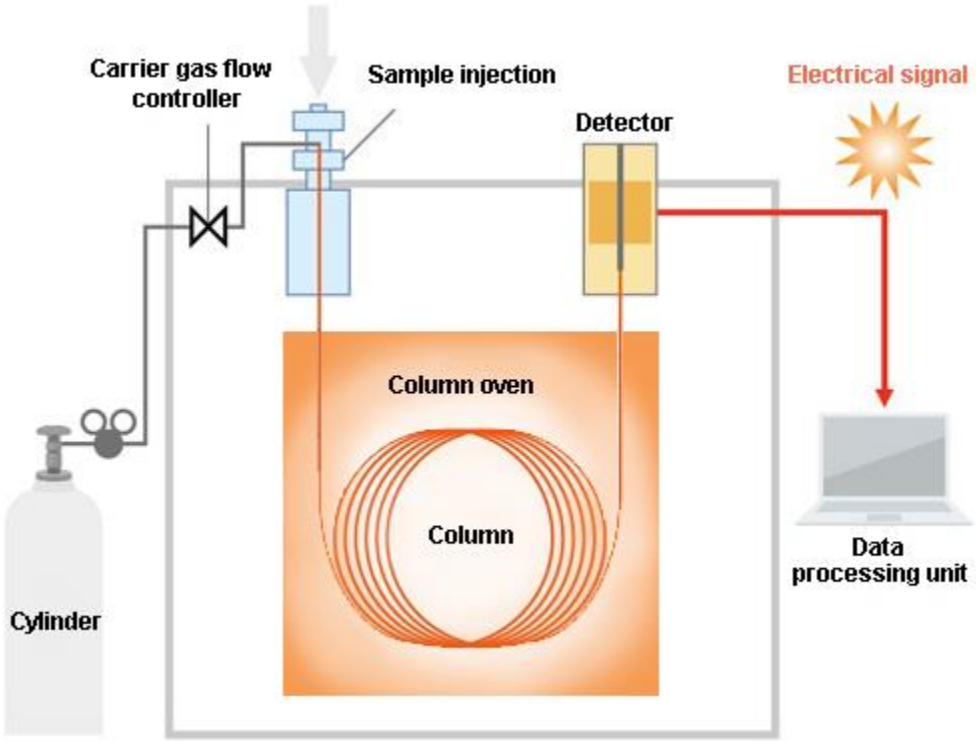


Figure 1-4. Diagram showing basic layout of a gas chromatography analyzer [12].

Laser spectroscopy, or more specifically Tunable Diode Laser Absorption Spectrometry (TDLAS) is a process which involves employing laser light tuned to specific frequencies in order to interact with different components of a gas mixture sample. Gas molecules absorb light in specific wavelengths depending on their molecular energy level and structure; these characteristics are unique to each molecular compound as long as physical properties (temperature and pressure) are held constant. In a TDLAS system, laser light is projected through the gas sample to be analyzed; it then passes through optical lenses which focus the light into a

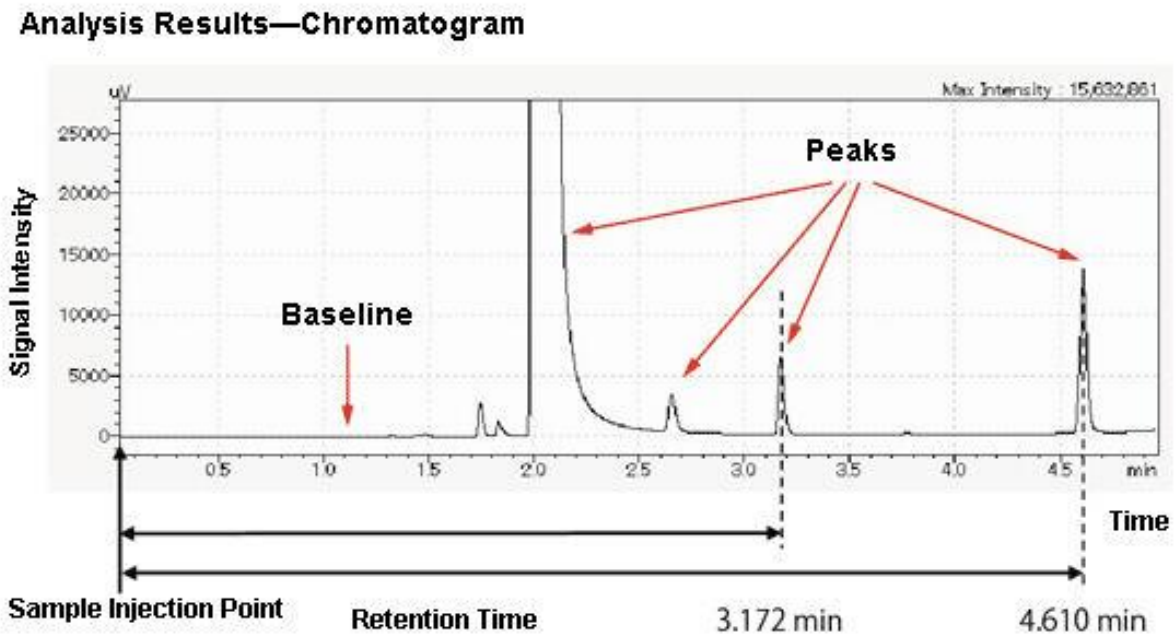


Figure 1-5. Example chromatogram showing signal peaks corresponding to retention time of the sample component in a GC column [12].

detector. The detector then feeds an analog signal to a processing unit which converts the signal into usable data giving the concentration and composition of the sample gas. Because different gaseous compounds each absorb specific wavelengths of light a typical TDLAS system is built with the intended analyte gas in mind. Each system is built using a laser with a specific design wavelength which corresponds to the specific absorption line of the analyte gas and is free from interfering absorption from other molecules [14]. According to Frish et al [14], "Accurate control of the laser injection current and temperature achieves rapid and precise tuning over a range of ±2 nm around the specified wavelength." Figure 1-6 shows a diagram of a simple TDLAS gas detector system.

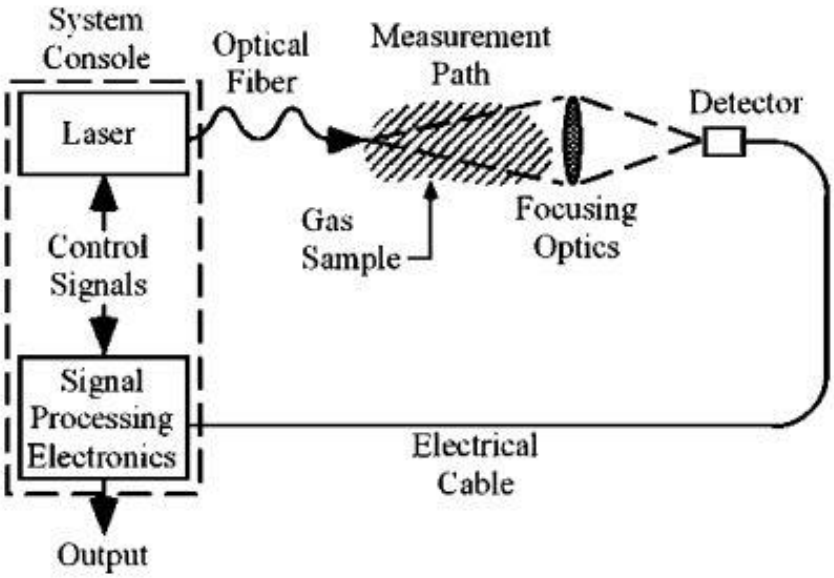


Figure 1-6. Simplified diagram of a typical TDLAS gas detector system [14].

Examples of currently available gas analyzing instruments using TDLAS are the SpectraSensors 3-pack [15], ABB LGR-ICOS [16], AP2E ProCeas [17] and Emerson Rosemount CT5800 [18]. Some available analyzers based on Gas Chromatography include the APIX ChromPix [19] and Elster EnCal 3000 [20].

1.3 Scope Overview

The main objective of this project is to test the capabilities of natural gas analyzers to determine which would be best for real-world in-the-field use at natural gas production and distribution sites. This objective will be completed based on multiple criteria; along with accuracy and precision of measuring gas mixture components each analyzer will be evaluated based on its level of required intervention and ease of repair by the end user which comprises Phase 1 of the project. Phase 2 is a long-term durability test in the field of the best-performing analyzers of

Phase 1. The first phase of the project will be performed in the Engines and Energy Conversion Labs at the CSU Powerhouse Energy Campus. The Engines Lab itself is a large open space within the Powerhouse that contains a separate enclosed area with sound insulation and privacy windows typically used for sensitive engine testing which is not to be displayed to the public; this enclosed space was selected for testing of the natural gas analyzers since it lends itself well to maintaining consistent ambient conditions and a secure area with lockable doors to prevent tampering with testing equipment and instruments. Figure 1-7 shows a top-down diagram of the general testing area layout.

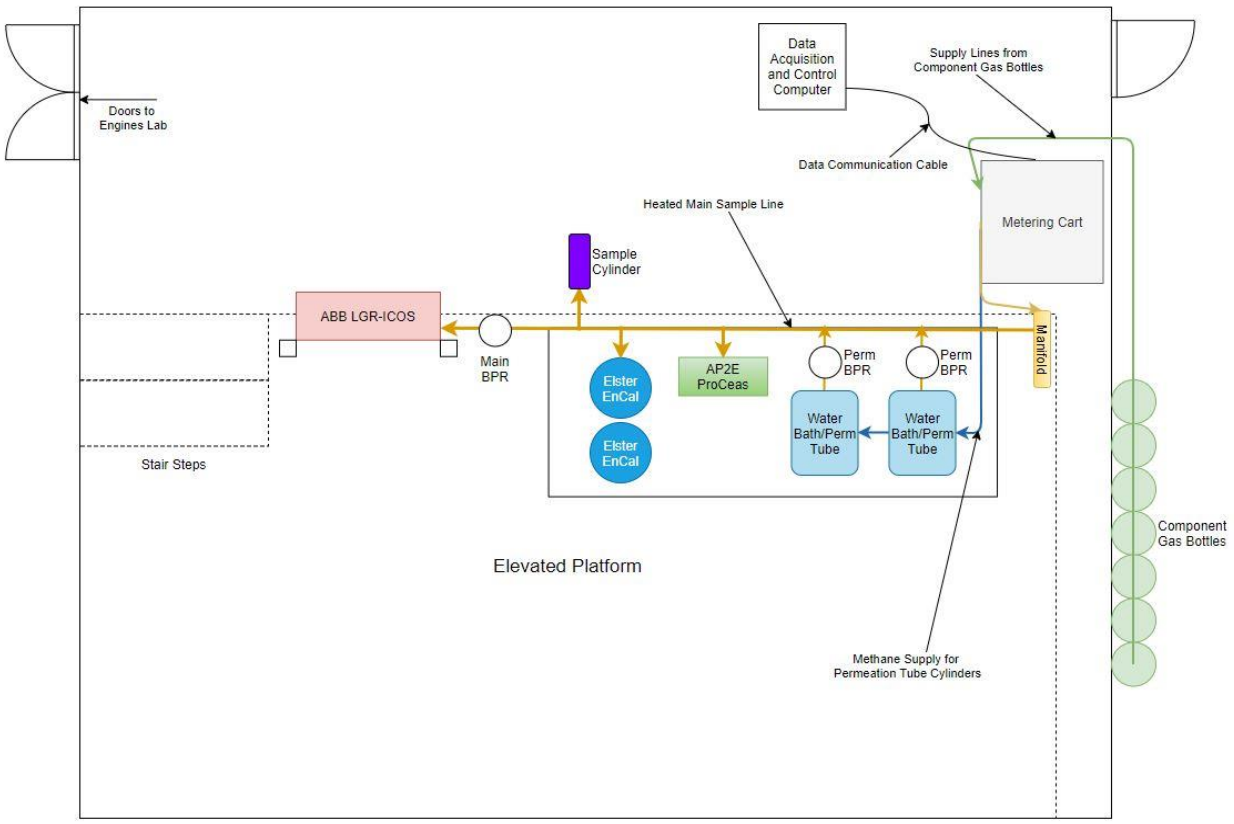


Figure 1-7. Top-down schematic of laboratory test area located within Engines Lab of CSU Energy Institute.

The structure of this thesis consists of five chapters. Chapter one is an introduction outlining the background and scope of the research project and its main objectives. Chapter two details the methods and materials used to perform the experiments by describing the testing approach and system design as well as a test plan and procedure and outlining the approach for determining uncertainty in the experimental results. Chapter three displays the experimental results and discusses what the results indicate in the context of the project objectives and goes into detail comparing the performance of the individual gas analyzing instruments. Chapter four discusses long-term field testing (Phase 2) of the project. Lastly, chapter five is a conclusion summarizing the findings and discussing how the experimental results allowed the objective criteria to be met; it also discusses ongoing work for the project outside the scope of this paper.

CHAPTER 2 – METHODS AND MATERIALS

2.1 Test Approach

Testing the functionality of the gas analyzers involves flowing gas mixtures simulating different compositions of commonly occurring natural gas. Four gas mixtures were chosen with varying levels of CO_2, O_2, H_2O and H_2S with the remaining composition consisting of primarily CH_4 (85 percent) and C_2H_6 (8 to 12 percent) with 2 to 3 percent C_3H_8. Contaminant target levels are displayed in Table 2-1.

Table 2-1. Gas mixture contaminant targets in mole percent.

Species	Contaminant Target			
	Low	Mid (a)	Mid (b)	High
CO_2 (%)	0.1	2	3.4	10
O_2 (%)	0.05	0.2	0.4	1
H_2O (ppm)	20	95	145	500
H_2S (ppm)	1	4.5	4.5	20

In order to test the analyzing instruments two methods were considered, one using pre-mixed natural gas blends and the other using online real-time gas blending with high-purity component gases typically found in natural gas. Both options had advantages and disadvantages; using pre-mixed gas blends would eliminate potential errors in the blending process but due to the volatile and explosive nature of the blends required there would be long lead times and high cost involved. It would also be difficult to procure pre-blended mixtures containing the required toxic and unstable sulfur compounds and use those mixtures in a timely fashion to reduce the potential of gas blend degradation within the bottles due to component separation or reaction either with

each other or with the container walls. Blending the gas in real time using individual ultra-high-purity component gases would reduce the cost and lead time for procuring the gas bottles but has more potential sources of error. This increased margin of error must be identified and accounted for by comparing results to sample analysis results from a third-party gas analysis laboratory in order to confirm the blending methods used. The latter option of blending gases in real time was chosen due to these advantages and the greater level of control and precision allowed in creating custom gas blends to our specifications. This required a custom designed and constructed blending system to control the individual flows of component gases. Most of the component gases would be stored in UHP gas bottles while the water and hydrogen sulfide contaminants would be introduced into the blended gas stream through permeation tube cylinders for greater safety and control.

Of the gas analyzers noted in Chapter 1 three were chosen to be tested with one being a gas chromatograph and the other two using laser spectroscopy; these will be referred to henceforth as Instrument A, Instrument B and Instrument C. Testing will be performed using a system designed and built in-house at the CSU Engines and Energy Conversion Laboratories to simulate real-world natural gas mixtures. Results from testing would be compared to gas mixture composition analysis by a third-party lab, EMPACT Analytical Systems Inc. located in Brighton, Colorado. EMPACT adheres to GPA (Gas Processors Association) 2261, 2145 and 2172 standard analysis procedures. These procedures outline the usage of gas chromatography in determining the composition of natural gas and similar gaseous mixtures and specify the range of gas components covered, methods for calibrating equipment, procedures for analyzing and calculating component concentrations and also the required level of precision (repeatability and

reproducibility) for each natural gas component [21]. Tables 2-2 and 2-3 describe the gas component molar concentration ranges and repeatability and reproducibility precision limits set by GPA Standard 2261 respectively. EMPACT declined from providing specific information on the type of instruments used in their analysis procedures for the sake of maintaining confidentiality in its specific equipment and methods used.

Table 2-2. List of natural gas components and concentration ranges specified by GPA 2261 [21].

Components	**Concentration Range Mol. %**
Helium	0.01 - 10
Oxygen	0.01 - 20
Nitrogen	0.01 - 100
Carbon Dioxide	0.01 - 20
Methane	0.01 - 100
Ethane	0.01 - 100
Hydrogen Sulfide	0.01 - 100
Propane	0.01 - 100
Isobutane	0.01 - 10
n-Butane	0.01 - 10
Isopentane	0.01 - 2
n-Pentane	0.01 - 2
Hexanes & Heavier	0.01 - 2

Table 2-3. List of precision limits for each gas component in percent relative to the specified mole percent ranges for GPA 2261 standard [21].

Component	Mol % Range	% Relative Repeatability	% Relative Reproducibility
Nitrogen	1.0 - 7.7	2	7
Carbon Dioxide	0.14 - 7.9	3	12
Methane	71.6 - 86.4	0.2	0.7
Ethane	4.9 - 9.7	1	2
Propane	2.3 - 4.3	1	2
Isobutane	0.26 - 1.0	2	4
n-Butane	0.6 - 1.9	2	4
Isopentane	0.12 - 0.45	3	6
n-Pentane	0.14 - 0.42	3	6
C_6^+	0.10 - 0.35	10	30

2.2 Utility/Field Natural Gas Testing

To provide a standard in which to compare the custom-blended natural gas mixtures three samples of utility natural gas were acquired. Two of the samples came from two different locations at a site in northeast Colorado called DCP Mewbourn (referred to as “Field Gas 1” and “Field Gas 2”), each from a separate pipeline which supplied gas from slightly different sources. The third sample was acquired on-site from the local natural gas utility supply at the CSU Powerhouse Energy Campus (referred to as “Utility Gas”). Due to the relative ease in plumbing these single gas bottles into the analyzer testing system they will be the first gases to be flowed through the analyzers. This will check the functionality of the testing setup and aide in any

debugging or modifications before proceeding to online blending of the individual component gases. As the source utility gas is flowed through the analyzers it will be captured in small sample cylinders to be taken to an outside lab for third-party analysis, EMPACT Analytics in Brighton, CO.

2.3 Selected Analyzer Operation

Instrument C

Instrument C uses process gas chromatography incorporating a Thermal Conductivity Detector using modern MEMS technology (Micro-Electro-Mechanical System) for a compact standalone analyzing device. The GC column is made of inert material (fused silica and stainless steel) formed into a spiral with a total length on the order of several meters and an internal diameter of less than 0.1 millimeter. Depending on the model of analyzer and gases to be analyzed the GC column within Instrument C can be one of four configurations, each utilizing different structures within the tubing to support the stationary phase [22]. The GC detector in Instrument C is of the Thermal Conductivity (TCD) type where two detectors (reference and measurement) are integrated into a "Wheatstone" configuration; the change in conductivity of the detector depends on the gas species which contacts the TCD and is how gas composition is determined.

Advantages of Instrument C include a fully integrated stand-alone design with each dual-column unit weighing around 67 lbs and having external dimensions of roughly a 13" wide by 13" tall cylinder. Its explosion-proof housing and internal thermal controls along with rugged physical construction allow it to be installed and operate in harsh real-world conditions encountered at

many gas processing and transport sites and is configured so that it can be mounted to a vertical or horizontal surface [22]. A main disadvantage is the need for an inert (typically Helium or Argon) carrier gas supply in addition to the sample gas supply.

Instrument A

Instrument A uses TDLAS technology but employed in a unique manner. In this system an arrangement of high-reflectivity mirrors create an enclosure into which laser light is admitted; the arrangement of the mirrors being slightly off-axis from the initial direction of the laser effectively traps the laser photon so that the photon makes thousands of passes before leaving the cavity. In this manner the effective optical path length is on the order of several thousand meters, significantly enhancing the measured absorption of light into the sample gas within the cavity. Along with this advantage, the lack of a required specific beam trajectory means the optical alignment is very robust compared to conventional multi-pass spectroscopy analyzers and is well suited for field use in harsh conditions [23]. Aside from this design feature Instrument A operates on conventional tunable-laser absorption-spectroscopy methods outlined previously. Even though it is a robust, low-maintenance design, its primary drawback is its large size (30in x 30in x 16in) and heavy weight, nearly 150 pounds. It also can only be mounted vertically on a wall or rack; it cannot be mounted horizontally, for example on a table or platform.

Instrument B

Similar in operation to Instrument A, Instrument B uses laser absorption spectroscopy to analyze the composition of gas mixtures. In this device a laser of specifically tuned wavelength enters a cavity made up of several high-reflectivity mirrors; this causes the laser to reflect back

and forth within the cavity hundreds of times before exiting into the detector unit. Based on its description, Instrument B operates similarly to Instrument A but with a smaller footprint and the ability to measure hydrocarbons such as CH_4 and C_2H_6. Also, unlike Instrument A, Instrument B uses Low Pressure Sampling (LPS) which reduces the pressure of the sample gas going into the laser cavity. This has the benefits of lowering the dew point of the sample gas, increasing the velocity and thus transfer time of the sample, reducing sample gas consumption and reducing gas optical interactions within the cavity which increases the spectrum resolution. This improves the ability to distinguish between spectrum peaks and reduces the likelihood of cross sensitivities and false positives [24]. Table 2-4 lists the selected instruments with their respective detection method and detected contaminants.

Table 2-4. Selected gas analyzers with their detection method and contaminants detected

Analyzer	Detection Method	Contaminants Detected
Instrument A	Laser Spectroscopy (TDLAS)	H_2O, H_2S, CO_2, O_2
Instrument B	Laser Spectroscopy (TDLAS)	H_2O, H_2S, CO_2, C_2H_6
Instrument C	Gas Chromatography	H_2O, H_2S, CO_2, O_2, C_2H_6

2.4 Testing System Layout

The system designed for metering and blending component gases into the desired mixture is based on choked-flow orifices for flow control. Figure 2-1 shows a detailed schematic of the blending system which includes all pressure regulators, valves and orifices with their respective target settings. Figure 2-2 shows a 3D model of the blending system created in SolidWorks.

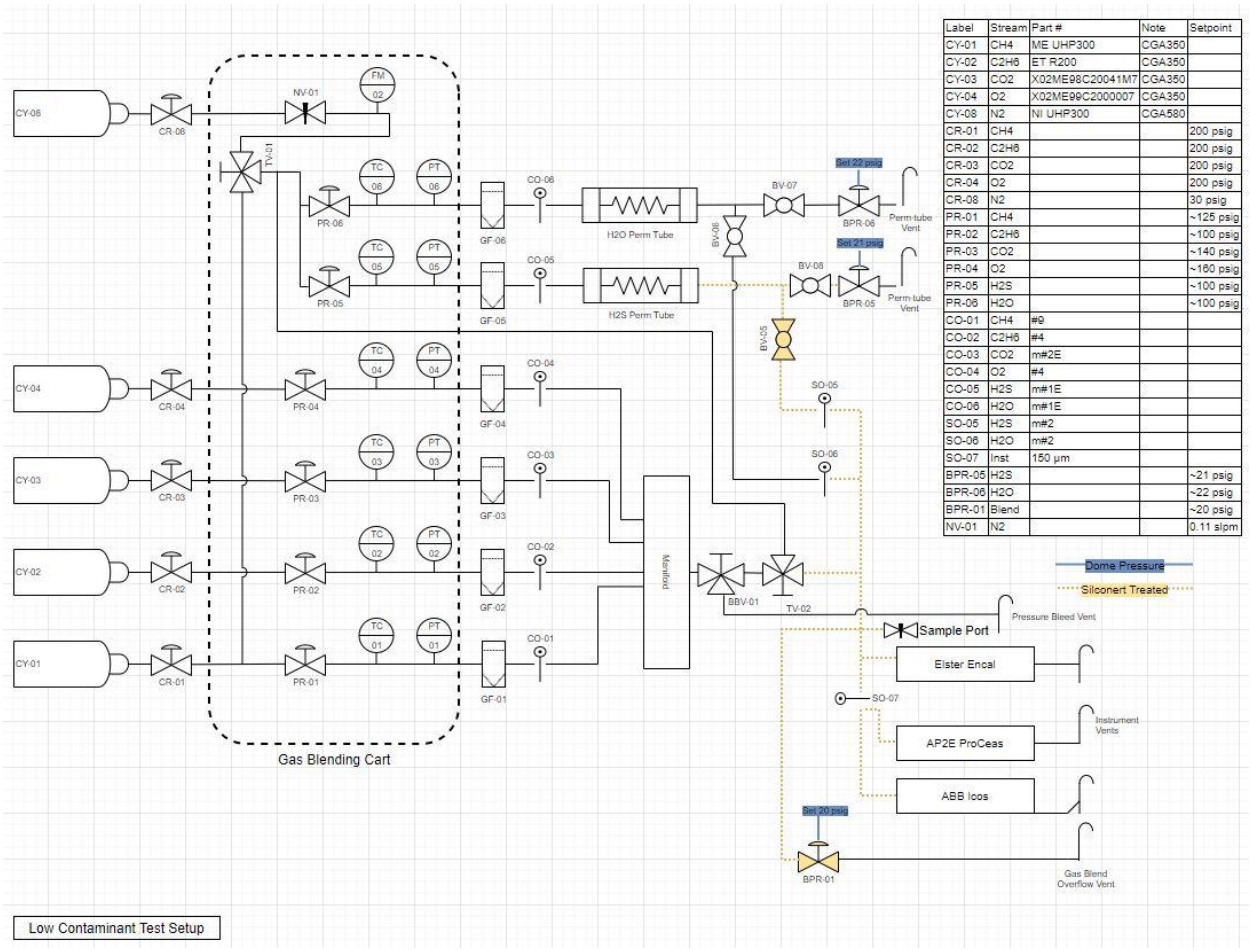


Figure 2-1. Schematic of blending system including gas bottle selection, pressure regulator settings and orifice selection for Low Contaminant test blend.

Component gases from gas bottles first flow to the "metering cart" which is essentially an arrangement of pressure regulators with pressure sensors and thermocouples on each regulator. The metering cart also contains PID controllers to power heat tape for heating gas tubing and a data acquisition unit to collect readings from the various sensors in the system. After the individual gas stream pressures are set the gases flow through choked-flow orifices into a manifold where they then mix and continue to the inlets of the analyzing instruments. Photos of the metering cart are shown in Figure 2-3 and the component gas bottles in Figure 2-4.

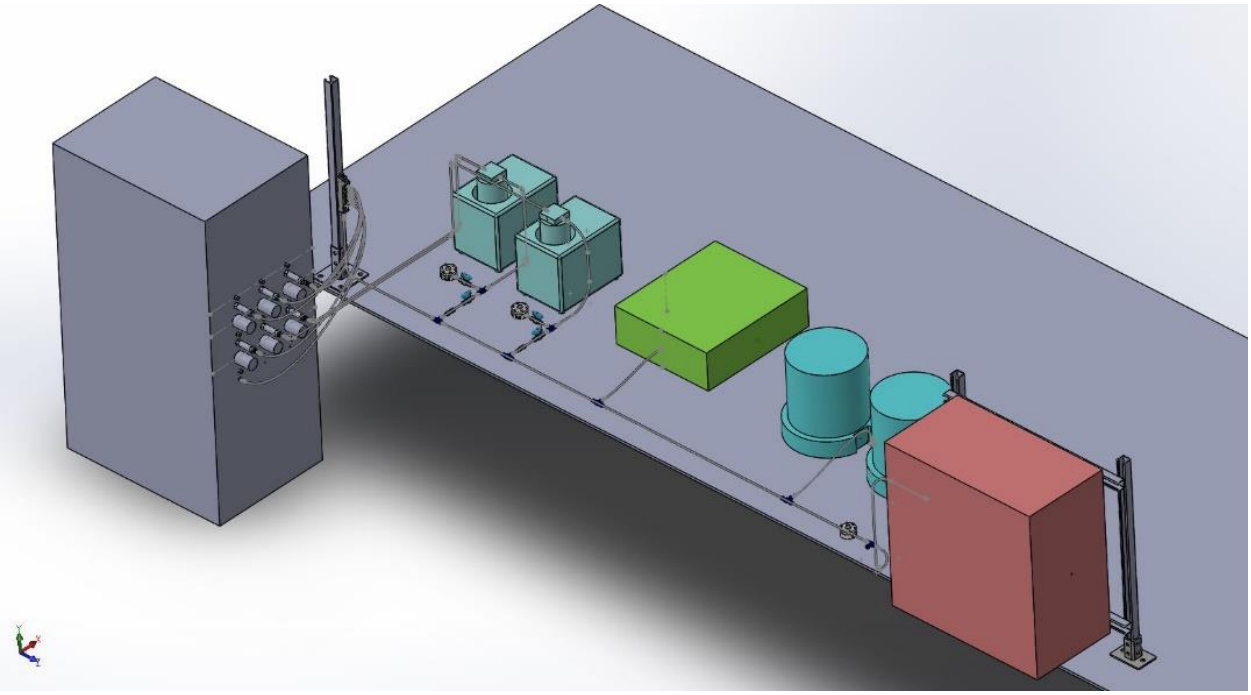


Figure 2-2. 3D SolidWorks model of testing system and gas analyzers.

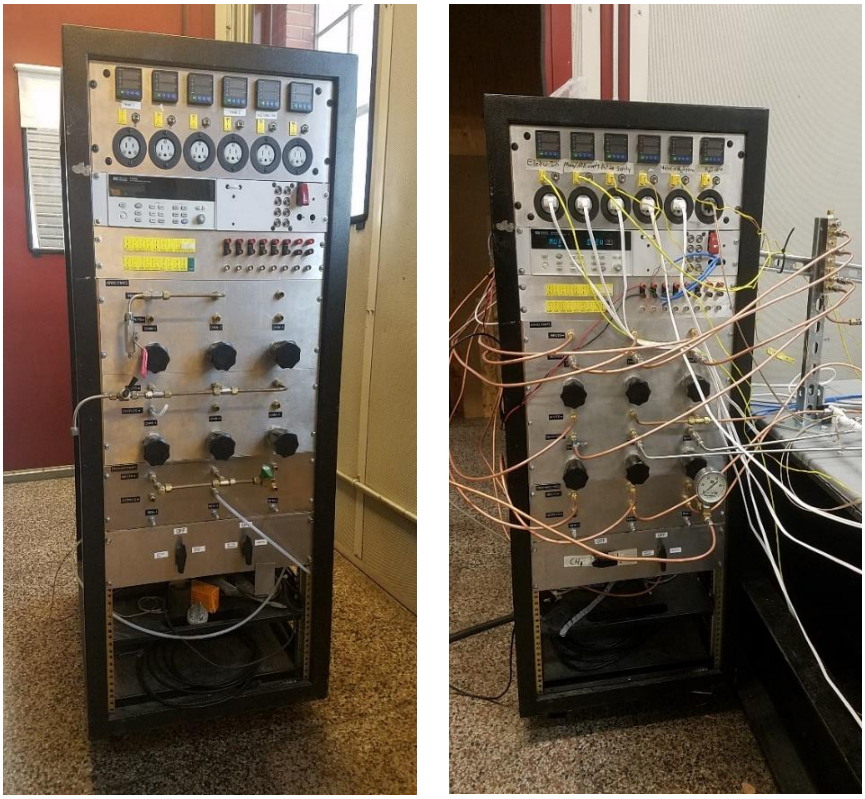


Figure 2-3. Images showing metering cart with heater tape PID controllers on the top row followed by the data acquisition unit below, then the six gas pressure regulators and their respective inlets and outlets.



Figure 2-4. UHP-grade component gas bottles supplied by AirGas.

Due to the volatility of the water and hydrogen sulfide contaminants these components are blended into the gas mixture stream on separate lines downstream of the manifold. These contaminants are supplied by permeation tube cylinders manufactured by Kin-Tek Analytical, Inc. (Figure 2-5) which emit gas at a rate based on their temperature. The temperature of the permeation tube cylinders is controlled by water bath ovens at a specified setpoint in the permeation tube literature supplied by Kin-Tek (Figure 2-5). The water baths are digital programmable units made by Walter Products Inc. and are also shown in Figure 2-6. Pure methane is flowed through the permeation tube cylinders to act as a carrier gas and the mixture is then plumbed to the main instrument supply line and flow-controlled with choked-flow orifices and a back-pressure regulator (BPR) for each of the two streams. Using back-pressure regulators instead of more conventional flow-through types allows more steady and precise pressure control; back-pressure regulators maintain a set pressure upstream of the regulator (as opposed

to downstream) and vent off excess gas. The flow rate of the upstream fluid does not affect the pressure set point of a BPR as it does with a conventional flow-through regulator. The back-pressure regulators used for this project were purchased from Equilibar, LLC. Figure 2-6 shows a



Figure 2-5. Diagram showing partial cutaway of Kin-Tek permeation tube cylinder on left [25] and Walter Products digital water bath on right [26].

simplified cross-section and exploded view of an Equilibar regulator. Temperatures before the choked-flow orifices on the metering cart gas outlets will need to be monitored and controlled to regulate flow to desired rates. Some parts of the gas supply tubing will also need to be heated to prevent any condensates from forming as the gas moves slowly through the system. Nitrogen purging of the system will also be accomplished through the metering cart and ball valves to switch main gas supply from methane to nitrogen. Ambient temperature will be maintained below target levels so tubing assembly components can be heated to desired temperature with electric resistance thermal tape. Thermal management of tubing is crucial to achieve accurate flow rates through the choked-flow orifices as well as minimize potential condensate formation

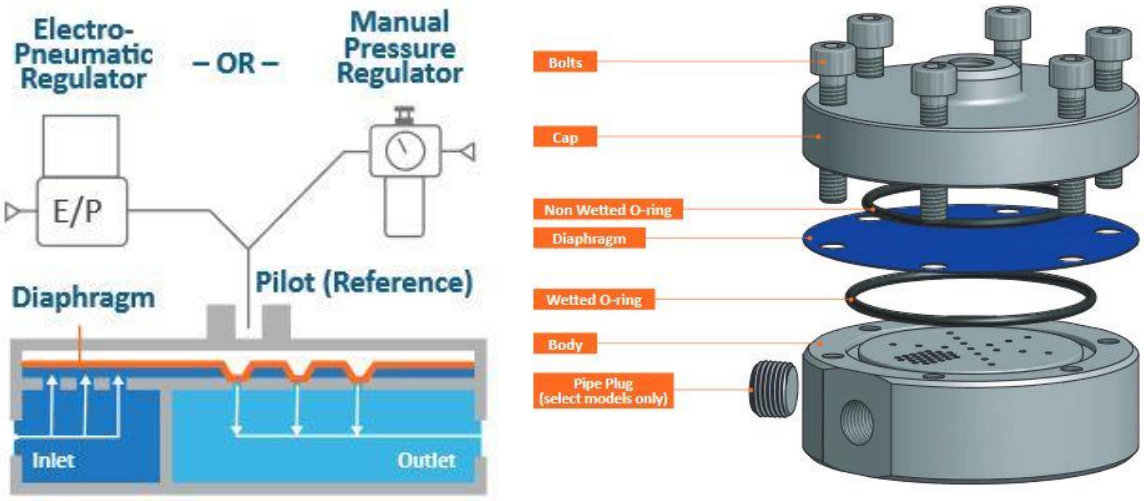


Figure 2-6. Cross-section (left) and exploded view (right) of Equilibar back-pressure regulator. Reference pressure is supplied by separate manual air pressure regulators [27].

within the tubing. Heat-sensitive areas are wrapped with heat tape to maintain constant temperature, thus pressures and flows. The main mixed gas line supplying the analysis instruments will be stainless steel tubing heat-wrapped and internally coated to prevent deposition of solid sulfides which could skew testing results and possibly damage downstream equipment over time. In order to reduce costs and lessen the required length of heat-controlled tubing the testing setup needed to be arranged in a way to keep the instrument gas supply line as short as possible. Once the required pressures and flows were determined, a schematic was drafted to lay out the tubing configuration and specify locations of valves, orifices, regulators and other flow control components. After multiple iterations with the analyzers and routing gas tubing in different orientations a simple uni-directional (in terms of gas flow) layout was decided upon to reduce tubing lengths downstream of the manifold and permeation tubes to a minimum. A 3D model of the testing apparatus was created using SolidWorks not only for visual representation to aide in constructing the system but also to keep track of all the required blending system components and produce an accurate bill of materials. The physical layout was

designed with consideration towards easy assembly and access of parts and materials, all-around access to tubing for wrapping with heat tape, and correct orientation of analyzing equipment (primarily Instrument A which is large, heavy and requires a vertical mounting position).

The gas blending system requires a supply of clean, dry compressed air for setting the back-pressure regulators as well as purging the enclosure of Instrument A. Although the compressed air supplied by the laboratory is passed through a filter and drier we had to be certain the air was as clean and dry as possible. Before being routed to the regulators and instruments, the shop air supply flows through a "master" pressure regulator then a desiccant drier followed by a particulate filter.

2.5 Molar Concentration Analysis

The first major step in designing the gas blending system is to calculate the flow rates of component gases required to reach target contaminant levels. Target levels would be measured on a molar basis to ensure consistency; this would be calculated from the volume fractions of each gas species. Due to the relatively near-atmospheric temperatures and pressures at which the gas mixtures will be sampled, the Ideal Gas Law could be applied in the determination of molar content of each species,

$$\dot{V}_{std} = \frac{\dot{N} * R_u * T_{std}}{P_{std}} \tag{2-1}$$

where $\dot{N}$ is the molar flow rate of gas, R_u is the universal gas constant, T_{std} is the temperature of the gas and P_{std} is the pressure of the gas [24]. By using this relation, it is possible to convert

volume flow rate ($\dot{V}$) to molar flow rate which allows molar gas concentration to be determined. The volume flow rate of each species was approached based on Amagat's Law of Partial Volumes,

$$\dot{V}_m = \sum_{i=1}^{k} \dot{V}_i(T_m, P_m) \tag{2-2}$$

which states that the extensive volume (or in this case volumetric flow rate) $\dot{V}_m$ of a gas mixture is equal to the sum of volumes $\dot{V}_i$ of the number k component gases, if the temperature T_m and the pressure P_m of the components remain the same [28]. Based on this law it can be determined that adding the flow rates of component gases and calculating the ratio of an individual component gas to the full mixture volumetric flow can give an accurate prediction of the absolute content of each component gas in the mixture. This allows target concentrations to be achieved by increasing or decreasing component gas flow rates which is a simple operation in practice using sized orifices and varying component gas pressure upstream of the sized orifices. The mole fraction of each gas component can then be determined from the molar or volume flow ratio

$$y_i = \frac{N_i}{N_m} = \frac{\dot{V}_i}{\dot{V}_m} \tag{2-3}$$

where N_i is the number of moles of component gas, N_m is the total moles of gas mixture, $\dot{V}_i$ is the volume flow rate of component gas and $\dot{V}_m$ is the total volume flow rate of the gas mixture.

In order to compute the required orifice size and upstream gas pressure first the volumetric flow of the component gas must be converted to a standard air density flow rate by

$$\dot{V}_{air} = \frac{\dot{V}_{gas}}{\sqrt{(S.G._{gas})}} \tag{2-4}$$

where $\dot{V}_{gas}$ is the volumetric flow rate of the component gas and $S.G._{gas}$ is the specific gravity of the component gas. Once the air standard volumetric flow rate is determined it is then used to determine the critical choked flow coefficient or C_v. The flow coefficient is determined by

$$C_v = Q_g * \frac{\sqrt{S.G.*T}}{816* P_1} \quad (2\text{-}5)$$

where Q_g is the volumetric flow rate in Standard Cubic Feet per Minute (SCFM), *S.G.* is the specific gravity of the gas relative to air, *T* is gas temperature and P_1 is the pressure upstream of the orifice. Note that this relation only applies to choked-flow conditions where the upstream pressure P_1 is more than two times the downstream pressure P_2 of the orifice. In this condition the relation between upstream pressure and volumetric flow rate through the sized orifice is linear which makes the control of gas flows far more straightforward in practical application.

2.6 Data Acquisition Program

In order to monitor all the sensors in the blending system and streamline the collection of data from the instruments a custom data acquisition (DAQ) program was created. This program runs on a host desktop computer which is connected to the DAQ switch on the metering cart. The DAQ switch collects raw inputs from all the sensors in the gas blending system for the DAQ program to log and convert to meaningful information such as pressure, temperature or flow rate. The DAQ program also captures all data from the analyzing instruments in real-time and archives the resulting time series data to files with common timestamps from the host computer. The DAQ program incorporates custom MODBUS readers to interface with the outputs of each of the analyzers over TCP MODBUS connections. The MODBUS outputs are

scaled to match the outputs of each analyzer according to the manufacturers' operating manuals and are regularly checked against values logged within each analyzer to ensure proper synchronization and accurate gathering of data.

2.7 Test Plan and Procedure

During the testing process several measurements will need to be taken including:

- Gas species temperatures, pressures and associated calibrated flow rates for the blending system
- Back pressure regulator control pressures and associated calibrated flow rates
- Water bath temperatures (record actual displayed values in real-time)
- Main gas mixture sample pressure and temperature
- Third-party sample mixture analysis
- Measurement outputs from analyzing instruments being tested
- Associated ancillary data from analyzing instruments being tested

Contaminant concentrations for species being delivered by the permeation tube cylinders (H_2S and H_2O) will be calculated based on manufacturer-specified mass emission rates with respect to temperature and measured dilution flow rates used to set the final concentration delivered to the instruments being tested. The gas blending system is designed to be compatible with the sample delivery specifications provided by each of the analyzing instrument manufacturers; these specifications are shown in Table 2-5.

Table 2-5. Sample delivery specifications for analyzing instruments under test.

Instrument	Max Pressure	Testing Target	Max Temperature	Testing Target	Max Flowrate	Testing Target
A	7.45 psig	<1 psig	105 C	40 C	1 SLPM	0.9 slpm
B	100 psig	20 psig	50 C	40 C	0.15 slpm	0.15 slpm
C	60 psig	20 psig	54 C	40 C	0.5 slpm	0.4 slpm

All analyzing instruments will be tested concurrently with each gas blend. Gas blends will be tested sequentially in a manner to maintain consistent setpoints between test replicates and ease calibration and setup. In practice it would be difficult to precisely reach exact contaminant targets as outlined in Table 2-1 so some flexibility in target concentrations is required; an example of target gas composition for each blend is shown in Table 2-6.

Table 2-6. Target calculated gas component concentrations for each contaminant blend.

Species	Test Blend Composition Estimate			
	Low	Mid (a)	Mid (b)	High
CH_4 (%)	87.58	83.12	88.02	78.13
C_2H_6 (%)	10.57	12.61	12.61	7.63
C_3H_8 (%)	1.69	2.02	2.02	3.05
CO_2 (%)	0.11	2.03	3.41	10.11
O_2 (%)	0.05	0.20	0.41	1.03
H_2O (ppm)	20.3	97.3	145.2	513.7
H_2S (ppm)	1.2	4.5	4.5	21.8

Following the initial setup of the analyzers, the remaining components of the gas blending system are installed including the critical orifices, heat tape on all lines downstream of the manifold, a sampling port just upstream of the main back pressure regulator and a rotameter to measure total exhaust flow rate from the system. The sampling port is used to collect gas mixtures in sample cylinders for third-party analysis and incorporates a needle valve to regulate flow out of the main mixture supply line in order to maintain consistent line pressure. The sample cylinders from EMPACT Analytics are of a flow-through design which incorporates valves on both ends; this allows sample gas to be flowed through the cylinder to evacuate any possible unwanted species. When a sample of the gas blend is to be collected one end of the cylinder will be connected to the sampling port while the other end is attached to an exhaust line. Once all connections are confirmed leak-free the cylinder inlet valve will be opened and the needle valve on the sampling port opened to a preset point to begin the flow of sample gas into the cylinder. Once the pressure in the cylinder has equilibrated to the line pressure (noted by watching the flow rate through the exhaust rotameter) the outlet valve on the cylinder is opened and sample gas is flowed through for 10 minutes to allow any unwanted gases to evacuate the cylinder. Next the outlet valve is closed to allow the cylinder to pressurize then the sample port needle valve is closed followed by the inlet valve on the cylinder. In this way the sample is captured in the most accurate way possible, eliminating the likelihood of atmospheric air contaminating the sample.

The flow rates of gases through their respective critical orifices and ultimately the overall system must be tested to confirm preliminary flow calculations. Each contaminant level testing case (Low, Mid (A), Mid (B), High) is set up with its respective critical orifices and bottled gases fed to the pressure regulators on the metering cart. Then a DryCal device is connected to the

outlet of the mixing manifold and each gas component flowed through at various pressures set by the regulator on the cart. A DryCal is a highly precise calibration device for testing volumetric flow rates of dry gases by using a weighted piston within a vertical cylinder; sensors at the top and bottom of the cylinder detect the position of the piston and calculate the flow rate of gas by measuring the time needed for the piston to travel from the bottom to the top of the cylinder. The DryCal operates cyclically by opening an internal valve until the piston reaches the top of its travel then closes to allow the piston to return to its starting position which restarts the cycle. The measured flow rate is averaged over 10 cycles and then recorded. By using the DryCal device the actual gas flow rates can be measured and compared to calculated target values which greatly simplifies system setup as well as determining uncertainty of the test results. A DryCal device is shown in Figure 2-7.



Figure 2-7. Image of a DryCal Defender 530+ device used in calibrating the gas blending system.

For each gas component and orifice combination four to six data points are recorded of the measured flow rate at each pressure; the regulator is set to a target pressure, allowed to stabilize for 15-20 minutes (until the signal from the pressure transducer for that regulator stops drifting) and the DryCal activated to take continuous flow measurements during that time. Each pressure and its corresponding measured flow rate are then plotted and fitted with a best-fit trendline to create a linear function of pressure versus flow rate. This allows a slope and y-intercept value to be applied to the calculation within the Data Acquisition Program to display calculated flow in real time making setting up each contaminant level test case much less time-consuming.

The procedures for initial pre-test setup, daily pre-test setup, the actual data-gathering testing and the post-testing procedures are outlined as follows:

Pre-Test Program Procedure

a) Perform leak checks for all gas blending and sample lines
b) Develop calibration tables for gas blending system at desired set points
c) Check operation of analyzers, blending system instruments and data acquisition system

Pre-Test Daily Procedure

a) Perform appropriate quality assurance and quality control checks for each analyzer
b) Prepare gas sampling vessels (cylinders) for third-party laboratory analysis
c) Check gas bottle pressures and ensure sufficient component gas supply for testing
d) Turn on permeation tube water baths and allow to reach temperature setpoint

Data Point Testing Procedure

a) Open bypass valve downstream of manifold to prevent unwanted pressure buildup
b) Set gas blending system (metering cart and back pressure regulators and valves) to achieve desired composition
c) Upon reaching steady outputs for pressure regulator setpoints in DAQ program, open 3-way valve to allow mixture flow into main sample line
d) Close sample bypass valve from step 'a)'
e) Check exhaust flow rate with rotameter and adjust for minimum wasted sample mixture
f) Enable gas analyzers to begin acquiring data
g) Wait until both the blending system and each of the analyzers have stabilized
h) Begin test point
i) Confirm at least 5 discreet samples from Instrument C (GC) have been taken, ~20 minutes
j) Acquire gas blend sample for third-party laboratory analysis
k) End test point
l) Toggle contaminant blend or Nitrogen purge with 3-way valve
m) Repeat h) to l) N times

End-of-Test Day Procedure

a) Turn off regulators at gas bottles to allow system to bleed down
b) Turn off permeation tube water baths
c) Close all pressure regulators at the metering cart

d) Open bypass valve to allow instruments to draw in ambient air while on standby or shut down instruments if no additional testing will be performed for an extended period

e) Confirm and backup all test data through network as well as physical USB flash drive

f) Shut down all equipment (DAQ program, metering cart, gas line heat trace)

2.8 Uncertainty Calculation Methods

Uncertainty calculations for the blending cart flows were approached on a numerical basis using the classic statistical method where the result, *R*, of a single-sample experiment is a function of *n* independent variables

$$R = f(x_1, x_2, x_3, \dots, x_n) \tag{2-6}$$

where *R* is the parameter for which to determine uncertainty and depends on parameters x_1, x_2, x_3, … , x_n [28]. If all parameters, x_i, are normally distributed, then the uncertainty in *R* is

$$\delta R = \sqrt{\left[\left(\frac{\partial R}{\partial x_1}\right)\delta x_1\right]^2 + \left[\left(\frac{\partial R}{\partial x_2}\right)\delta x_2\right]^2 + \ldots + \left[\left(\frac{\partial R}{\partial x_n}\right)\delta x_n\right]^2} \tag{2-7}$$

where $\partial R/\partial x_i$ is the partial derivative of *R* with respect to x_i and δx_i is the uncertainty of the measurement of x_i, which is the sum of all sources of uncertainty including both random errors quantified with standard deviation as well as fixed errors such as linearity and hysteresis [29].

Determining uncertainty for the testing results in a detailed and comprehensive manner was necessary due to the nature of the experiment; several factors influenced the results and there were multiple potential sources of error in the blending system as well as the analyzers themselves. Such details as temperature-influenced variations in gas flow rates and species

concentrations and inconsistencies in flow-control orifices were carefully considered. Manufacturer uncertainties for component gas bottles, pressure regulators, water baths and permeation tube cylinders were also included in the calculations.

Individual uncertainties for the analyzer results and EMPACT third-party testing were calculated in a straightforward manner based on manufacturer specifications and standard deviation of reported results. However, the uncertainties for concentrations calculated from the gas blending system sensors and metering cart ("Gas Standard-Diluted") were more involved. These uncertainties considered fixed errors specified by equipment manufacturers (permeation tube emission rates, DryCal device uncertainty, component gas bottles, water bath temperature) as well as random error quantified with standard deviation of the metering cart outputs. Figure 2-8 shows an example spreadsheet displaying all the measured average values, random and fixed errors for the 'Low Contaminant' blend test performed in March 2020. Calculating uncertainties from the metering cart and blending system outputs which are shown in the "Gas Standard-diluted" section in Figure 2-8 was done on a separate spreadsheet using values reported by the DAQ program for all the pressure and temperature sensors. Pressures and temperatures were used to calculate flow rates based on known gas and sized orifice properties which were then used to calculate component gas concentrations and their associated errors. An example is shown in Figure 2-9 of the 'Gas Standard-diluted' uncertainty calculations for the 'Low Contaminant' test blend performed in March 2020.

			H2O	H2S	CO2	O2
Inst A	Average	%	0.000715398	9.33101E-05	0.1065025	0.07273389
	Average	ppm	7.153977	0.933101	1065.025	727.3389
	StDev	ppm	2.479158	0.017085	7.953328	120.5371
	Precision	ppm	1.4	0.014	8	70
	Total Unc	ppm	3.879158	0.031085	15.953328	190.5371
	Total Unc	%	0.000387916	3.1085E-06	0.001595333	0.01905371
Inst C	Average	Nrm Mol %	0	0	0.118397471	0.006300893
	StDev	Nrm Mol %	0	0	0.000588214	0.01806813
	Repeatability	%	0	0	0.000591987	3.15045E-05
	Total Unc	%	0	0	0.001180202	0.018099635
			ppm	ppm	mol %	
Inst B	Average		17.061549	0.73328325	0.032367882	0
	StDev		0.05582419	0.01831088	9.62493E-05	0
	Precision		0.085307745	0.003666416	0.000161839	0
	Total Unc		0.141131935	0.021977296	0.000258089	0
EMPACT	Reported conc.	Nrm Mol %	0	0	0.16	0.06
	Precision		0	0	0.0048	0.0006
Gas Standard-diluted	Average	%	0.001808447	0.000137864	0.116786686	0.056409124
	Average	ppmv	18.08447015	1.378637217	1167.866861	564.0912376
	Uncertainty	%	3.129441	3.936791	2.410717	2.350458
	Error	%	5.65943E-05	5.42741E-06	0.002815396	0.001325873
	Error	ppmv	0.565942823	0.054274066	28.15396495	13.25872762

Figure 2-8. Low-Contaminant test blend from March 2020 spreadsheet showing calculations for total uncertainties for each analyzer under test, EMPACT third-party testing and concentrations calculated from blending system sensor readings ("Gas Standard-diluted").

The first step in calculating concentrations was to determine the volumetric flow for each component gas stream (columns labeled "Reg1-CH4" through "H2O perm blended" in Figure 2-9); these calculations were performed automatically by the DAQ program based on specified inputs in the program coding which were selected orifice sizes, component gas properties and output values from pressure and temperature sensors in the gas blending system. Then the individual flows were summed to give a total volumetric flow rate ('TOTAL' in upper right-hand corner of Figure 2-9) and the volume fractions ("vol frac" row in Figure 2-9) of component gases

computed from the total flow rate. These volume fractions were then converted to parts-per-million (ppm) by multiplying by a factor of 1,000,000. Because some of the component gas bottles were blends of more than one gas, the concentrations for those streams were then multiplied by the specified ratios of gases within each bottle and each component gas

	Perm-tubes	ng/min	T (C)		COV H2S press	COV H2O press	mol/L=	0.041418095	
	H2O	473345	80		0.002583563	0.006046009			
	H2S	63365	30						
	Reg1-CH4 (slpm	Reg2-C2H6 (slp	Reg3-CO2/CH4	Reg4-O2/CH4 (	H2S perm blen	H2O perm blen	H2S perm total	H2O perm total	TOTAL
Avg	5.820495044	0.651278029	0.473276893	1.35319161	0.025740048	0.024148054	0.100399119	0.101470678	8.348129677
stdev	0.006601138	0.000475731	0.000552931	0.001426428	0.0000665010	0.000145999	0.000168392	0.000161041	
Device cal	0.05820495	0.00651278	0.004732769	0.013531916	0.0002574	0.000241481	0.001003991	0.001014707	
Gas bottle cal	0.00058205	6.51278E-05							
Water bath temp									
							0.00415834	0.004202722	
delXn	0.065388138	0.007053639	0.0052857	0.014958344	0.000323902	0.00038748	0.001172383	0.001175748	
dCO2/dXn	141.72	141.72	-2356.99	141.72	140.5797101	140.5797101			
CO2 term	85.87371096	0.999283546	155.2102647	4.493961436	0.002073343	0.002967178			
dO2/dXn	68.46	68.46	68.46	-353.66	68.11594203	68.11594203			
O2 term	20.03880104	0.233184801	0.130941933	27.98587817	0.00048677	0.00069662			
dH2S/dXn	0.1495	0.1495	0.1495	0.1495	-53.43478261	0.15942029			
H2S term	9.55609E-05	1.11201E-06	6.24435E-07	5.00091E-06	0.000299553	3.8158E-09			
dH2O/dXn	2.09	2.09	2.09	2.09	2.028985507	-747.2173913			
H2O term	0.018676286	0.00021733	0.000122039	0.000977371	4.31901E-07	0.083828613			
CH4 ppm			979280	9.97E+05	999431	993577			
other ppm					447.1259043	6251.911829			
vol frac	0.697221446	0.078014843	0.056692566	0.162095183	0.003083331	0.00289263			
CH4 ppm	697221.4459		55517.89609	161531.092	3081.576709	2874.051024			920226.0617
CO2 ppm			1167.866861						1167.866861
O2 ppm				564.0912376					564.0912376
C2H6 ppm		78014.84333							78014.84333
H2S ppm					1.378637217				1.378637217
H2O ppm						18.08447015			18.08447015

Figure 2-9. Portion of spreadsheet for Low-Contaminant test blend from March 2020 used for calculating component gas concentrations based on gas blending system sensor readings and their associated uncertainties.

concentration listed in the bottom six rows of Figure 2-9. Component gas concentrations for each stream were summed to give total calculated concentrations shown in the lower right-hand corner of Figure 2-9. After the concentrations were determined, all the error sources were incorporated and summed together (rows labeled “delXn” to “H2O term” in Figure 2-9) then were multiplied by the concentrations to give total uncertainty for each contaminant gas.

CHAPTER 3 – COMPARISON OF CONTAMINANT ANALYZERS

3.1 Initial Analyzer Start-Up

The first gas analyzer to be set up and tested for operation was Instrument B. The analyzer operating software for Instrument B is highly detailed and allows adjustment of many aspects of analyzer operation; this allows large-scale changes or repairs to be performed without requiring the analyzer to be shipped back to the manufacturer but also makes initial setup more involved as a higher level of knowledge of the analyzer is required. For this reason, the manufacturer of Instrument B sent a team of personnel to aid in initial setup and provide a detailed walkthrough of analyzer features and operation. The Graphical User Interface (GUI) for Instrument B is well laid-out with a lot of information but without being overwhelming. The main display shows the current concentration readings in the center with the two laser spectra underneath along with current date and time. A toolbar on top has buttons to view real-time results and plots, transfer data to external drive (USB), system diagnostics and advanced settings. Since Instrument B was the first gas analyzer to be started up it was used to double-check the functionality of the custom gas blending system. A major issue in the design of the blending system became apparent when testing its operation with UHP nitrogen: more water vapor than specified in the component gas supplier specifications was being detected by the analyzer. This was determined to be caused by the nylon tubing used for transporting the component gases to the metering cart. The issue was confirmed by connecting a temporary stainless steel line directly from the nitrogen bottle to Instrument B; after running overnight to purge any remaining water

vapor from the tubing and regulator the H_2O levels were showing around 2.78 ppm, down significantly from 3.8 ppm when performing the same test with nylon tubing. It was determined that water molecules were permeating from the ambient air through the walls of the nylon tubing causing inaccurate readings; this would be unacceptable for testing as H_2O is one of the contaminants to be included in the natural gas blend and must be controlled precisely in order to provide accurate results. After this discovery all nylon tubing upstream of the metering cart for supplying bottled gas was replaced with copper tubing, preventing water molecules from permeating into the gas stream and skewing analyzer readings.

Initial start-up and testing of Instrument A turned out to be straightforward in comparison to Instrument B. The GUI incorporated into the analyzer was designed for use by personnel with little to no training in the operation of the device so it is simple and easy to use. The main display shows current concentrations and can easily be switched between time-series plots or simple text display of current results. Two bars below the results display the status of the cavity temperature and analyzer operation. A bar on the bottom displays current date and time, current file results are being written to, sample gas temperature and pressure, laser time-constants (Tau) and sampling rate. One issue arose with regards to the analyzer purge system; the specific model of analyzer sent by Instrument A's manufacturer requires a high flow of dry air or nitrogen to purge the analyzer enclosure. In order to not risk having the analyzer readings skewed from the presence of water in the purge air it was decided to use UHP 300 nitrogen for purging the Instrument A enclosure and restrict the purge gas flow to an acceptable rate which would not deplete the nitrogen supply too quickly.

Setup of Instrument C proved to be more involved. The manufacturer did send out a pair of representatives to go over the analyzer's operation and setup, but it was before the analyzer arrived which was not very helpful. When the analyzer did arrive, it was found that it had not been configured correctly from the manufacturer and required adjustments both to the device's software settings and the physical electrical and plumbing connections. Responses from the technician were delayed and inconsistent and no technician was ever sent to our location to aid in setup so getting the analyzer up and running correctly took more time than should have been necessary. Because of the more complex operation of a GC device the GUI for Instrument C was more in-depth and required initial setup to configure the display to show what was required for testing. Our configuration had four sub-windows in the application display; one for results of the last GC run, one for current instrument status, and two chromatographs to check the peaks of the contaminant gas species.

3.2 Analyzer Source Natural Gas Contaminant Results

For each of the two custom-blend testing sessions the instruments were first run on source natural gas obtained from the CSU Powerhouse Energy Campus ("Utility Gas") as well as two natural gas processing sites ("Field Gas 1" and "Field Gas 2"). In order to provide meaningful insight to analyzer performance only the CO_2 results are compared; specifications on the source natural gas were not able to be obtained at the time of sampling so the only verification of actual contaminant concentrations came from EMPACT third-party laboratory results. EMPACT was unable to detect H_2O and had issues accurately detecting H_2S; also, O_2 is unable to be detected

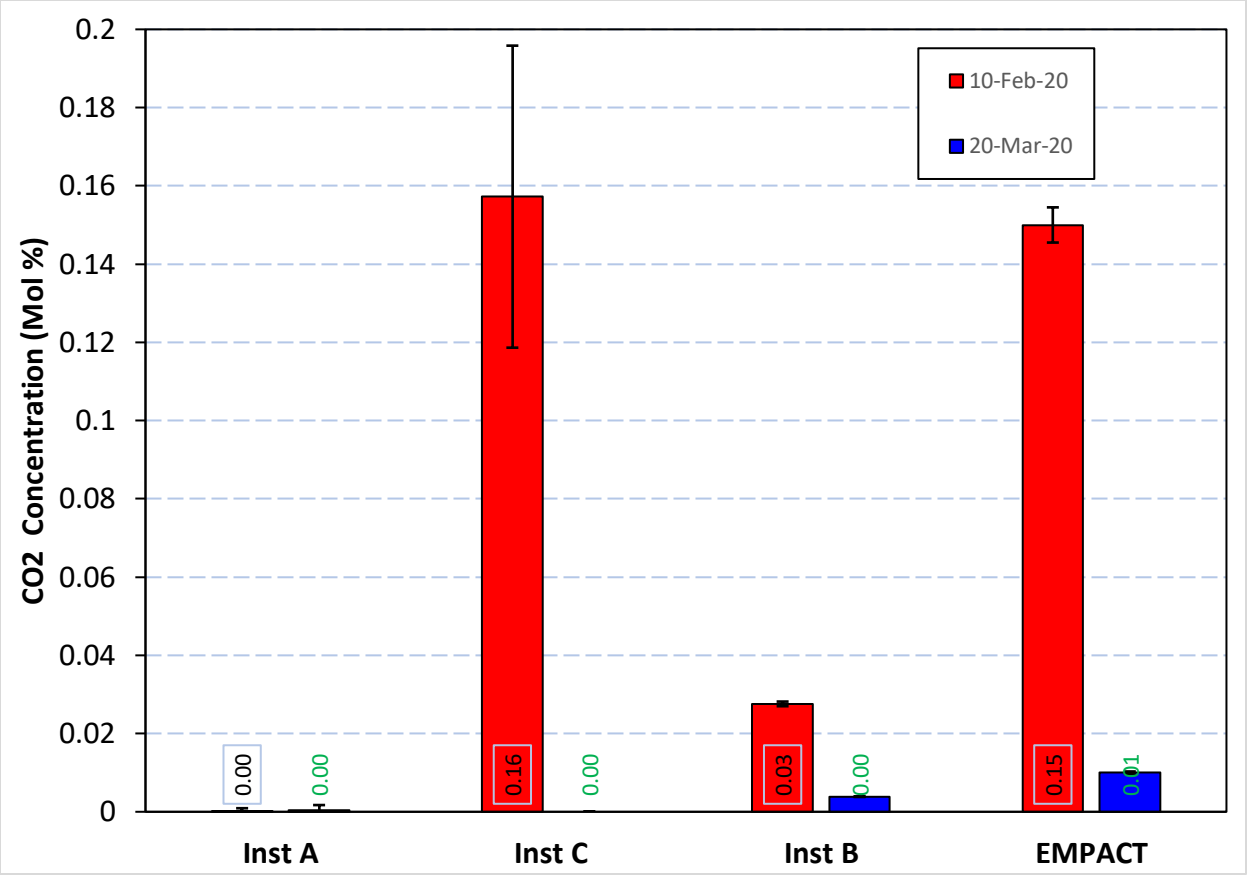


Figure 3-1. Plot showing results for CO_2 concentrations in Field Gas 1 source natural gas testing.

by Instrument B so those results are displayed in Appendix A. Figures 3-1, 3-2, and 3-3 show CO_2 concentrations for Field Gas 1, Field Gas 2 and Utility Gas respectively.

Field Gas 1 had very low levels of CO_2, in some cases undetectable. Interestingly the CO_2 content changed between 10-Feb-20 testing and 20-Mar-20 testing; the lower detected levels in later testing indicates whatever small amount of CO_2 had been in the Field Gas 1 mixture either reacted with other gas species or was adsorbed into the surface of the gas bottle itself. The change in sample tubing routing could also have influenced how homogeneous the mixture remained in transit to the instruments. CO_2 concentrations below 0.2 mole percent proved to be non-detects for Instrument A as both test runs indicate in Figure 3-1. Instrument C detected an

average concentration closest to that detected by EMPACT third-party testing for 10-Feb-20 but with a high level of uncertainty. Instrument B detected CO_2 in 10-Feb-20 testing but at a much lower level than Instrument C and EMPACT.

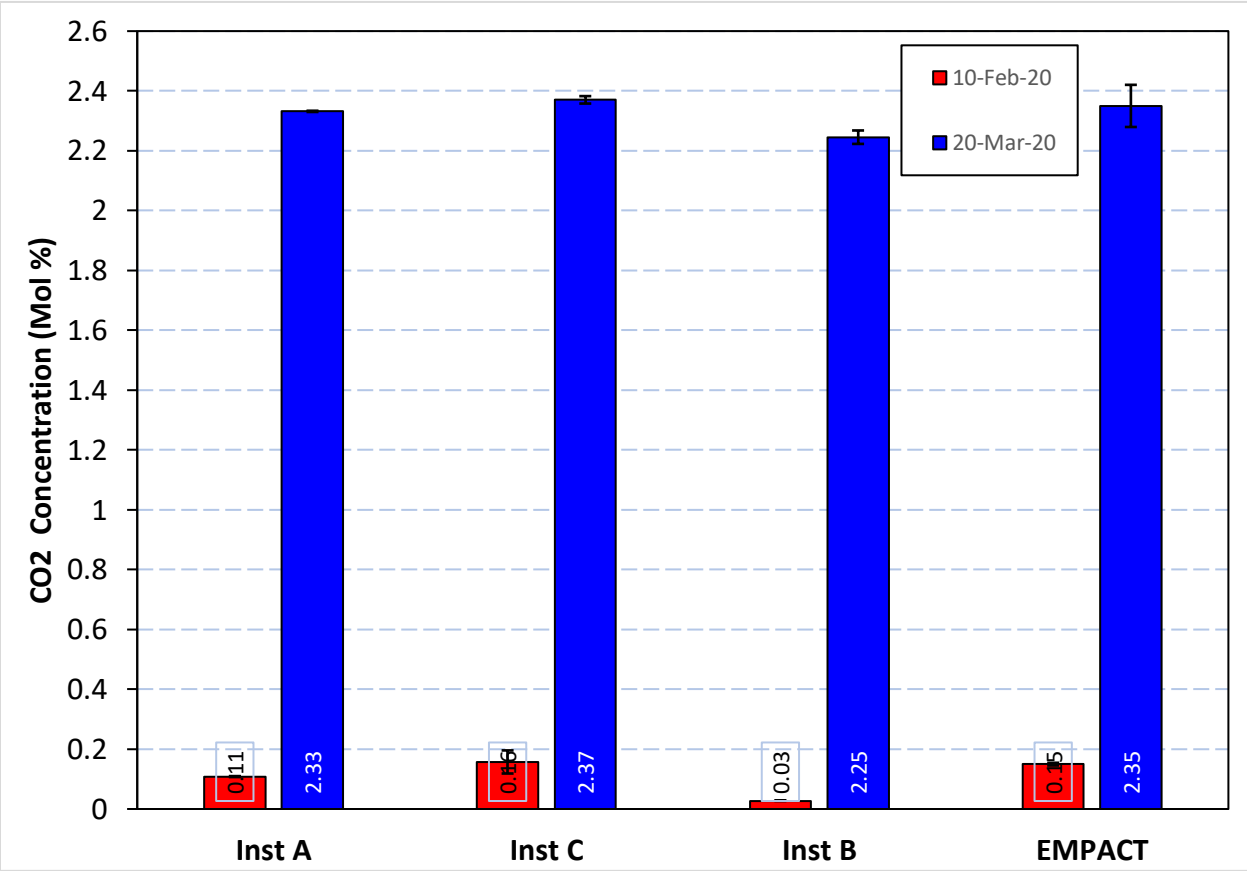


Figure 3-2. Plot showing results for CO_2 concentrations in Field Gas 2 source natural gas testing.

Field Gas 2 interestingly had opposite results as Field Gas 1 with respect to CO_2 concentration where the level increased from 10-Feb-20 testing to 20-Mar-20 testing as opposed to decreasing. One possible reason is the change in sample tubing routing between the two testing dates; another would be that the CO_2 dissociated from the gas mixture between the two dates. Regardless of this issue the results for 20-Mar-20 testing of Field Gas 2 indicated consistency between all three analyzers as well as EMPACT third-party testing. Average reported concentrations from the instruments are all within less than 5 percent of the concentration

reported by EMPACT and the measured uncertainty was also minimal as can be seen by the small error bars for the instrument results in Figure 3-2.

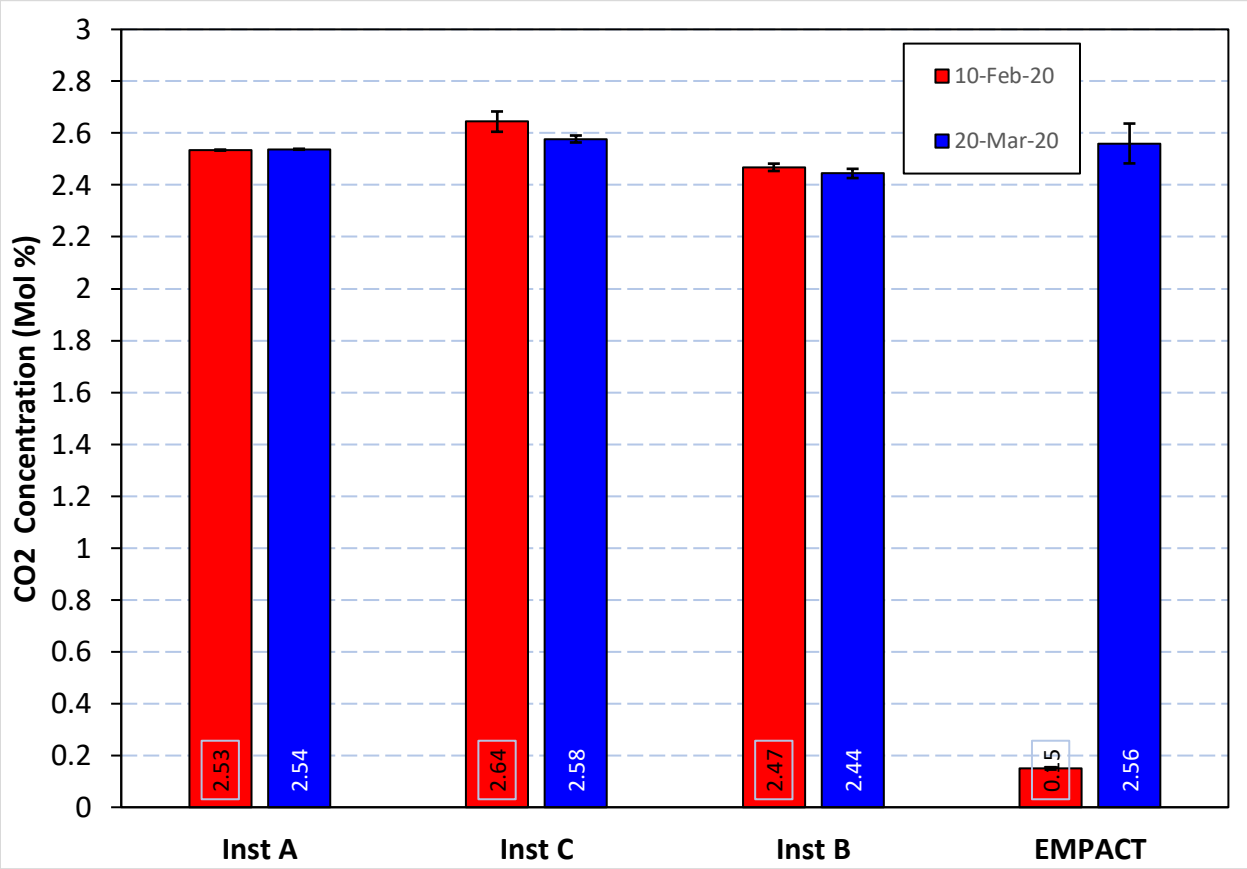


Figure 3-3. Plot showing results for CO_2 concentrations in Utility Gas source natural gas testing.

Utility Gas results for CO_2 concentrations proved to be more consistent than Field Gas 1 or Field Gas 2. The levels detected by each of the analyzers stayed almost the same between 10-Feb-20 and 20-Mar-20 testing with the greatest difference being for Instrument C; even so the difference was small at only a 3.3 percent relative decrease (0.06 mole percent decrease). Instruments A and B were even more consistent between test sessions. Oddly the results from EMPACT for 10-Feb-20 are far below those for 20-Mar-20; this may have been due to operator error in collecting the sample for EMPACT in 10-Feb-20 testing. Overall, the analyzers performed well in this test; the greatest difference from actual was reported by Instrument B but even then,

only by less than 5 percent relative to EMPACT third-party results in 20-Mar-20 testing. Uncertainty was also low for all three instruments to the point of being almost negligible in 20-Mar-20 results.

3.3 Analyzer Contaminant Custom Blend Results

The contaminant detection results from each instrument as well as the third-party results (EMPACT), calculated concentrations from sensor readings (Gas Standard-diluted) and target values for the Mid-A Contaminant level testing are shown in Figures 3-4, 3-5, 3-6, and 3-7. Two test series are displayed in the same figure to show the difference in results before and after modifications to the gas blending system, motivated by inconsistent instrument results. Looking over the then-current gas tubing routing indicated the sample inlet for Instrument B was too close to the outlet of the H_2S stream and was not allowing the gases to fully mix before entering the analyzer. It was also discovered that the 'dead-end' setup of having the exhaust from the main BPR going directly into Instrument A without any bypass was giving erroneous results and pressure fluctuations at the analyzer inlet. To remediate these issues, the blending system was reconfigured to have all three analyzers drawing sample gas from the same point as far downstream from the manifold and permeation tube cylinders as possible. It was also configured to have Instrument A drawing sample gas from a constant-flow bypass arrangement instead of a dead-end configuration. The '10-Feb-2020' results show before the modifications and the '20-Mar-20' results show after the modifications. Table 3-1 shows a summary of test results for the analyzers, computed values and EMPACT third-party testing for the March 2020 test run.

Table 3-1. Summary of results from March 2020 testing from all analyzers, calculated values ("Gas Standard-Diluted") and EMPACT third-party testing.

	Contaminant Concentrations (Mar 2020 testing)			
	H2O (ppm)	H2S (ppm)	CO2 (mol %)	O2 (mol %)
Low Targets	**20**	**1**	**0.1**	**0.05**
Inst A	7.15	0.933	0.107	0.073
Inst B	17.06	0.733	0.032	0
Inst C	0	0	0.118	0.006
EMPACT	0	0	0.16	0.06
Gas Standard-Diluted	18.08	1.379	0.117	0.056
Mid-A Targets	**100**	**4.5**	**2**	**0.2**
Inst A	87.1	3.97	2.01	0.21
Inst B	102.8	4.02	1.96	0
Inst C	20.2	2.69	2.04	0.12
EMPACT	0	0	2.04	0.2
Gas Standard-Diluted	96.5	4.54	2.03	0.199
Mid-B Targets	**145**	**4.5**	**3.4**	**0.4**
Inst A	139.4	4.22	3.44	0.438
Inst B	150.6	4.42	3.34	0
Inst C	30.4	2.61	3.51	0.271
EMPACT	0	0	3.45	0.41
Gas Standard-Diluted	149	4.83	3.49	0.406
High Targets	**500**	**20**	**10**	**1**
Inst A	487	19.3	10.55	1.094
Inst B	497	20.8	10.33	0
Inst C	0	0	10.63	0.689
EMPACT	0	0	10.54	1.1
Gas Standard-Diluted	503	20.3	10.84	1.097

Throughout the testing process, getting accurate, repeatable, and certifiable results for H_2O concentrations proved to be difficult since EMPACT Analytics did not have the capability to detect H_2O in sample gas analyses (shown as '0.0' in Figure 3-4). Also Instrument C had not been configured to detect H_2O accurately; having water detection shared with other gas species in the same GC column did not allow for accurate measurement of H_2O from that instrument. However, regarding comparison of the results from Instruments A and B to the target levels as well as the concentrations calculated from measured flow rates these two instruments performed well.

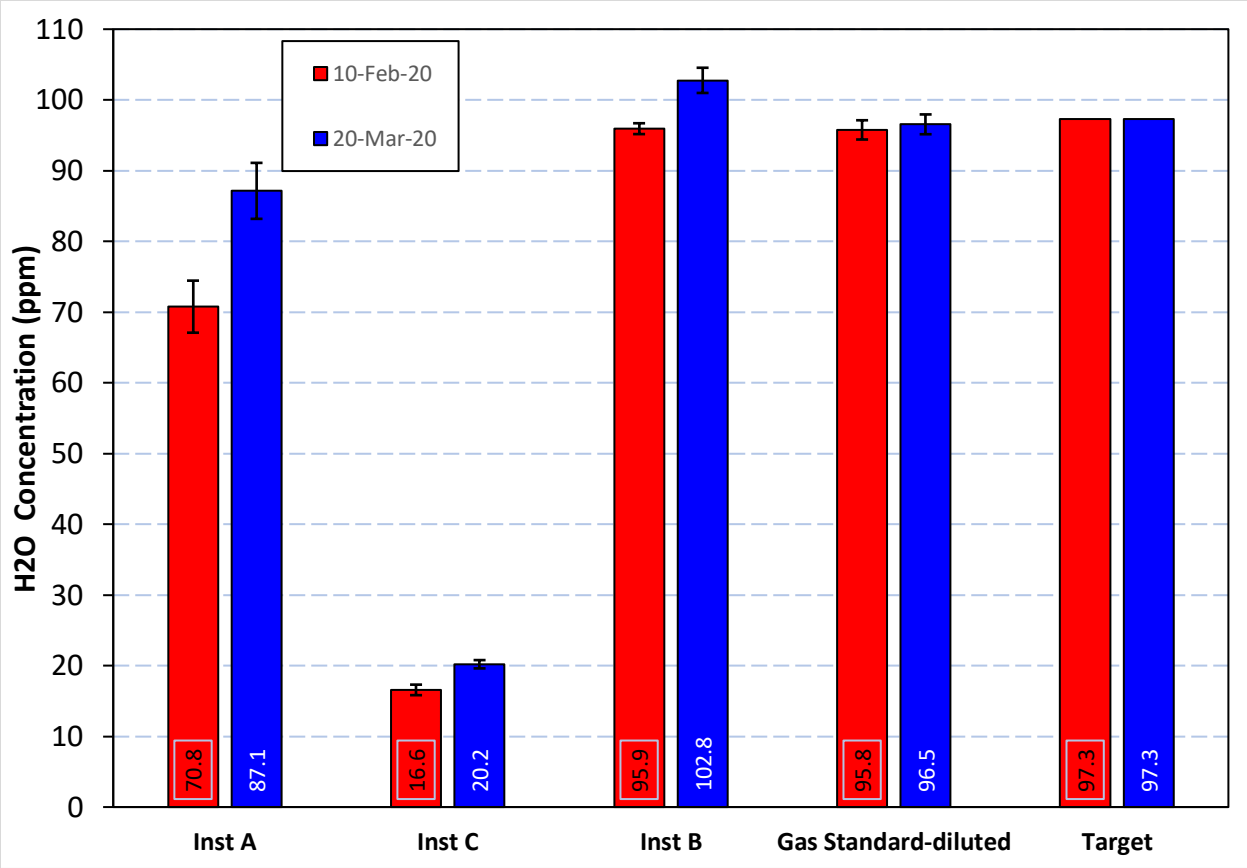


Figure 3-4. "Mid-A" blend H_2O concentrations detected by each analyzer along with the calculated levels (Gas Standard-diluted) and target level. EMPACT third-party lab analysis was not able to detect H_2O and is not shown.

Instrument B did read slightly high in the 20-Mar-20 test run but only by 6.5 percent more than the calculated ("Gas Standard-diluted") concentration. More importantly Instrument A was initially 26 percent lower than calculated levels in 10-Feb-20 testing but after reconfiguring the sample gas blending system the results improved greatly to within 10 percent of calculated values. Overall, testing for H_2O at these concentrations and under these conditions proved that it is a difficult species to detect accurately without a dedicated gas analyzer set up specifically for water detection.

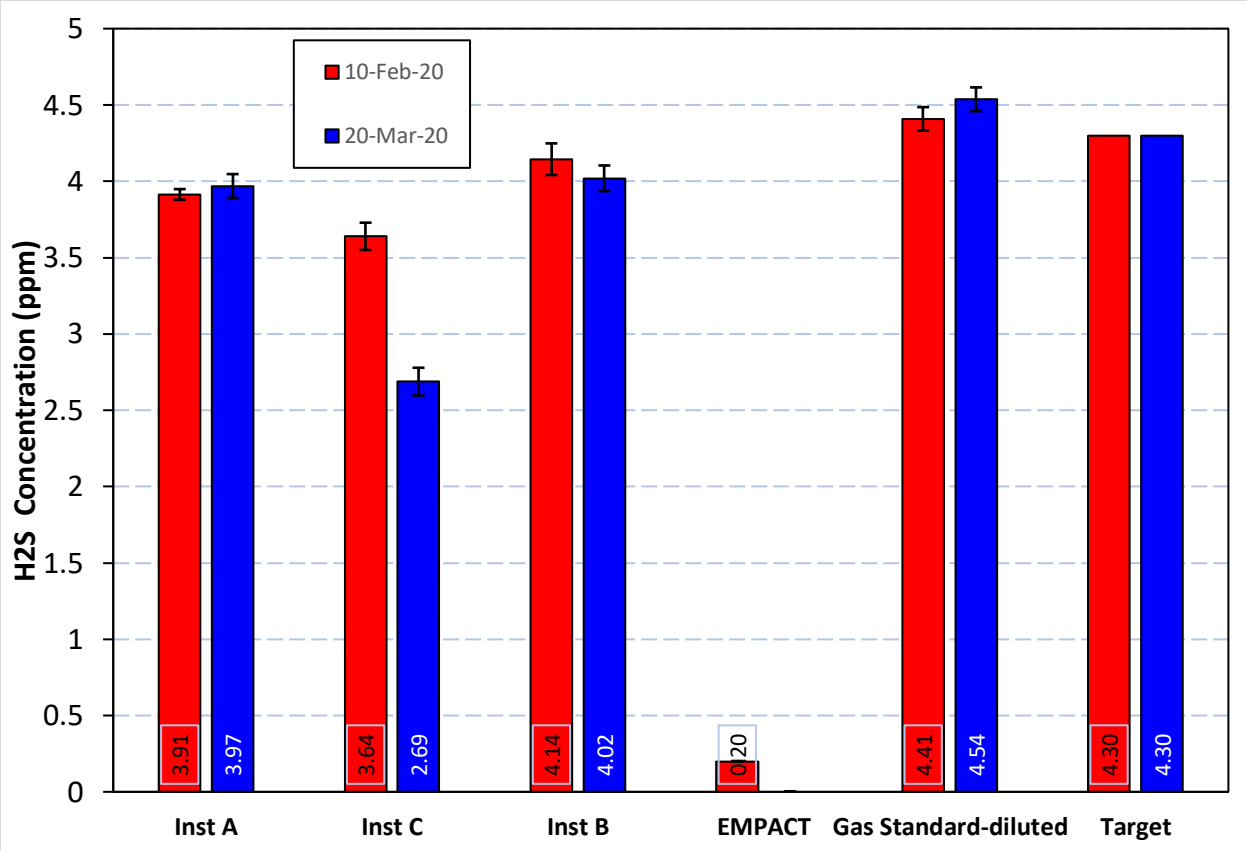


Figure 3-5. "Mid-A" blend H_2S concentrations detected by each analyzer along with calculated levels (Gas Standard-diluted), EMPACT third-party results and target level.

The next results to discuss are for H_2S. Unfortunately, an issue arose with EMPACT where their detected levels of H_2S were far below both calculated amounts and measured amounts reported by the analyzers, in some cases being below detectable limits. Additional tests were performed specifically to verify EMPACT H_2S results and unfortunately, they were far off (non-detect or trace detection) from both calculated values and results reported by the analyzers; all future testing from that point would not include EMPACT results for H_2S. Based on the concentrations calculated from species gas flow rates, however, Instruments A and B performed with only approximately 12 percent variance from calculated. Interestingly the results for Instrument C became less accurate (40 percent below calculated) after the gas blending system was reconfigured; the lower reported concentration for the 20-Mar-20 testing indicates that

somehow less of the H_2S was reaching the analyzer than before. This trend continued across the other test blends (Low, Mid-B, High) for the same testing date and the actual cause was never able to be determined and corrected. The results from Instruments A and B turned out much closer to calculated values in comparison; in 20-Mar-20 testing Instrument A was only 12.5 percent below calculated and Instrument B was even better at 11.5 percent below calculated levels. More importantly the results from those two analyzers were within less than 1.5 percent of each other.

Analyzing CO_2 content proved to be the most reliable of the four contaminant species as it was detected accurately by all three instruments and was also able to be quantified by third-party tests. As Figure 3-6 shows the EMPACT results were within 0.5 percent of the concentration calculated from species flow rates which confirms our calculation methods. Instrument C read slightly high for 10-Feb-20 testing but after reconfiguring the gas blending system it reported results within 0.5 percent of calculated for 20-Mar-20. In both test runs Instrument B reported slightly below calculated by about 4.5 percent. Finally, Instrument A also reported values very close to calculated; even the slight reduction in calculated CO_2 concentration from 10-Feb-20 to 20-Mar-20 trends with the Instrument A results. For 20-Mar-20 testing Instrument A came within 1.0 percent of calculated.

Detecting O_2 proved to be difficult for Instrument C and was not a gas species able to be detected by Instrument B. Instrument C did not detect O_2 at all in the 10-Feb-20; it did detect in 20-Mar-20 testing but was still 40 percent below Gas Standard-diluted calculated and EMPACT third party levels. However, Instrument A performance improved after the gas blending system

reconfiguration and improved from being 10 percent below actual in 10-Feb-20 testing to 5 percent above actual levels in 20-Mar-20 testing. The large uncertainty relative to average values for Instrument A reading O_2 indicate the concentration used in the Low and Mid-A (Figure 3-7) test blends were near the lower limit of detection of the instrument. This trend is reflected in Figure 3-8 which shows O_2 concentration for the High Contaminant test blend.

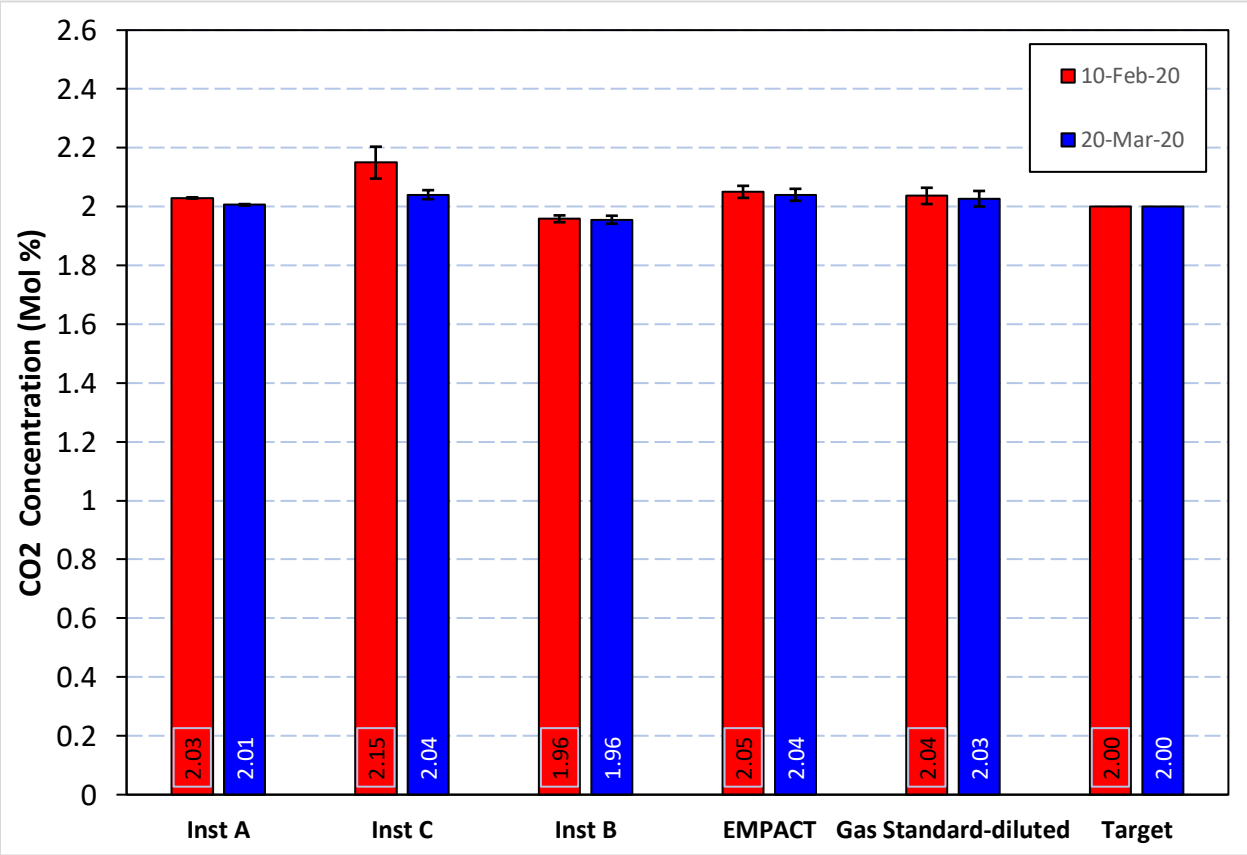


Figure 3-6. "Mid-A" blend CO_2 concentrations detected by each analyzer along with calculated levels (Gas Standard-diluted), EMPACT third-party results and target level.

The error bars for Instrument A in Figure 3-8 are noticeably smaller than in Figure 3-7 verifying that Instrument A performs with less uncertainty measuring O_2 levels as concentrations increase above 0.5 mole percent. Figure 3-8 also shows Instrument C to again be reading about 40 percent below actual values for O_2, similar to Figure 3-7.

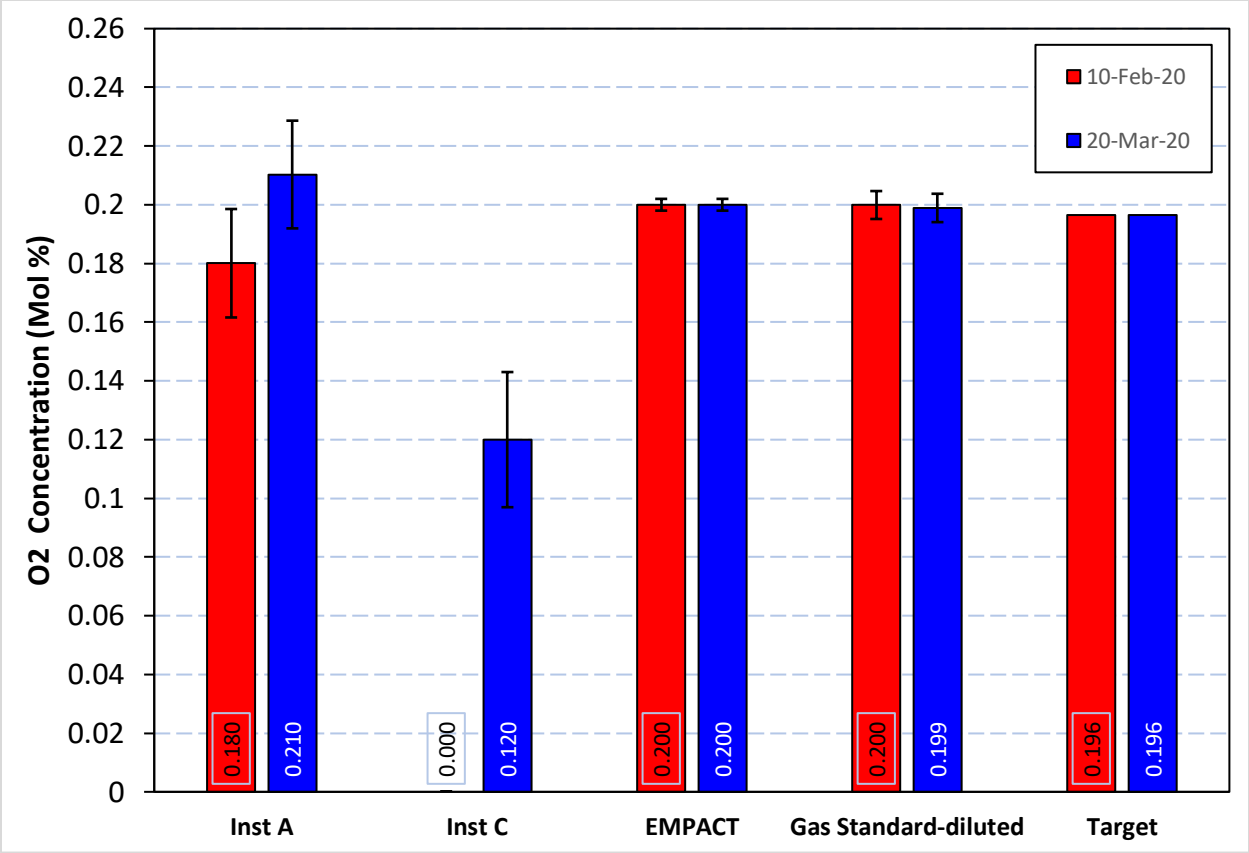


Figure 3-7. "Mid-A" blend O_2 concentrations detected by each analyzer along with calculated levels (Gas Standard-diluted), EMPACT third-party results and target level. Instrument B omitted due to non-detect of O_2.

In order to get a better understanding of how the instruments performed for each contaminant species, equivalency line plots were created comparing quantification techniques to the "Gas Standard-diluted" concentrations calculated from gas blending system pressures and orifice sizing for all four contaminant levels. While there is some uncertainty associated with these calculated species concentrations it was determined to be within tolerable levels when compared to the total uncertainties of results reported by the three analyzers. Third-party results from EMPACT are shown for CO_2 and O_2; EMPACT results were not available for H_2O or H_2S so they are not shown. Figures 3-9, 3-10, 3-11 and 3-12 show equivalency plots for each

contaminant using results from Low, Mid-A, Mid-B and High custom gas blends, respectively, in test runs performed in March 2020 ('20-Mar-20' testing).

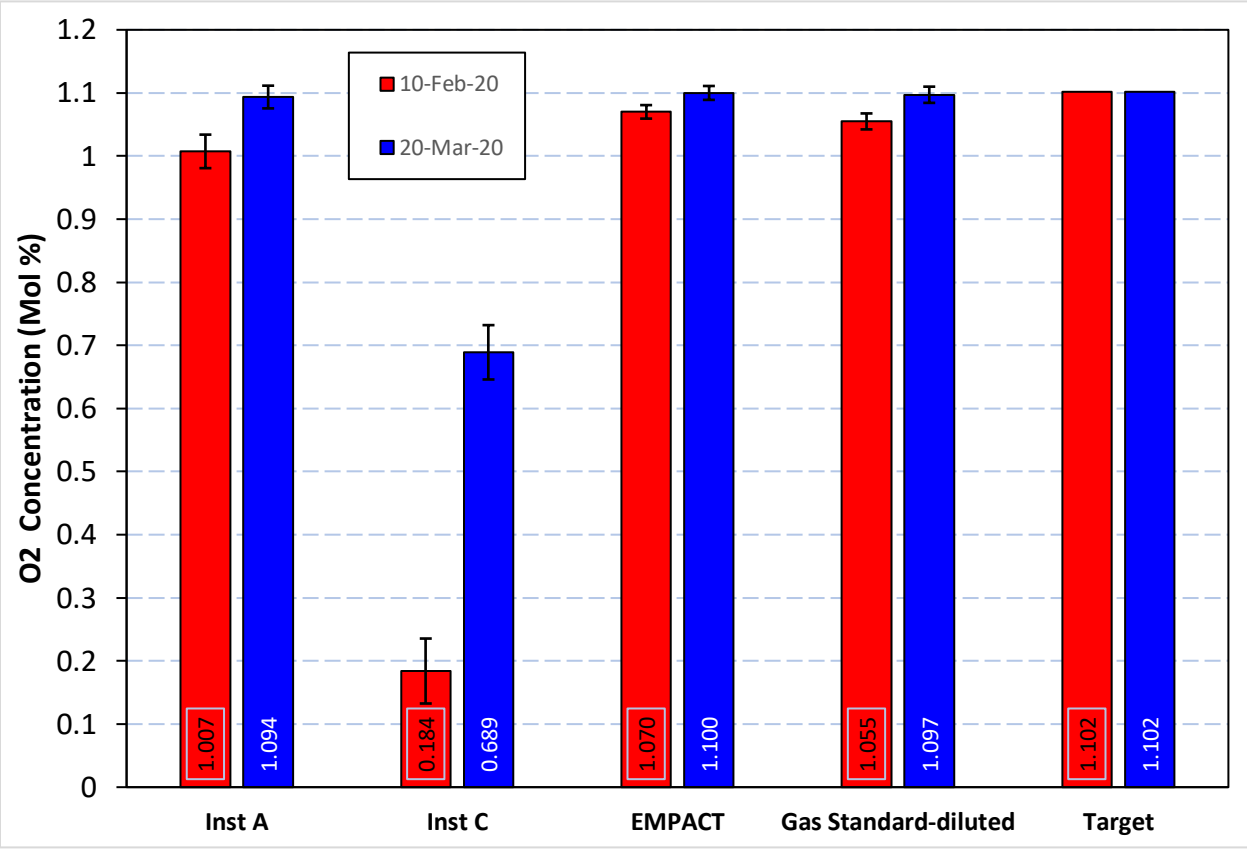


Figure 3-8. "High" blend O_2 concentrations detected by each analyzer along with calculated levels (Gas Standard-diluted), EMPACT third-party results and target level. Instrument B omitted due to non-detect of O_2.

Instruments A and B were successful in detecting H_2O with consistent results relative to each other as well as calculated concentrations for each contaminant blend. Instrument B did display increased uncertainty at High level blends as can be seen by the larger error bars at the 500 ppm data point in Figure 3-9; this is likely due to being the Instrument B upper detection limit for H_2O which is 600 ppm. Instrument C had unacceptable performance with results consistently

much lower than actual concentrations (by over 70 percent) but this is to be expected as that analyzer had not been configured from the manufacturer to detect H_2O.

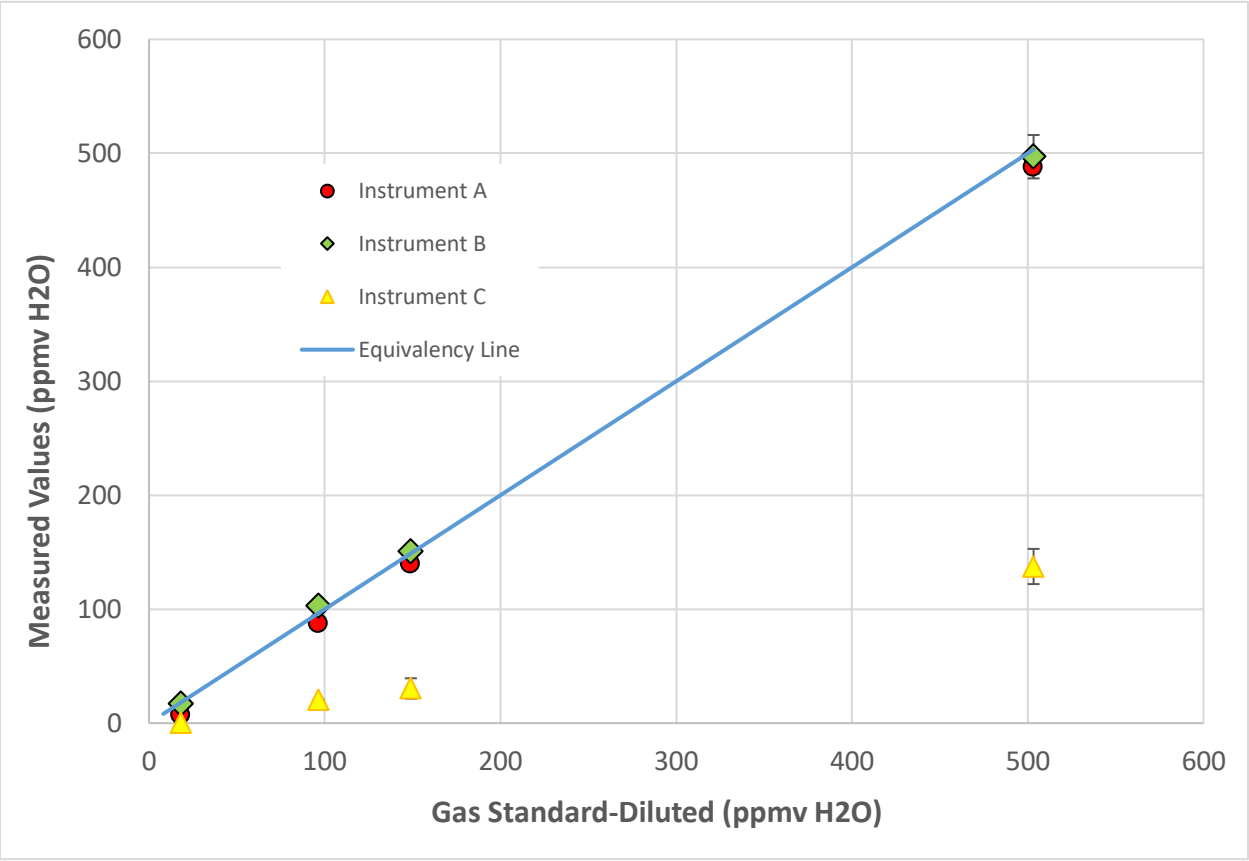


Figure 3-9. Equivalency line plot for H_2O comparing instrument results to calculated (Gas Standard-diluted) concentrations for all four contaminant blends.

Instrument C did perform better for H_2S than for H_2O but still reported results farther off from actual than Instruments A and B as can be seen by the vertical offset of the data points in Figure 3-10. The measured error for Instrument C for the High contaminant blend level of H_2S (target of 20 ppm) also was very large as can be seen by the error bars for the Instrument C data point at 17 ppm (y-axis value) in Figure 3-10. Instrument A had the lowest measured uncertainty of all instruments and was within 5 percent of actual H_2S concentration at High blend levels, seen by the Instrument A data point at 19.32 ppm in Figure 3-10 also indicating the highest accuracy of

the three analyzers. Instrument B also reported results similar to Instrument A with even lower inaccuracy of 3.5 percent variance from calculated and only slightly higher uncertainty than Instrument A, again at High blend levels seen by the Instrument B data point at 21.79 ppm.

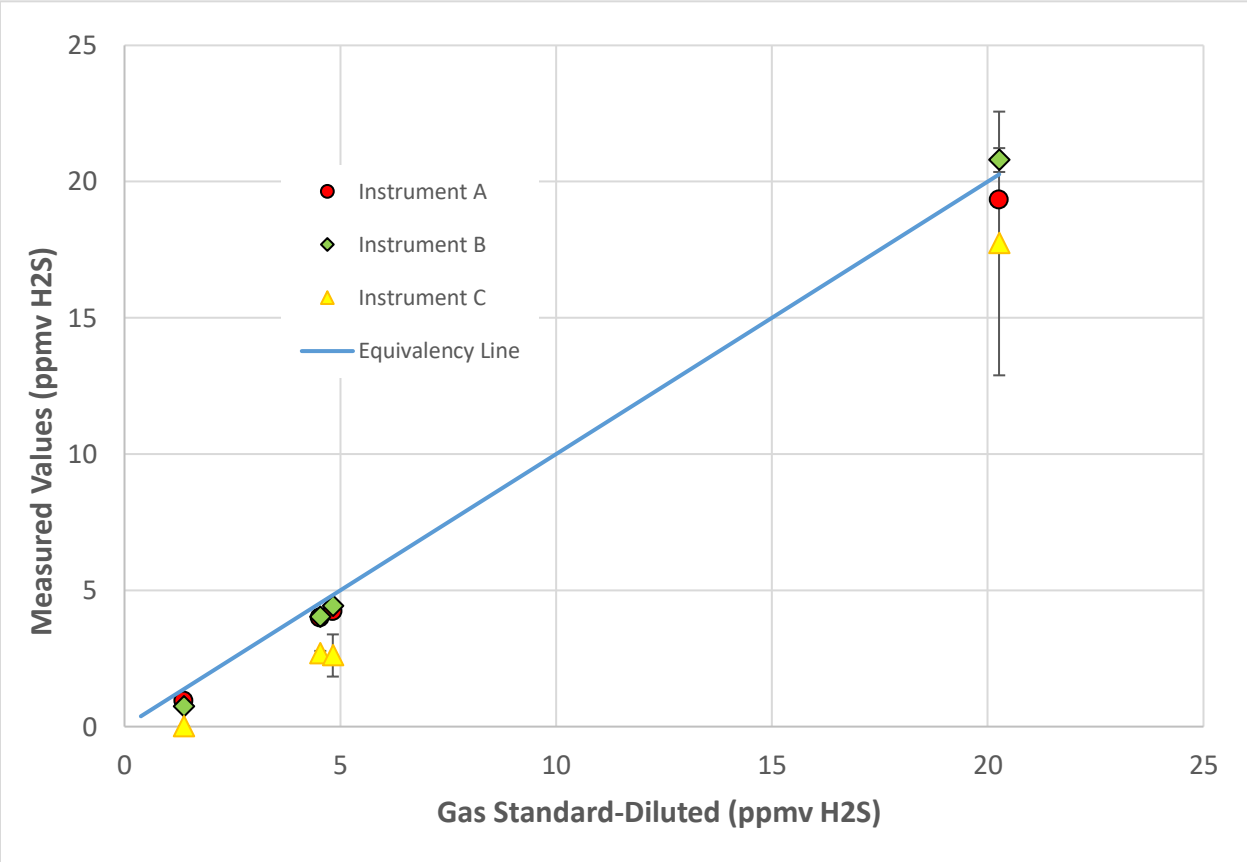


Figure 3-10. Equivalency line plot for H_2S comparing instrument results to calculated (Gas Standard-diluted) concentrations for all four contaminant blends.

In the case of detecting CO_2, all the instruments reported average values within 5 percent of calculated concentrations and maximum uncertainty of only ±0.182 mole percent in Instrument C results with Instruments A and B being ±0.005 mole percent and ±0.104 mole percent, respectively. Unlike for the H_2O and H_2S contaminants, Instrument C gave results consistent with the other two analyzers as well as actual measured concentrations with reported High concentration CO_2 having only 2 percent offset from calculated values. EMPACT results

were consistent with calculated concentrations with the largest offset being 3 percent for the High contaminant blend CO_2 level.

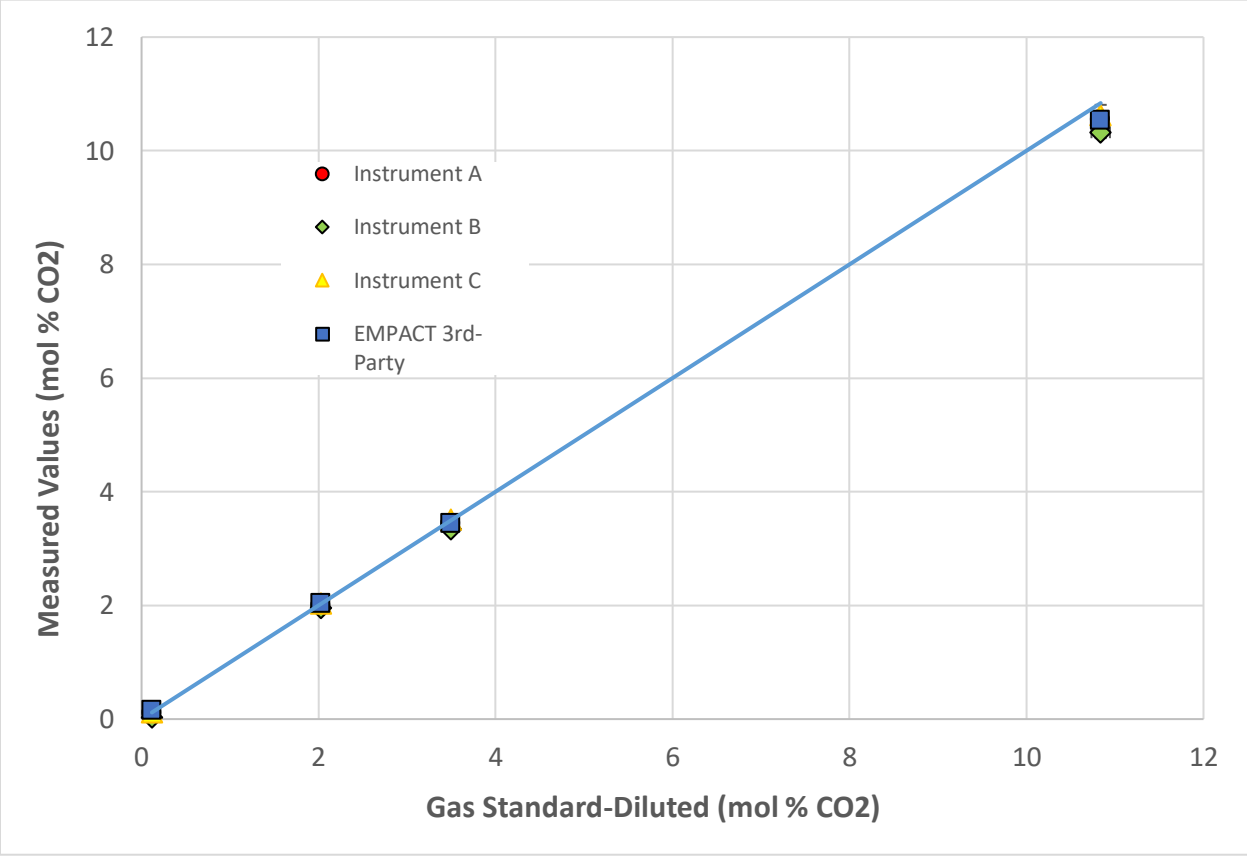


Figure 3-11. Equivalency line plot for CO_2 comparing instrument and EMPACT results to calculated (Gas Standard-diluted) concentrations for all four contaminant blends.

Since Instrument B was unable to detect O_2 there are no results for that analyzer displayed in Figure 3-12. The only analyzer which accurately and reliably detected O_2 was Instrument A with reported values within 8 percent of actual measured concentrations. Instrument C did detect O_2 but at levels much lower (on the order of 45 percent) than actual values for all contaminant blend levels as can be seen by the data points being significantly offset on the y-axis from the O_2 equivalency line in Figure 3-12. EMPACT third-party lab testing results were consistent with calculated concentrations with a maximum offset of 1 percent for the High contaminant blend O_2 level.

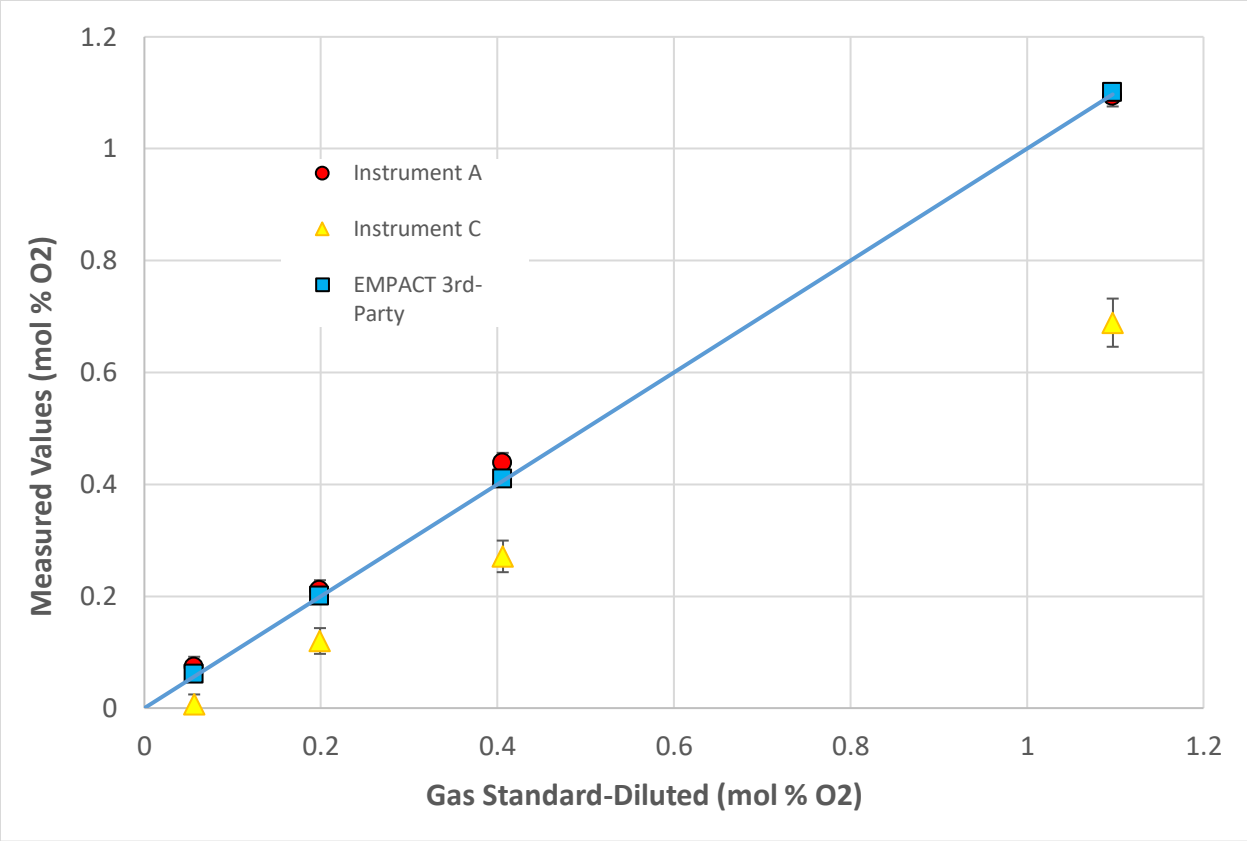


Figure 3-12. Equivalency line plot for O_2 comparing instrument and EMPACT results to calculated (Gas Standard-diluted) concentrations for all four contaminant blends. Instrument B omitted due to non-detect of O_2.

3.4 Analyzer Performance Evaluation

Each of the analyzing instruments' performance was evaluated based on multiple criteria including accuracy in reporting species concentrations, which of the gas contaminant species under test are detected by each instrument, and the level of intervention required by users to maintain proper operation.

Starting with detection of CO_2 contaminant by the analyzers, except for a few specific cases all instruments were able to detect and report concentrations very close (within 5 percent) to calculated and third-party results. Instrument B reported results 70 percent below calculated

for Low Contaminant custom blend and was essentially a non-detect for Field Gas 1; based on the data trends this seems to be due to the lower detection limit of CO_2 for Instrument B being in the 0.1 mole percent range as test runs with higher concentrations of CO_2 gave results consistent with the other instruments as well as calculated and third-party values.

Moving on to O_2 contaminant detection, only Instruments A and C were configured to detect O_2; Instrument B was not configured for that capability in this testing. Instrument A did display a high level of noise (500 ppm peak-to-peak, standard deviation in the 110-120 ppm range) when measuring O_2 but was only readily apparent in Low Contaminant custom blend and source natural gas tests where the O_2 concentration was closer to the lower LOD (Limit Of Detection) of the instrument. At higher concentrations the noise was still present but stayed within the same range of values so the relative uncertainty became lower as the O_2 concentration increased. Instrument C did detect O_2 but at levels consistently lower (by 40 to 50 percent) than Instrument A as well as calculated and third-party reported values.

Results for the remaining two contaminants (H_2O and H_2S) were less consistent due to their volatile nature and lower concentrations compared to CO_2 and O_2. For H_2S all instruments were able to detect but with more variation in both accuracy and uncertainty. Instruments A and B reported consistent results with a maximum offset of 5 percent from actual values; Instrument A had a maximum uncertainty of ±0.078 ppm while Instrument B had a maximum uncertainty of ±0.438 ppm for H_2S, both well within acceptable levels. Instrument C reported a non-detect for H_2S in the Low Contaminant blend tests but was able to detect at higher concentrations. However, the H_2S values reported by Instrument C were consistently lower (by about 45 percent) than the other instruments as well as calculated and third-party lab levels. The uncertainty for

H_2S on Instrument C in High Contaminant blend testing was also very high at ±4.84 ppm from an average value of 17.73 ppm.

For H_2O, Instruments A and B both performed without issue reporting average concentrations within 10 percent of calculated values. Instrument B did have increased uncertainty at High Contaminant blend levels of ±19.04 ppm (from an average value of 497 ppm) but this was within acceptable levels and likely due to approaching the instrument's upper LOD for H_2O. Instrument C occasionally detected H_2O but at levels far below other instrument and calculated values, by as much as 73 percent; it had not been configured to measure H_2O concentrations from the manufacturer so that was to be expected to some degree.

Looking at the overall performance of the individual analyzers, Instrument C performed the least satisfactorily out of the three analyzers tested. It technically was able to detect all four contaminant species but the accuracy and uncertainty for H_2O and O_2 were unacceptably poor. It also required substantial user intervention during initial startup and over the course of lab testing to get the instrument operating properly. Combined with its requirement of a constant helium supply to act as carrier gas, the overall performance and suitability for in-field use is inferior to the performance and suitability of the other gas analyzers.

Instrument B performed much better than Instrument C in terms of serviceability and user-friendly operation as well as accuracy in detecting gas contaminant concentrations. However, it lacked the capability of detecting O_2 altogether and was still slightly less accurate in detecting gas concentrations overall than Instrument A. It was also found to be somewhat fragile since on two separate occasions the analyzer stopped reporting appropriate readings and

required physical adjustment of the laser cavity mirrors and/or adjustment of settings in the instrument's firmware with guidance from the Instrument B manufacturer's technical support personnel to restore it to operational status.

After all testing and comparison of results Instrument A performed the best out of the three analyzers tested. While it did have a high noise-to-signal ratio near the lower LOD's the time-averaged results were still the most accurate of the three analyzers. It also gave the most reliable and trouble-free operation especially after the custom gas blending system was reconfigured to give a more consistent supply of sample gas. On only one occasion a technician from the Instrument A manufacturer visited the testing location to check the laser cavity alignment and system settings but they were found to be working well within specification and no major changes were required. Instrument A had no issues detecting all four gas contaminant species and did so in a consistent, repeatable fashion with in most cases less uncertainty than the other analyzers. While its large physical size, relatively high weight and requirement of constant purge air supply can be seen as disadvantages (particularly when compared to Instrument B), the fact that it reliably detected all four contaminant species with high accuracy and low uncertainty and also required minimal user intervention gave it the highest scores in terms of evaluating analyzer performance and suitability for field testing. Based on these evaluation results, Instrument A was chosen out of the three analyzers to proceed with in-field testing.

CHAPTER 4 – FIELD TESTING OF CONTAMINANT ANALYZERS

4.1 Field Test Site

Upon completion of lab testing of the three contaminant analyzers, Instrument A was selected as the best in terms of performance and was chosen for continued long-term testing in the field. Instrument B was also later agreed upon for field testing as the manufacturer believed the analyzer did not perform to its full potential and provided additional funding and technical support for the next phase of the project. The site chosen for field testing is the Watkins Compressor Station in Aurora, Colorado which is operated by Kinder Morgan. This site was chosen due to its proximity to CSU as well as the level of operations and willingness by the Kinder Morgan personnel to aid in the project. Watkins Compressor Station serves as a Colorado Interstate Gas pipeline compressor facility helping to distribute natural gas to consumers in populated areas along Colorado's Front Range of the Rocky Mountains including Denver, Colorado Springs and Pueblo. At this site natural gas is recompressed for transportation through the regional pipeline network and undergoes final processing to ready the gas for commercial and residential use and make sure it meets local gas tariff standards. Natural gas distributed by the Watkins Compressor Station is sourced from the Wattenberg plant located in northeastern Colorado which is owned and operated by Anadarko Petroleum Corporation and processes the natural gas from field production. Figure 4-1 shows a map of the route to the Watkins site from the Colorado State University campus in Fort Collins, Colorado. Figure 4-2 is a satellite image of the Watkins Compressor Station compound with the on-site location of the field test highlighted.

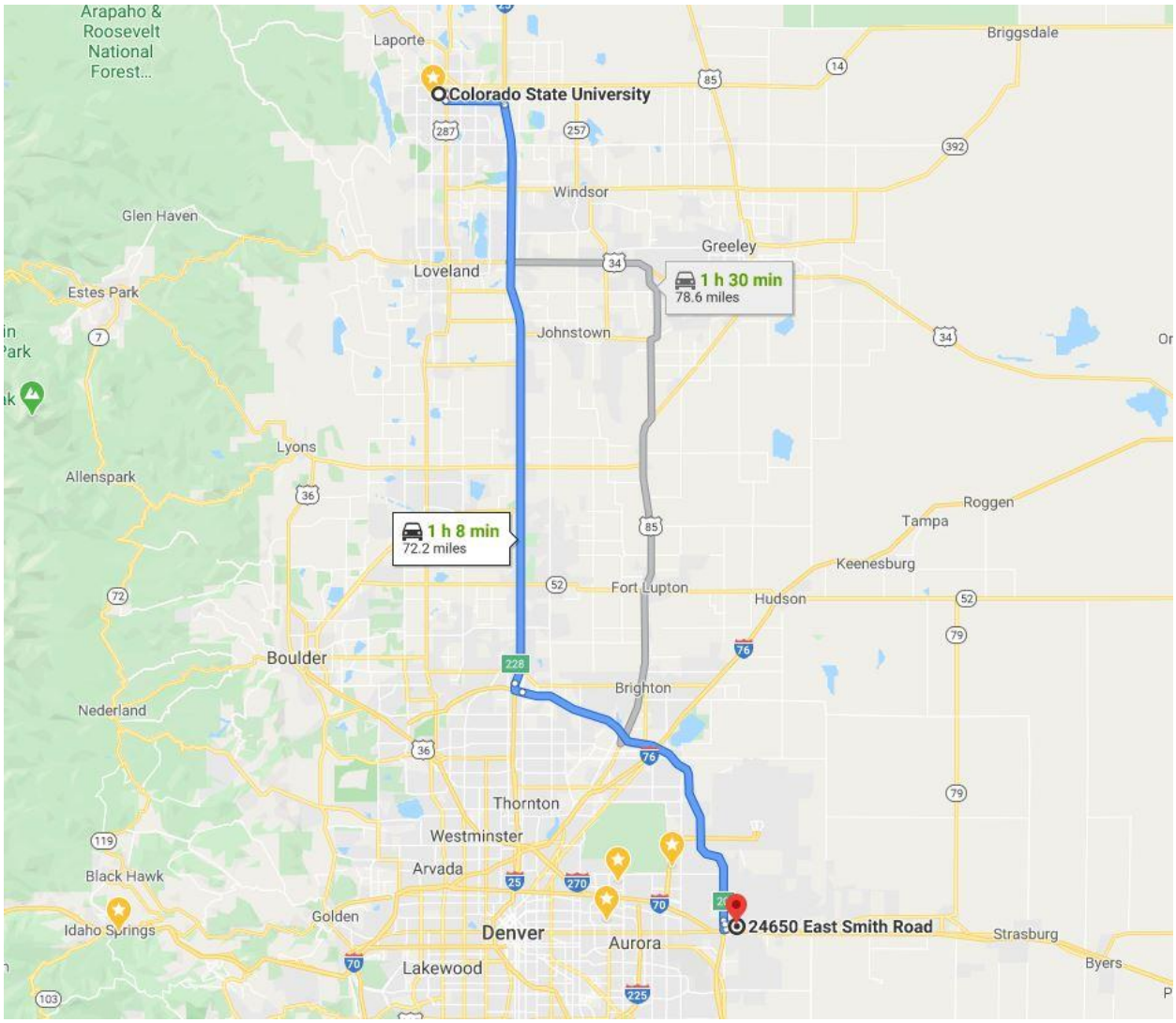


Figure 4-1. Map of the northern Colorado Front Range showing the location of the Watkins Compressor Station (24650 East Smith Road) and the route from CSU in Fort Collins.



Figure 4-2. Top-down satellite image of Watkins Compressor Station compound with location of field test installation highlighted in lower-right corner.

Field testing of the selected analyzers involves drawing natural gas from one of the site supply lines using a pipeline probe regulator assembly and setting a constant flow of sample gas through the analyzers. The analyzers are set up outdoors in temperature-controlled enclosures just outside the small buildings which house the gas analyzing instruments for the Watkins site. Data from the on-site Kinder Morgan analyzers will be compared alongside data collected by Instrument A and Instrument B. These sets of data will be processed and analyzed to determine the performance and accuracy of the instruments under test relative to the on-site gas analyzing instruments. Figure 4-3 is a photo of the sample probe regulator mounted in the pipeline used for sampling along with the sample line and its heat trace; since there is about 40 feet (13 meters) distance from the sample probe to the instruments the line must be heated to prevent condensation and dropout of any heavier species in the sample gas mixture. Figure 4-4 shows a top-down schematic of the site test area configuration.



Figure 4-3. Photo of sample probe regulator (circled in red) installed in natural gas pipeline along with the sample gas line and its heat trace wrapping (black line going to overhead bridge).

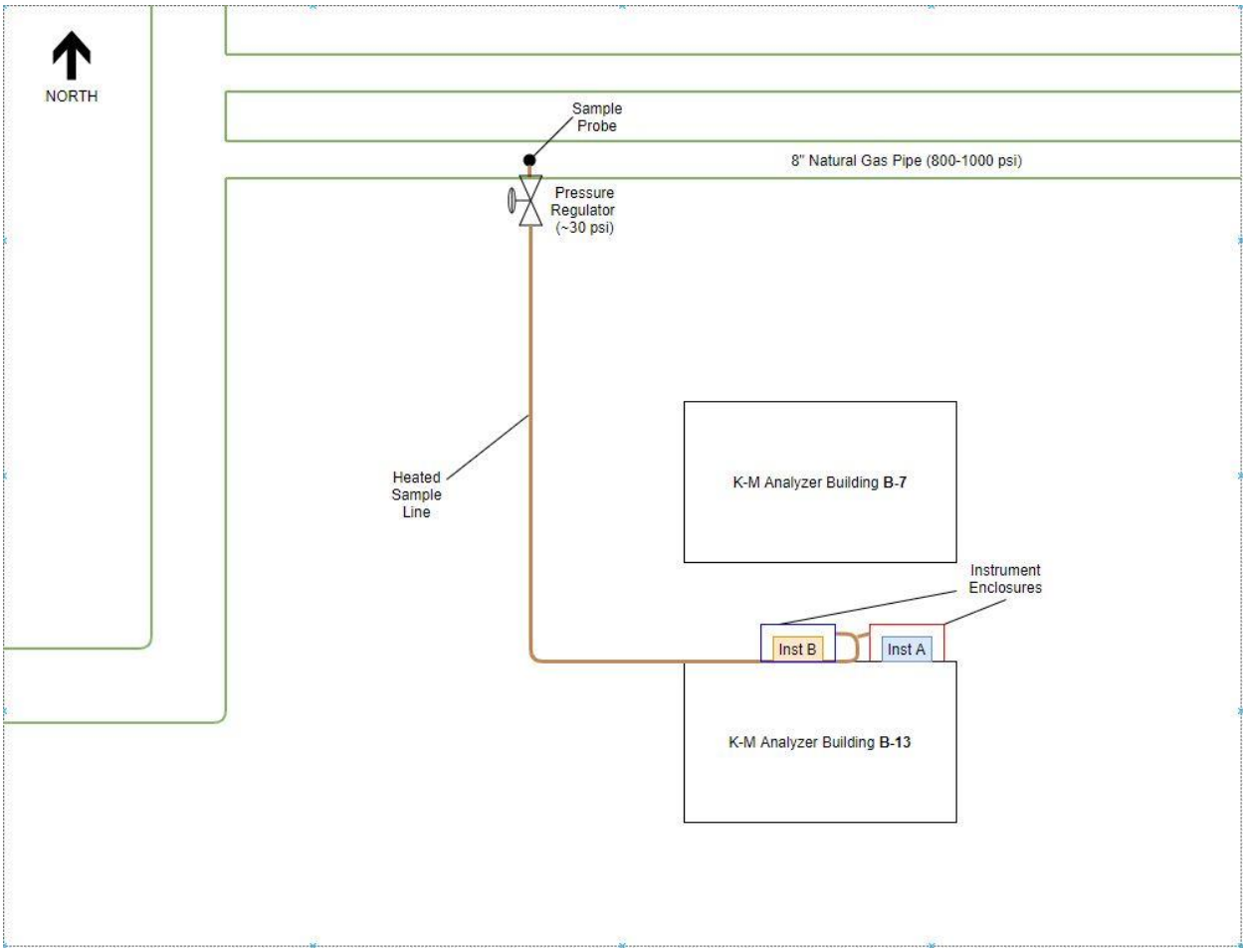


Figure 4-4. Top-down schematic of analyzer testing configuration at the Watkins Compressor Station

4.2 On-Site Gas Analyzers

To ensure the quality of the natural gas being supplied by the Watkins Compressor Station meets required standards, on-site gas analyzers constantly monitor the gas composition and concentration of O_2, H_2O and H_2S. For measuring O_2 content a Teledyne Trace model OT-3 Oxygen Analyzer is used (Figure 4-5). The Teledyne OT-3 is a single-channel analyzer using Micro-fuel Cell sensor technology. The Micro-fuel Cell is an electrochemical galvanic device that contains a cathode and anode immersed in an aqueous electrolyte and converts energy from a

chemical reaction into an electrical potential that can produce current in an external electrical circuit; its action is similar to that of a battery but with one of the reactants (oxygen) introduced from outside the cell instead of being contained within it [30].



Figure 4-5. Photo of Teledyne OT-3 Trace Oxygen Analyzer installed at Watkins Compressor Station with front panel open showing internal components.

For measuring H_2S concentration in the pipeline natural gas stream, an Envent Engineering Model 331 H_2S Analyzer is employed by the Watkins Compressor Station (Figure 4-6). The Envent Model 331 is a single-channel analyzer using ASTM D4084-07: Standard Test Method for analysis of hydrogen sulfide in gaseous fuels (Lead Acetate reaction rate method) [31]. The analyzer uses lead acetate impregnated paper ("H_2S Sensing Tape") which reacts when exposed to H_2S at a rate dependent on concentration in the sample stream; the reaction produces a visible darkening stain on the tape. The electronics built into the analyzer use an LED

and photodiode detector and are programmed to measure the rate of darkening over time which translates to the level of H_2S concentration in the sample gas [31].

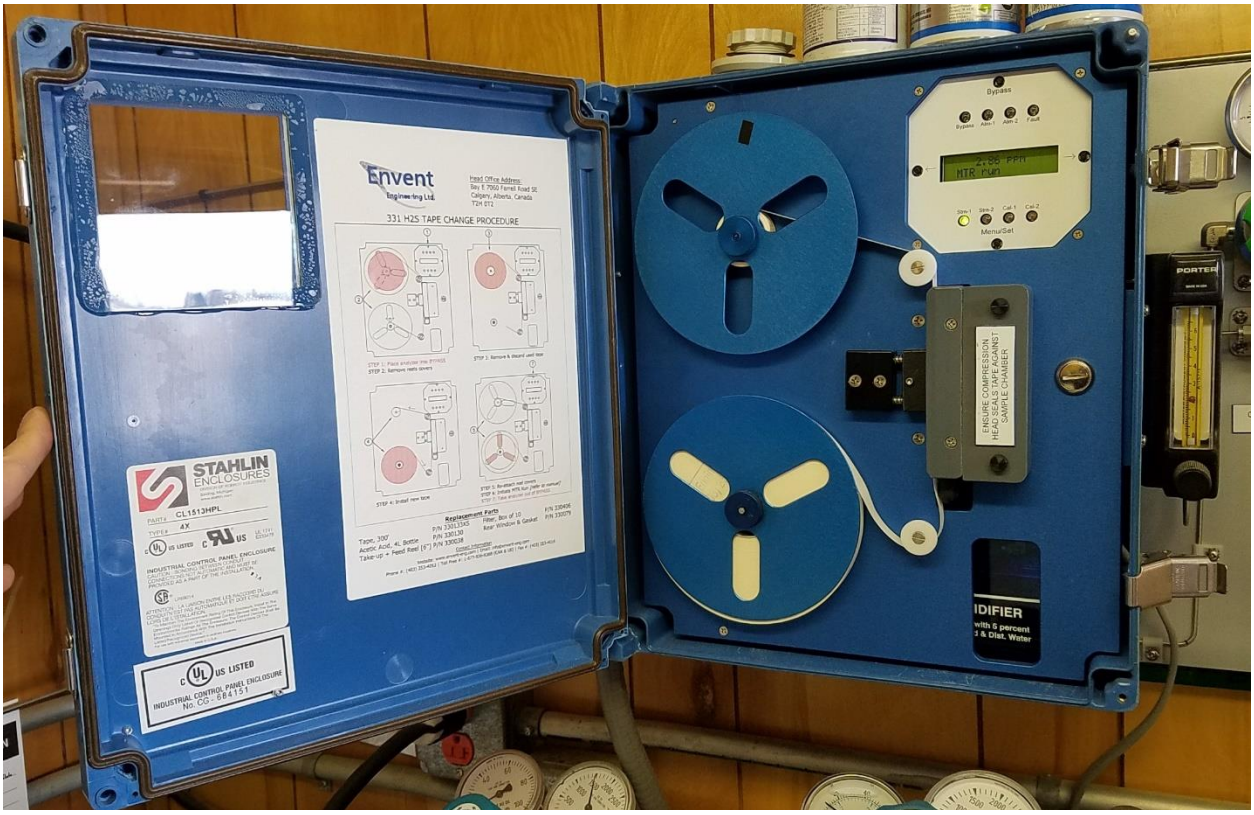


Figure 4-6. Photo of Envent Model 331 H_2S Analyzer installed at Watkins Compressor Station with front panel open showing H_2S Sensing Tape reels and detector module.

The analyzer used for measuring H_2O content in the pipeline natural gas stream at the Watkins Compressor Station is the SpectraSensors Model SS2000 (Figure 4-7). The SpectraSensors SS2000 is a single-channel analyzer using TDLAS (Tunable Diode Laser Absorption Spectroscopy) which is the same theory of operation as Instrument A and Instrument B. Like Instruments A and B, the SpectraSensors SS2000 contains a sample cell with a mirror on one end and a window at the opposite end through which a laser beam can pass [32]. The laser beam is tuned to the specific absorption spectrum of the gas species to be analyzed and enters the cell where it then reflects off the mirror making a pass through the sample gas and is absorbed by

the component gas molecules. The reduction in intensity of the beam leaving the cell is measured by a detector and is processed to determine H_2O concentration [32].



Figure 4-7. Photo showing front panel of SpectraSensors Model SS2000 H_2O analyzer installed at Watkins Compressor Station

Lastly for measuring CO_2 content in the pipeline natural gas a Daniel Danalyzer 500 Gas Chromatograph is used in conjunction with a Daniel 2350 GC Controller. This device operates on standard GC principles wherein a small volume of sample gas is injected into a column which contains a stationary phase packing. The packing causes selective retardation of the sample through the column which separates the sample into its component gases; separation of the sample in this instrument takes approximately 10 to 15 minutes [33]. A detector at the outlet of the column senses the component gases from the column and produces electrical outputs proportional to the concentration of each component [33]. The outputs are then processed into

chromatograms and recorded for reference. Figure 4-8 is a manufacturer image of a Danalyzer 500 chromatograph with optional explosion-proof controller.



Figure 4-8. Image of Daniels Danalyzer 500 Gas Chromatograph and explosion-proof Daniel 2350A Controller.

4.3 Field Test Experimental Setup

Instruments A and B are set up at the field test site outdoors in order to monitor the effects of changing ambient conditions such as temperature, pressure and humidity. However, the analyzers themselves are not designed to be exposed to the elements and must be enclosed to protect from water and dust intrusion and temperature extremes. The enclosures are equipped with automatic electric heaters to keep the temperature at or above 70 degrees

Fahrenheit. To meet industry safety requirements the enclosures are also set up with a constant supply of purge air to ensure any possible leaking sample gas cannot collect inside the enclosure and form a dangerous explosive mixture. Figure 4-8 shows the installed enclosures for Instruments A and B.



Figure 4-8. Enclosures for Instruments A (left) and B (right) installed at field test site showing sample gas, purge air and electrical connections

In order to ensure adequate sample gas flow rate and prevent potential dropout of gas components a fast-bypass loop was incorporated into the sample inlet tubing configuration for Instrument A; this is required due to the low sample flow rate of the analyzer. This was not required for Instrument B as it already comes factory-configured with a sample bypass loop due to its very low sample flow rate, even lower than Instrument A. Figure 4-10 is a schematic of the

fast-bypass loop used for Instrument A; the setpoint values displayed were adjusted slightly to coincide with the requirements for the instrument. In the fast-bypass loop the sample gas flows from the probe regulator and passes through a filter to prevent any unwanted solid or liquid species traveling into the analyzer. A portion of the flow passes through a pressure regulator set

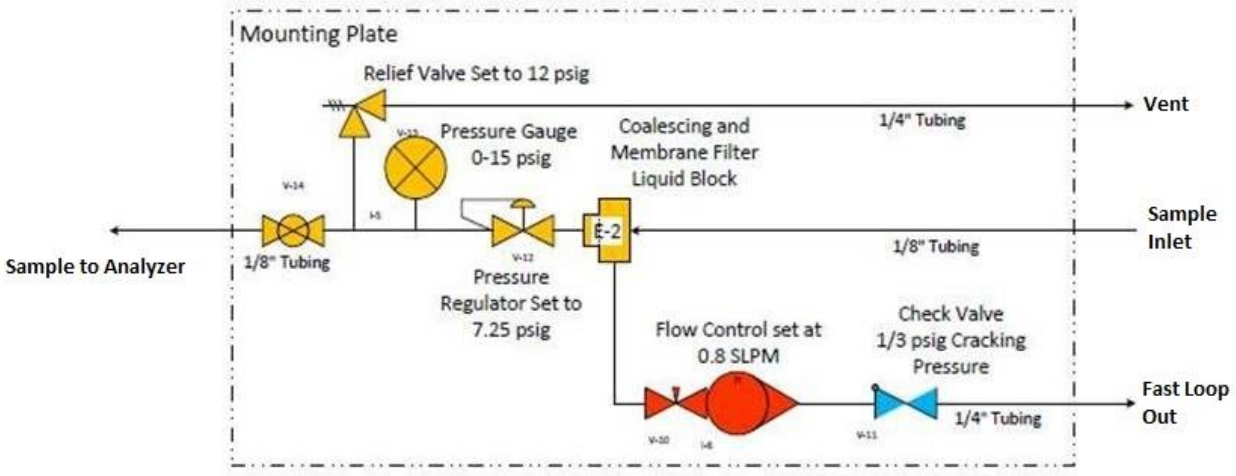


Figure 4-10. Schematic of sample gas Fast Bypass Loop for Instrument A.

to the required inlet pressure of the analyzer. The remaining flow which doesn't pass through the regulator is diverted to a needle valve to set the bypass flow rate with a check valve downstream of the needle valve to prevent unwanted back-flow. After flowing through the pressure regulator the sample gas travels to the sample inlet of the analyzer; a relief valve is incorporated into the analyzer sample inlet tubing to prevent an overpressure condition from potentially damaging the analyzer. Figure 4-11 shows the physical fast bypass loop configuration installed in the enclosure for Instrument A.



Figure 4-11. Photo of installed sample gas Fast Bypass Loop inside enclosure for Instrument A also showing purge air filters, electrical wiring and heater thermostat on right with enclosure heater mounted on left.

Data from the instruments is transmitted remotely in real-time using a cellular network router. This also allows remote access to the instruments to check their operation and make any necessary adjustments without requiring a visit to the field test site. The instruments are connected to the router via ethernet cable which then broadcasts the signal through the cellular phone data network of the chosen wireless carrier. The specific model of cellular router selected for this application is the Teltonika RUT240 LTE Router. Figure 4-12 shows the cellular router mounted inside the building housing the pipeline analyzers for the Watkins Compressor Station along with the external roof-mounted antennas.



Figure 4-12. Photos showing cellular router for remote communication (left) with roof-mounted antennas (right).

4.4 Initial Field Test Results

Once the two analyzers were installed and sampling pipeline natural gas on January 15, 2021 the data collection routine was started. At the end of the month the Kinder Morgan personnel release gas composition data for each day, averaged over 15-minute intervals for laser-based analyzers (H_2O, H_2S, O_2 levels) or 1-hour intervals for the GC analyzer (CO_2 and assorted hydrocarbons). The data from Instruments A and B is averaged to the same time interval and compared to the on-site analyzer results. Contaminant concentrations from January 15 to January 26 are shown in Figures 4-13, 4-14, 4-15, and 4-16. Concentrations for January 31 to February 18 are shown in Figures 4-17, 4-18, 4-19, and 4-20 as there was a lapse in data collection from January 26 to January 30.

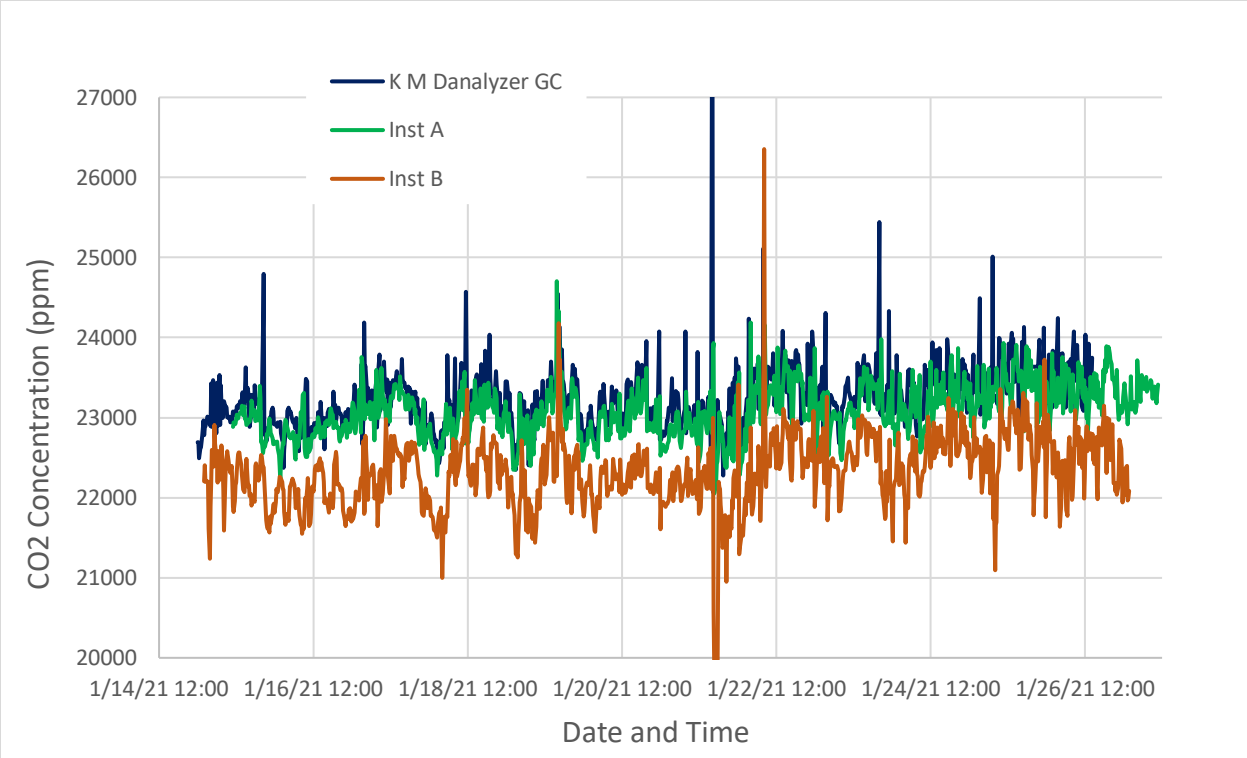


Figure 4-13. Time-series data for CO_2 concentrations from Instruments A, B, and Kinder Morgan on-site analyzers for 1/15/21 to 1/26/21.

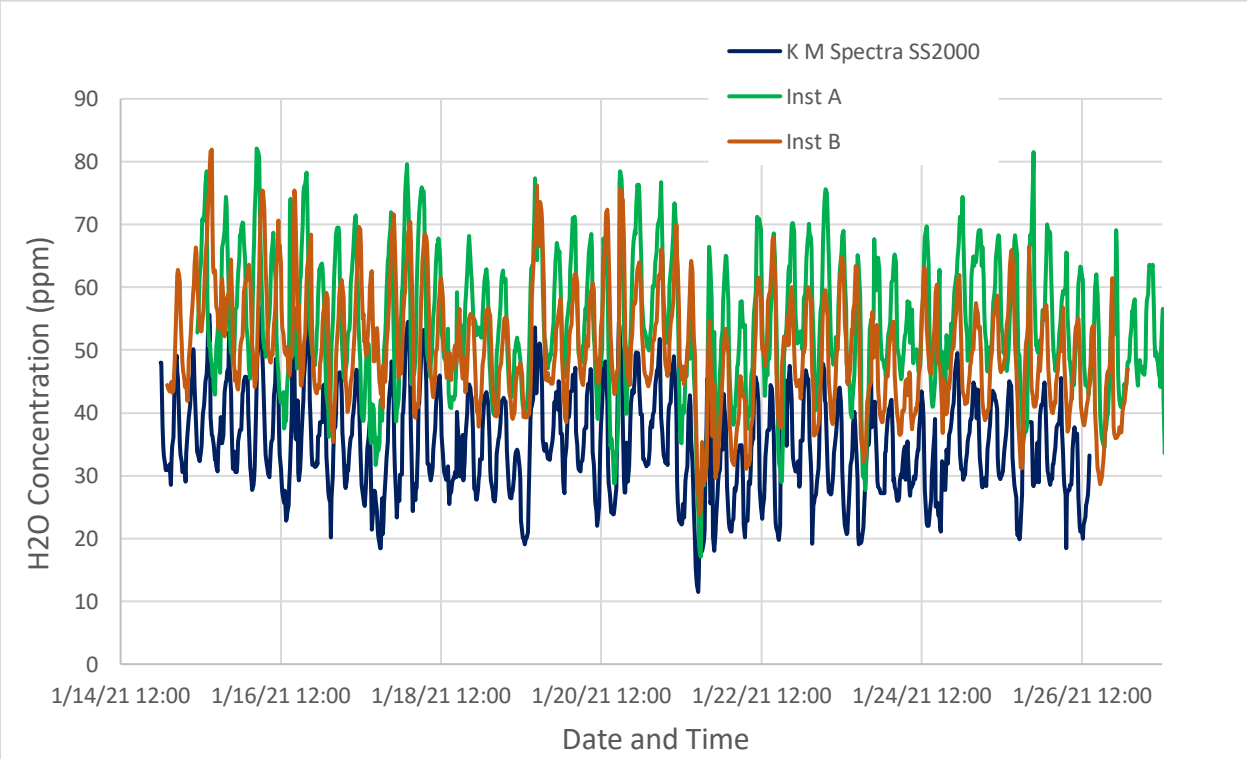


Figure 4-14. Time-series data for H_2O concentrations from Instruments A, B, and Kinder Morgan on-site analyzers for 1/15/21 to 1/26/21.

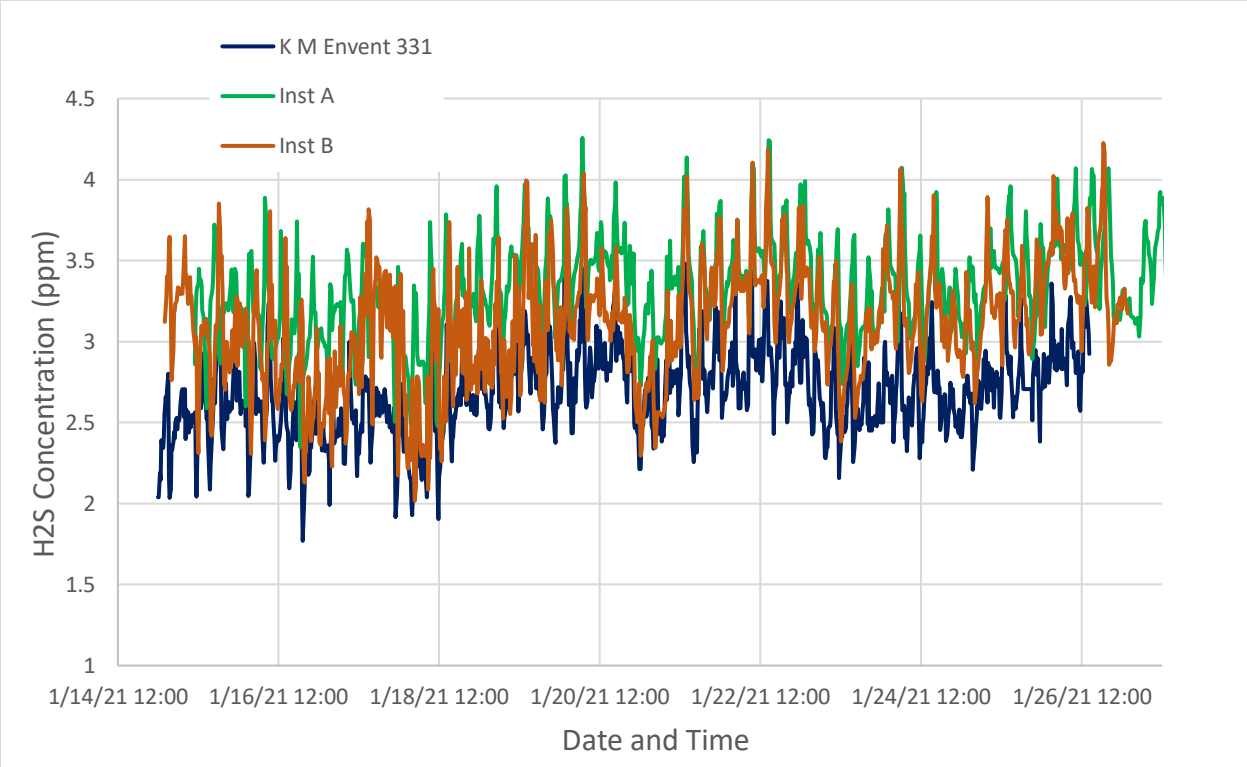


Figure 4-15. Time-series data for H_2S concentrations from Instruments A, B, and Kinder Morgan on-site analyzers for 1/15/21 to 1/26/21.

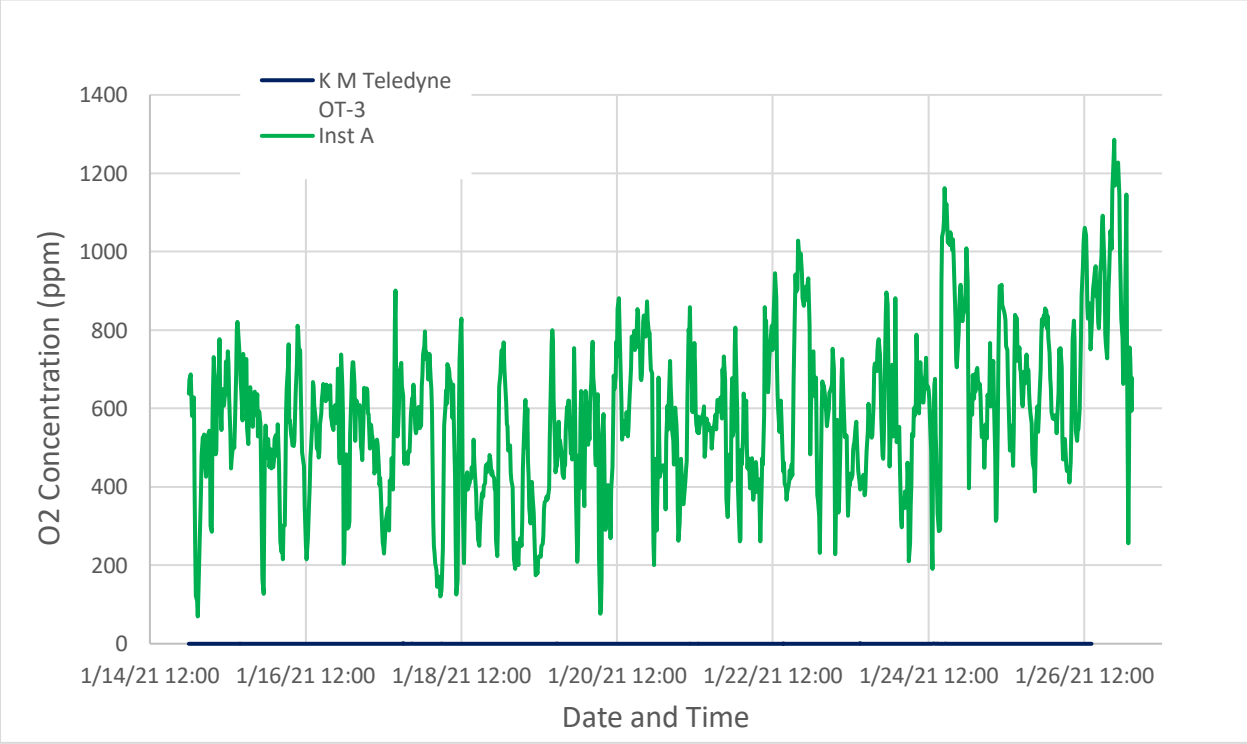


Figure 4-16. Time-series data for O_2 concentrations from Instrument A and Kinder Morgan on-site analyzers for 1/15/21 to 1/26/21.

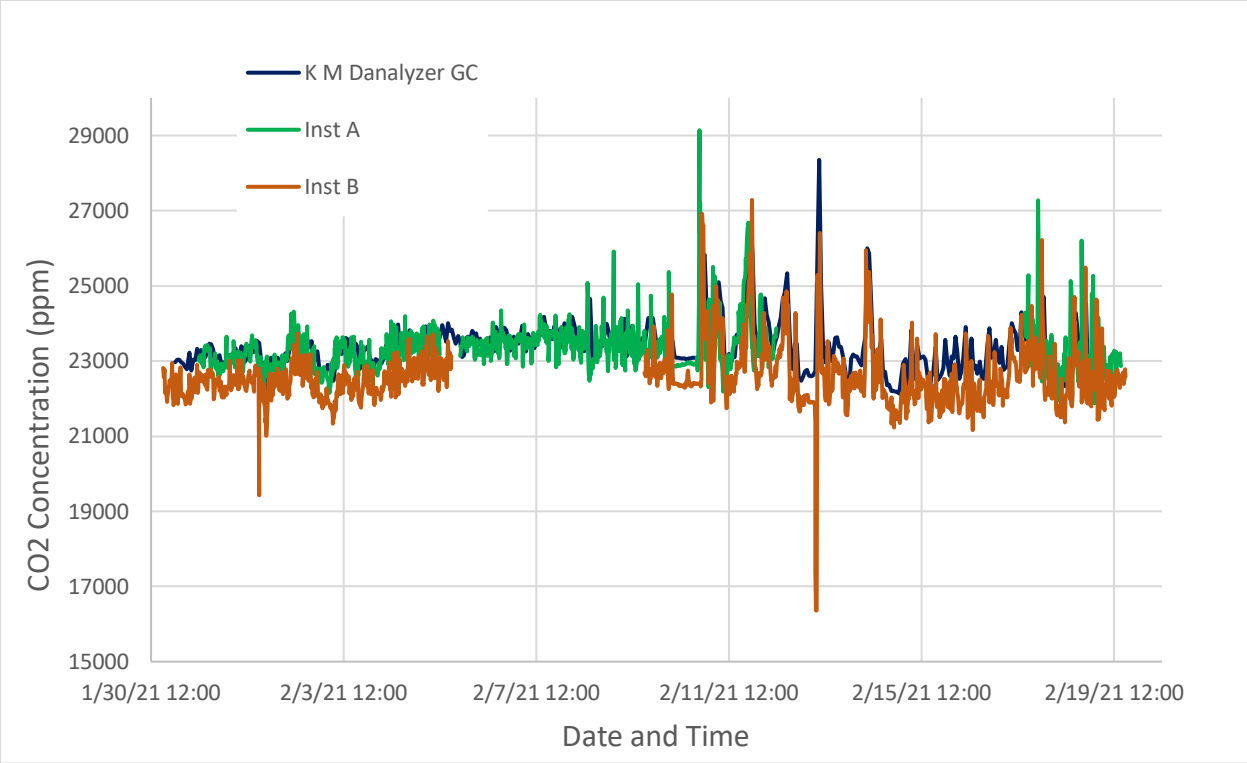


Figure 4-17. Time-series data for CO_2 concentrations from Instruments A, B, and Kinder Morgan on-site analyzers for 1/31/21 to 2/19/21.

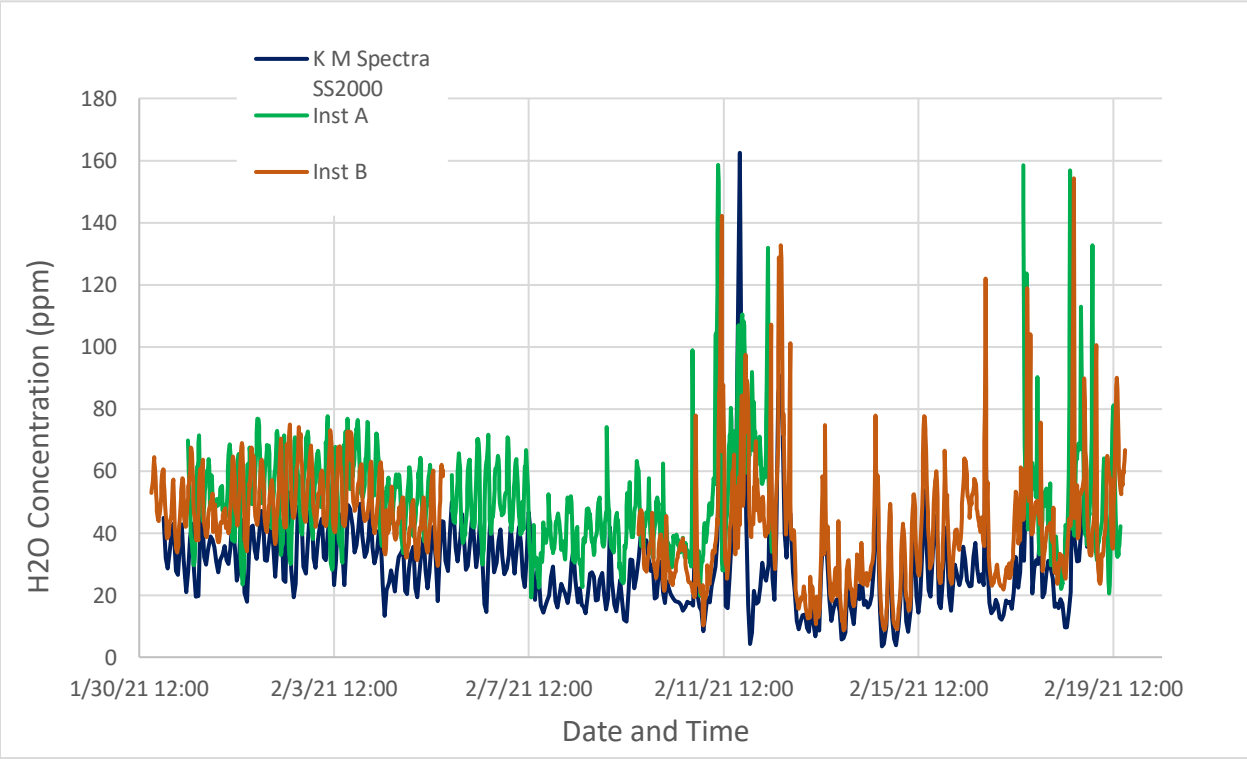


Figure 4-18. Time-series data for H_2O concentrations from Instruments A, B, and Kinder Morgan on-site analyzers for 1/31/21 to 2/19/21.

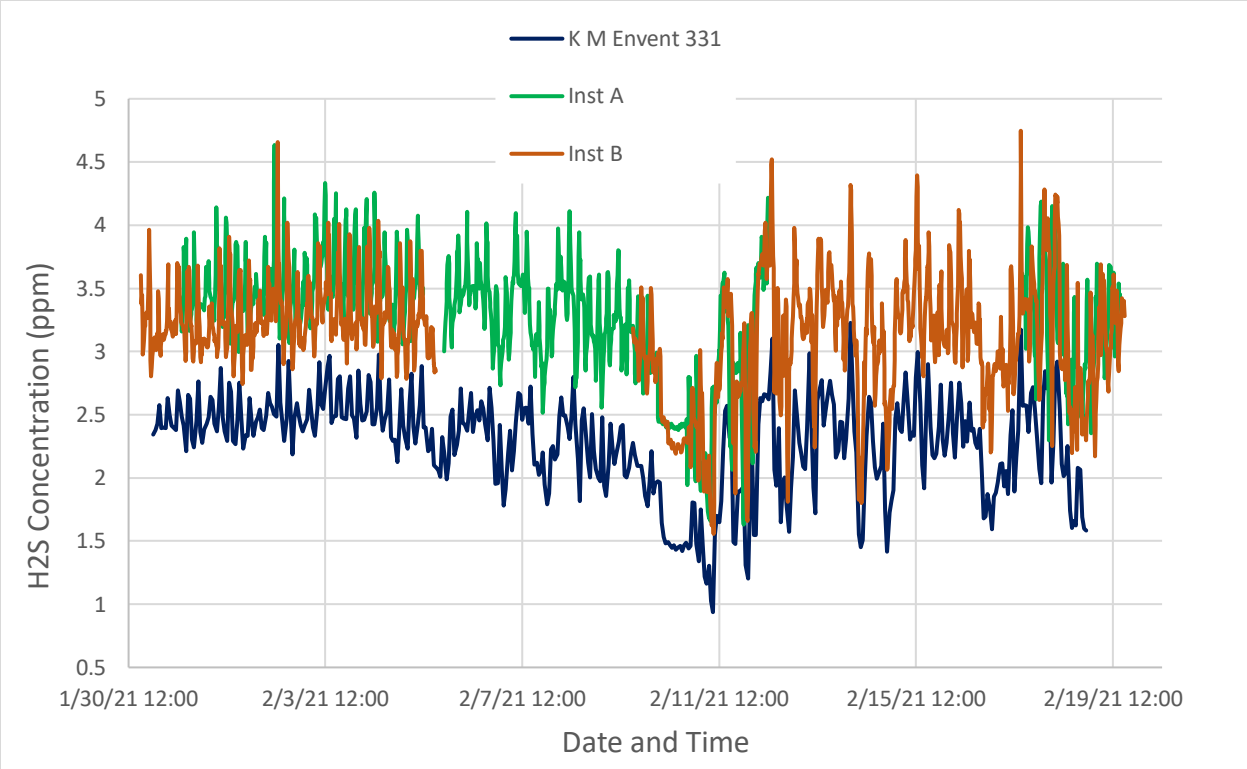


Figure 4-19. Time-series data for H_2S concentrations from Instruments A, B, and Kinder Morgan on-site analyzers for 1/31/21 to 2/19/21.

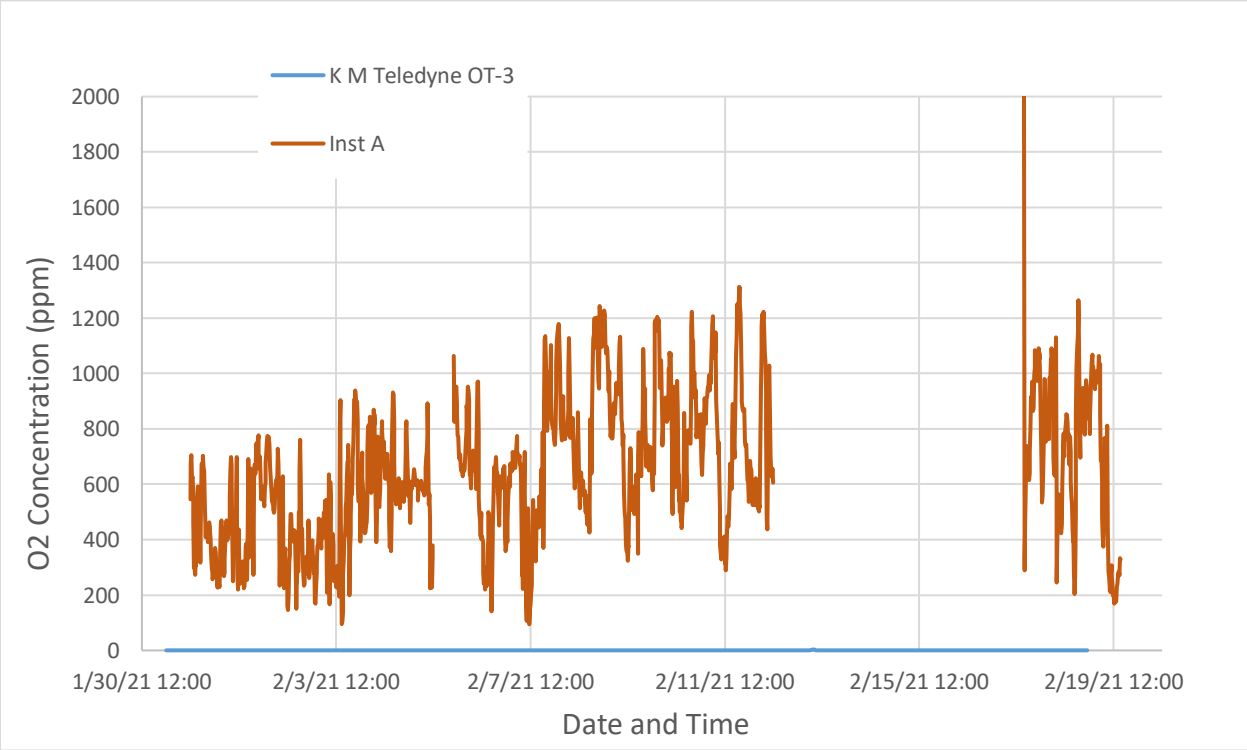


Figure 4-20. Time-series data for O_2 concentrations from Instrument A and Kinder Morgan on-site analyzers for 1/31/21 to 2/19/21.

According to the relative consistency in the CO_2, H_2O and H_2S data, Instruments A and B are in agreement with each other as well as the on-site Kinder Morgan analyzers for the Watkins Compressor Station. In order to make the multiple sets of data correlate between the different analyzers a time-offset of +68 minutes was applied to Instruments A and B for the first set (Jan 15-26) of data. Much larger offsets of +12 hours for Instrument A and -6 hours for Instrument B were required for the second set (Jan 31-Feb 19) of data; the cause of this is unknown although the instruments did experience lapses in data collection as can be seen in the second data set plots. The lapse in data was likely caused by a power outage or similar issue which caused the instruments to go offline; it is likely that once the instruments rebooted and attempted to synchronize their individual system clocks to the internet the previously-set time synchronization between the instruments and Kinder Morgan analyzers was lost.

Only Instrument A can detect O_2 so its results could not be compared with Instrument B. However even though Instrument A can detect O_2 its lower limit of detection of 0.01 mole percent or 100 ppm is far above the O_2 concentrations detected by Kinder Morgan analyzers which is on the order of 0.4 to 0.7 ppm. For this reason the results for O_2 cannot be compared accurately as can be seen in Figures 4-16 and 4-20. The high level of noise in the Instrument A readings makes results nearly impossible to distinguish. An alternative method to verify O_2 concentration will be required and with expected levels as low as they are it may be inconclusive to continue monitoring O_2 with Instrument A.

CHAPTER 5 – CONCLUSION

Three natural gas contaminant analyzers were selected for testing their operation and functionality, referred to as Instruments A, B, and C. These instruments have the ability to detect and measure multiple natural gas components simultaneously as opposed to current natural gas site analyzers which typically only each detect one component species. Three commercially available gas analyzers were tested to find the most capable and best-performing unit to potentially be installed at natural gas processing and distribution sites. The analyzer with the best performance was selected for additional in-field testing to evaluate its performance in "real-world" conditions.

5.1 Laboratory Testing Evaluation

Each of the gas analyzing instruments employed unique technology and methods of operation to measure gas concentrations. Instruments A and B each used their own unique application of Tunable Diode Laser Absorption Spectroscopy (TDLAS) technology while Instrument C is a multi-column Gas Chromatograph (GC). The contaminant gas species chosen to be measured by the analyzers are CO_2, O_2, H_2O, and H_2S. The analyzers were tested using three locally sourced pipeline natural gas blends as well as four custom gas blends created in a laboratory in real-time using ultra-high-purity component gases. These four custom blends represented typical Low-level, Mid-level (two versions) and High-level contaminants commonly found in natural gas. The instruments were also evaluated in terms of their ease-of-use and level of required user intervention to maintain satisfactory operation.

The results from the analyzers under test were compared to third-party laboratory sample analyses (for CO_2 and O_2) and post-test calculations of component gas concentrations (referred to as Gas Standard-diluted) based on outputs from the gas blending system sensors. The Gas Standard-diluted values are considered to be the true values of contaminant concentrations. After comparing the results between the analyzers, third-party lab analyses, and calculated values it was concluded that Instrument A was the best-performing gas analyzer of the three tested. Aside from having a relatively low signal-to-noise ratio when measuring concentrations near its LOD (Limits of Detection) the time-averaged results were the most accurate compared to the other two analyzers. Instrument A also gave the most reliable operation with minimal issues and has a well-designed Graphical User Interface (GUI) which gave a simple and trouble-free interface with the analyzer control software and settings. Instrument A was also the only analyzer able to accurately detect all four contaminant species in a reliable and repeatable manner and with minimal uncertainty. For these reasons Instrument A was concluded to be the best choice of the three analyzers for field testing.

Instrument B came in a close second-place to Instrument A in terms of accuracy and uncertainty in measuring gas contaminant concentrations. However, it had not been configured from the manufacturer to detect O_2 like the other analyzers had been which gave it a lower evaluation 'score' and also had multiple occasions where the instrument stopped reporting correct results (or any results entirely) and required on-site visits by a technician to correct the problems. Its detection accuracy overall was also slightly less than Instrument A.

Instrument C was the worst-performing analyzer of the three tested by a wide margin in terms of accuracy, uncertainty and ability to detect the four selected gas contaminant species. It

technically was able to detect all four species but the accuracy and uncertainty in detecting H_2O and O_2 were unacceptably poor. This could have been remedied by a reconfiguration of the GC columns to target those species but was not considered due to time constraints and the expectation that Instrument C should have been configured correctly in the beginning since all instrument manufacturers had been notified of the target species long before actual testing began. Being a gas chromatograph, Instrument C also requires a constant supply of He (Helium) to act as carrier gas for the GC columns which reduces its ease of installation in a field application.

More specific, quantitative results from the laboratory comparison are listed below:

- The average quantification errors for Instrument A are
    - CO_2: 3.49%
    - O_2: 10.5%
    - H_2O: 19.9%
    - H_2S: 10.7%
- The average quantification errors for Instrument B are
    - CO_2: 21.2%
    - O_2: N/A (non-detect)
    - H_2O: 3.61%
    - H_2S: 17.3%
- The average quantification errors for Instrument C are
    - CO_2: 1.13%
    - O_2: 49.7%
    - H_2O: 77.1%
    - H_2S: 33.1%

5.2 Field Testing

Instruments A and B were selected for field testing to simulate "real-world" conditions. They were installed at the Watkins Compressor Station which is a natural gas distribution site owned by Kinder Morgan and located in Aurora, Colorado. The instruments are set up to constantly draw from the on-site pipeline natural gas supply and reported contaminant concentrations are compared to those reported by on-site contaminant analyzers.

Initial results from the field testing indicate the following:

- Instruments A and B are in general agreement with Kinder Morgan on-site analyzers aside from mismatched timestamps (currently undergoing analysis and correction)
- O_2 results are difficult to verify; Instrument B is non-detect for O_2 and Instrument A has a high level of noise near its lower detection limit of 100 ppm O_2 with no known way to verify concentrations

5.3 Ongoing/Future Work

Field testing for Instruments A and B began at the Watkins Compressor Station natural gas site in January 2021 and is expected to continue for a full year until January 2022. Both analyzers will be sampling pipeline natural gas on a constant basis and their results will be compared monthly to results produced by the existing on-site analyzers used by Kinder Morgan to monitor pipeline gas quality. After the testing period is complete the best-performing analyzer will then be approved for use by pipeline natural gas regulating bodies and will then be able to start being incorporated into natural gas sites across the United States.

REFERENCES

[1] U.S. Energy Information Administration, 2020, “U.S. Natural Gas Total Consumption”, from https://www.eia.gov/dnav/ng/hist/n9140us2a.htm

[2] Faramawy, S., Zaki, T. and Sakr, A.A.-E., 2016, “Natural gas origin, composition, and processing: A review”, *Journal of Natural Gas Science and Engineering,* **34**, pp. 34-54.

[3] Kinder Morgan, 2020, “Asset Map”, from https://www.kindermorgan.com/Operations/Asset-Map

[4] Colorado Interstate Gas Company, 2013, “FERC Gas Tariff”, Second Revised Volume No. 1, Federal Energy Regulatory Commission, Colorado Springs, Colorado, pp. 232-233

[5] Jianwen, Z., Da L. and Wenxing, F., 2011, “Analysis of chemical disasters caused by release of hydrogen sulfide-bearing natural gas”, Procedia Engineering, **26**, pp. 1879

[6] Rubright, S. L. M., Pearce, L. L. and Peterson, J., 2017, “Environmental toxicology of hydrogen sulfide”, *Nitric Oxide,* **71**, pp.7

[7] National Institute for Occupational Safety and Health, 1994, “Hydrogen sulfide: Immediately Dangerous to Life or Health Concentrations (IDLH)”, from https://www.cdc.gov/niosh/idlh/7783064.html

[8] Occupational Safety and Health Administration, 2020, “Hydrogen Sulfide – Health Hazards”, from https://www.osha.gov/SLTC/hydrogensulfide/hazards.html

[9] Khoma, M.S., 2010, “Problems of Fracture of Metals in Hydrogen-Sulfide Media”, *Materials Science*, **46**(2), pp. 191

[10] Caterpillar, 2010, “Cat Gas Engine Lubricant, Fuel, and Coolant Recommendations”, SEBU6400-05, Caterpillar, pp. 8

[11] Ettre, L.S., 2008, “The Beginnings of Gas Adsorption Chromatography 60 Years Ago”, *LCGC North America*, **26**(1), pp. 48-60

[12] Shimadzu, 2020, “What is Gas Chromatography?”, from https://www.ssi.shimadzu.com/products/gas-chromatography/fundamental-guide-to-gas-chromatography/what-is-gas-chromatography.html

[13] Shellie R.A., 2013, “Gas Chromatography”, *Elsevier*, **1**, pp. 146-153

[14] Frish, M.B., Wainner, R.T., Laderer, M.C., Green, B.D. and Allen, M.G., 2010, “Standoff and Miniature Chemical Vapor Detectors Based on Tunable Diode Laser Absorption Spectroscopy”, *IEEE Sensors Journal*, **10**(3), pp. 639-646

[15] SpectraSensors 3-pack website: https://www.spectrasensors.com/2-3-pack/

[16] ABB LGR-ICOS website: https://new.abb.com/products/measurement-products/analytical/laser-process-analyzers/laser-icos-950-series

[17] AP2E ProCeas website: https://www.ap2e.com/en/our-gas-analyzers/proceas-general-analyzer/

[18] Emerson Rosemount CT5800 website: https://www.emerson.com/en-us/catalog/rosemount-ct5800-continuous-gas-analyzer

[19] APIX ChromPix website: https://www.apixanalytics.com/chrompix/

[20] Elster EnCal 3000 website: https://www.honeywellprocess.com/en-US/explore/products/gas-measurement-and-regulation/metering/gas-analyzers/Pages/encal-3000.aspx

[21] Gas Processors Association, 2000, “Analysis for Natural Gas and Similar Gaseous Mixtures by Gas Chromatography”, GPA 2261

[22] (Instrument C User Manual)

[23] (Instrument A User Manual)

[24] (Instrument B User Manual)

[25] KIN-TEK Analytical, Inc., 2020, “Trace Source™ Permeation Devices”, 2020/02 Rev. 0004, KIN-TEK Analytical, Inc., p. 3

[26] Walter Products Inc., 2010, “Walter Digital Water Bath, 2L”, from http://www.walterproducts.com/products-main/laboratory-equipment/water-baths/walter-digital-water-bath-2l

[27] Equilibar, 2019, “Research Series 1/16”-1/4” Back Pressure Regulators”, R5, Equilibar LLC, p. 2

[28] Cengel, Y.A. and Boles, M.A., 2011, *Thermodynamics: An Engineering Approach*, 7th ed., McGraw-Hill, New York, NY, Chap. 13

[29] Kline, S. J. and McClintock, F. A., 1953, “Describing Uncertainties in Single-Sample Experiments”, Mechanical Engineering, **75**, pp. 3-8

[30] Teledyne Analytical Instruments, 2000, “Operating Instructions for Model OT-3”, M74173, Teledyne Analytical Instruments, pp. 6-10

[31] Envent Engineering Ltd., 2019, “Hydrogen Sulfide Analyzer Model 330S & 331S, Model 330SDS & 331SDS User Manual”, Revision 2.4, Envent Engineering Ltd., p. 8

[32] SpectraSensors, 2020, “SS500/SS2000 Single Channel Gas Analyzer Hardware Installation and Maintenance Manual”, 4900002285 rev. B, SpectraSensors Inc., pp. 1—4 - 1—7

[33] Emerson Process Management, 2010, “Model 500 Gas Chromatograph Hardware Reference Manual”, 3-9000-537 Revision K, Daniel Measurement and Control, Inc., p. 1-4

APPENDIX A: OTHER SPECIES RESULTS

Source Natural Gas Lab Test Results

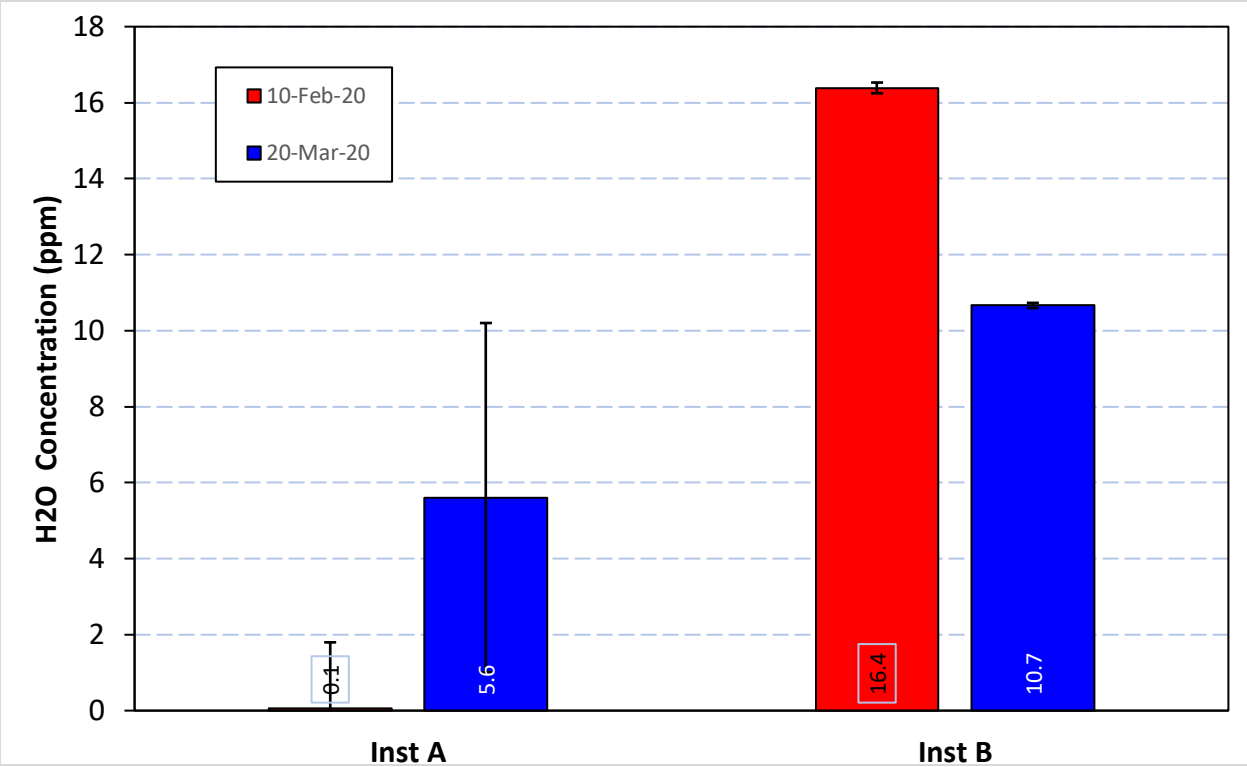


Figure A-1. Field Gas 1 H_2O lab test results; Instrument C and EMPACT non-detects.

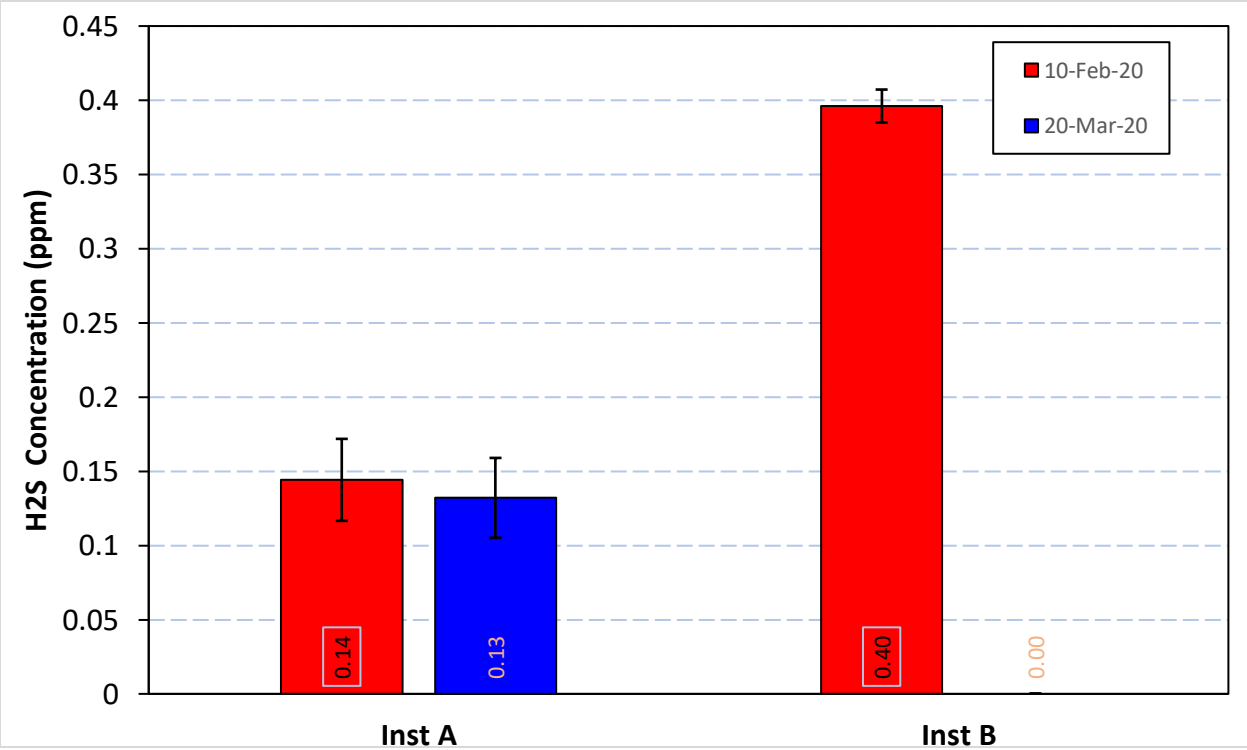


Figure A-2. Field Gas 1 H_2S lab test results; Instrument C and EMPACT non-detects.

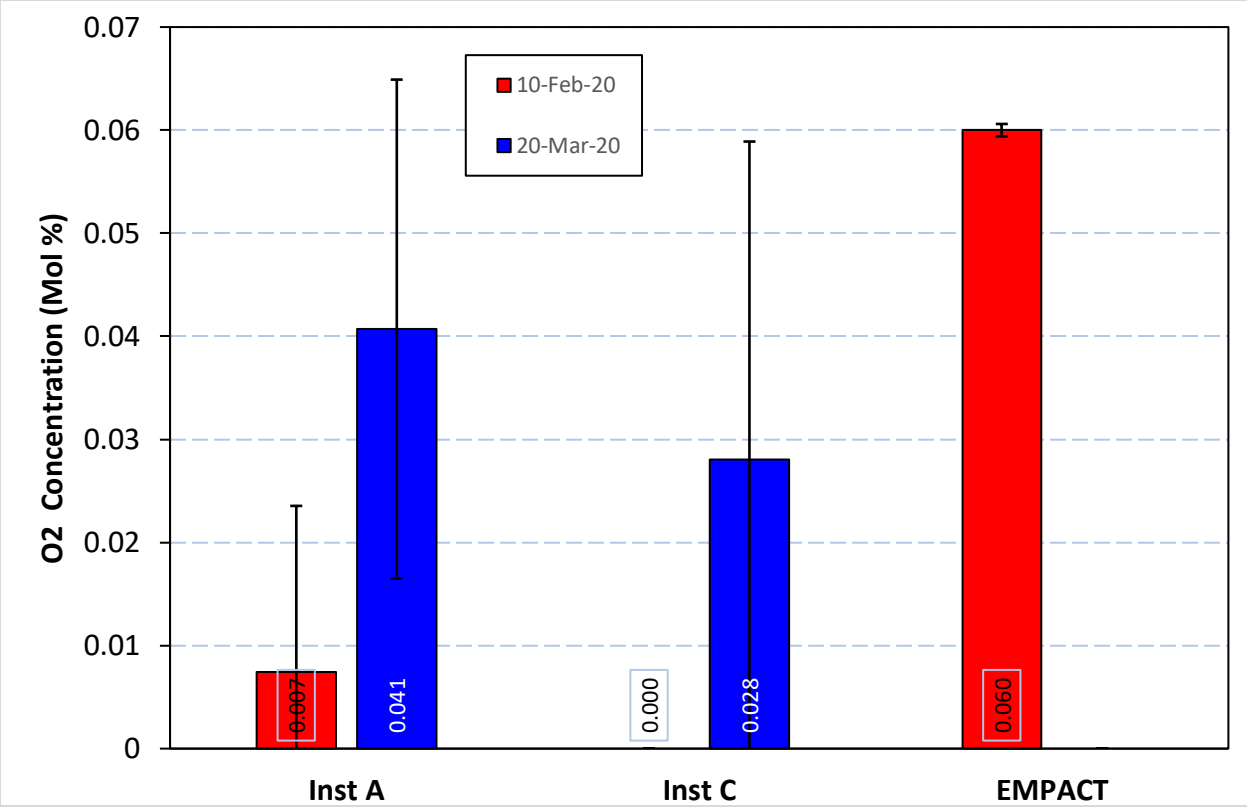


Figure A-3. Field Gas 1 O_2 lab test results; Instrument B non-detect.

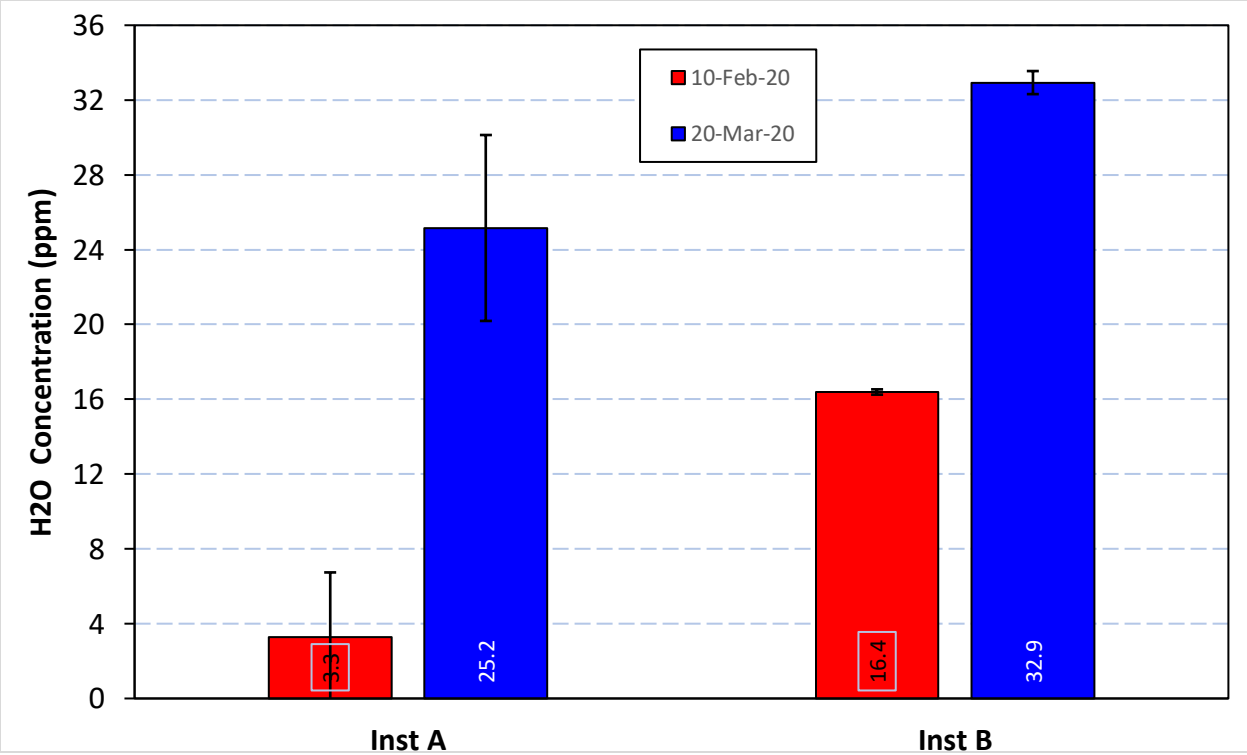


Figure A-4. Field Gas 2 H_2O lab test results; Instrument C and EMPACT non-detects.

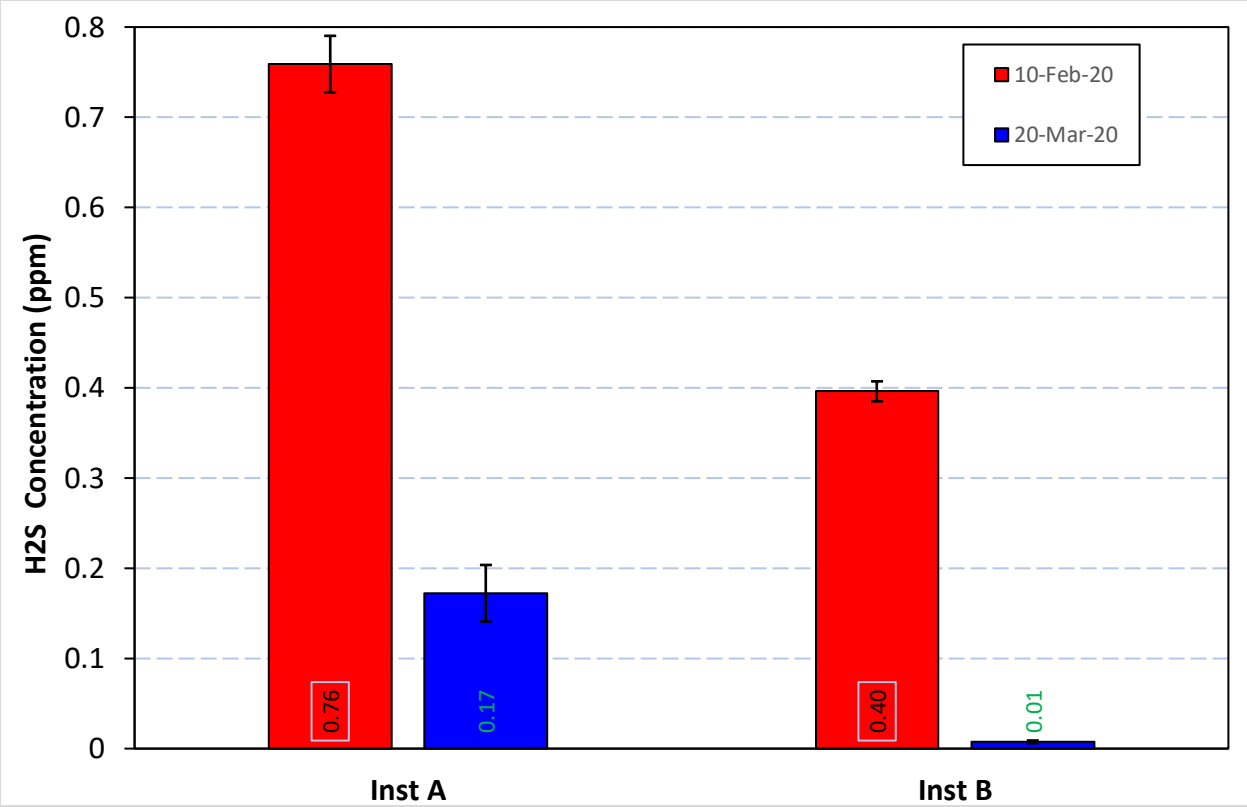


Figure A-5. Field Gas 2 H_2S lab test results; Instrument C and EMPACT non-detects.

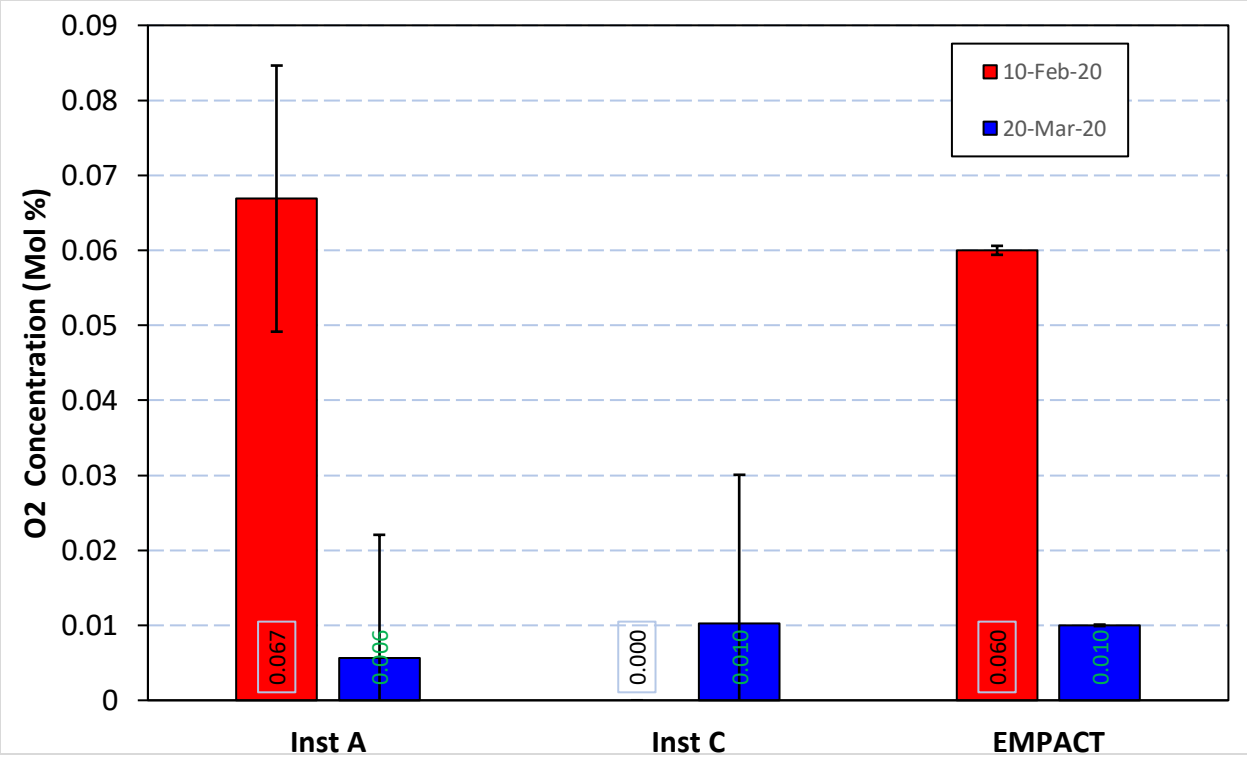


Figure A-6. Field Gas 2 O_2 lab test results; Instrument B non-detect.

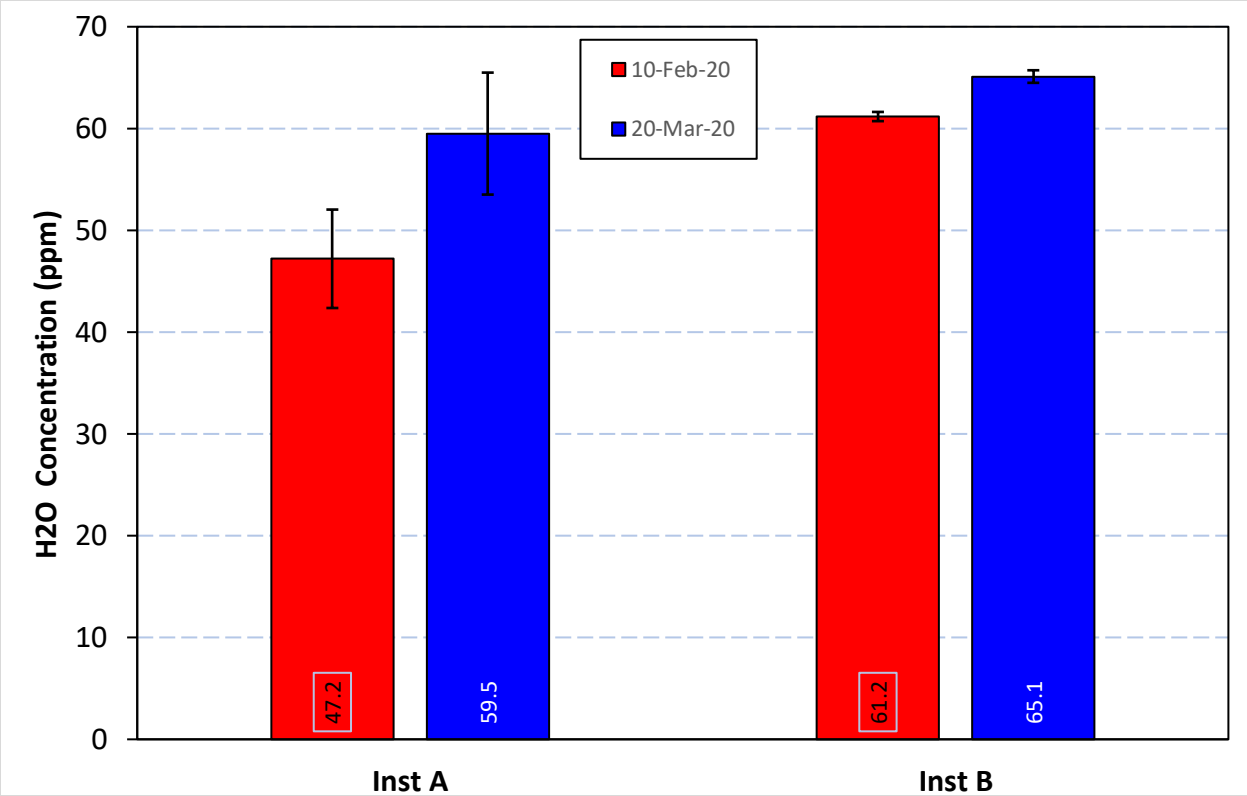


Figure A-7. Utility Gas H_2O lab test results; Instrument C and EMPACT non-detects.

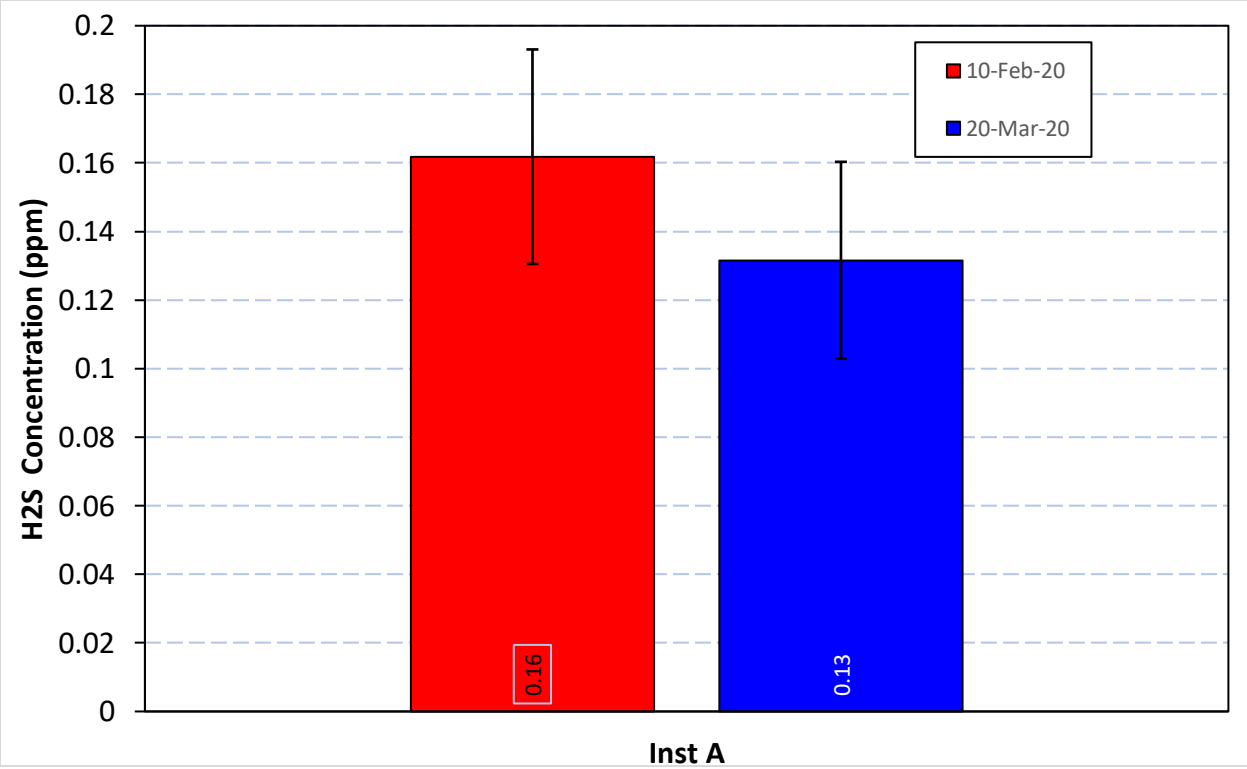


Figure A-8. Utility Gas H_2S lab test results; Instruments B and C and EMPACT non-detects.

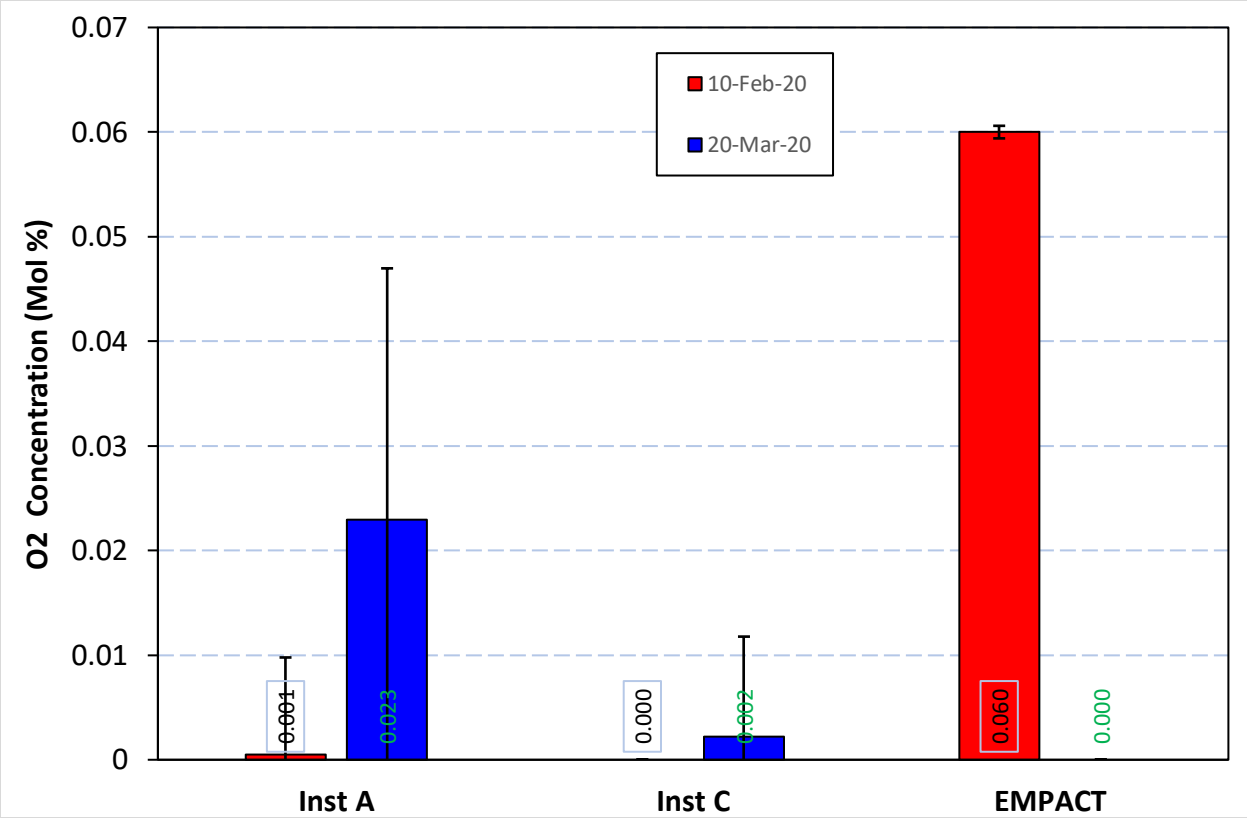


Figure A-9. Utility Gas O_2 lab test results; Instrument B non-detect.

Custom Gas Blend Lab Test Results

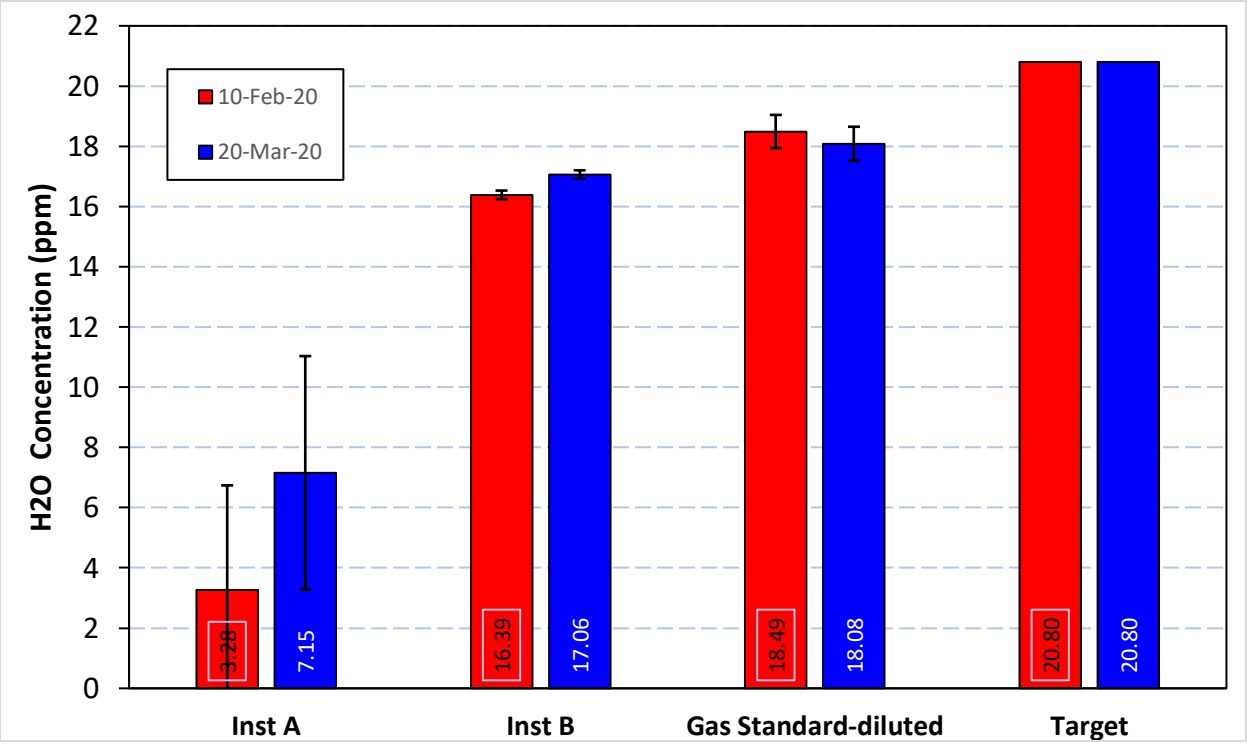


Figure A-10. Low Contaminant Blend H_2O lab test results; Instrument C and EMPACT non-detects.

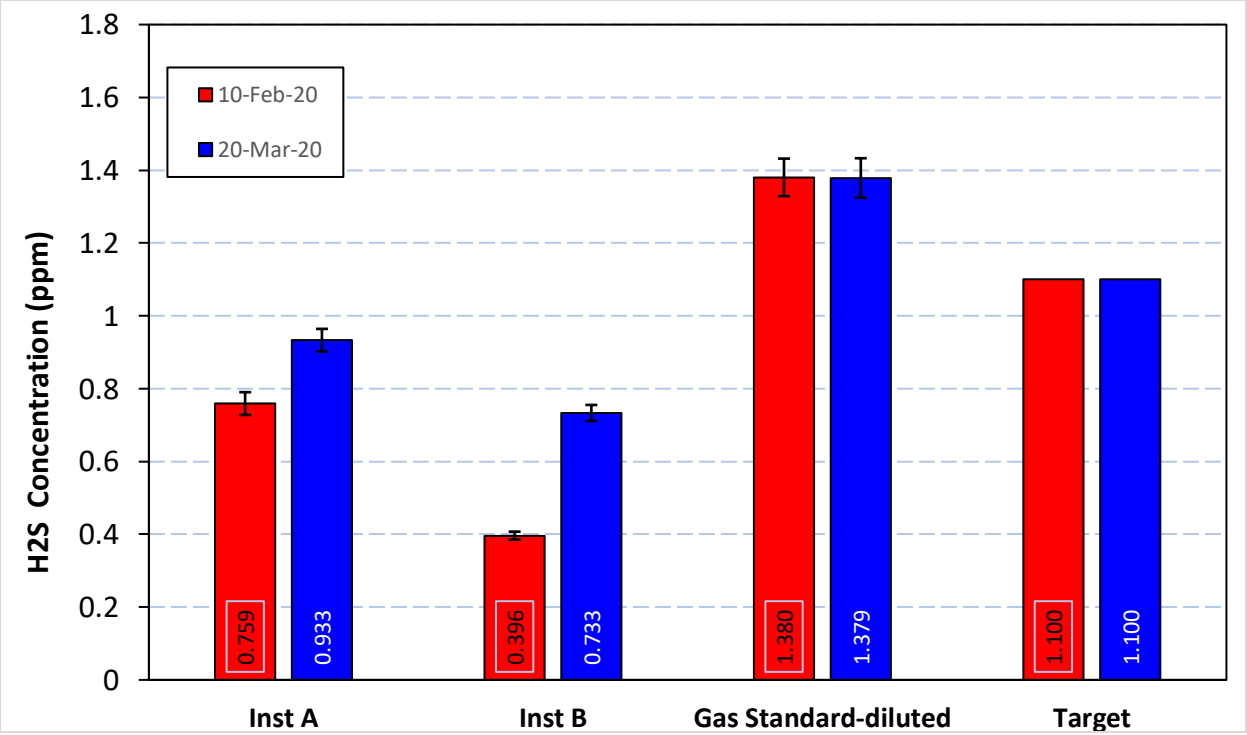


Figure A-11. Low Contaminant Blend H_2S lab test results; Instrument C and EMPACT non-detects.

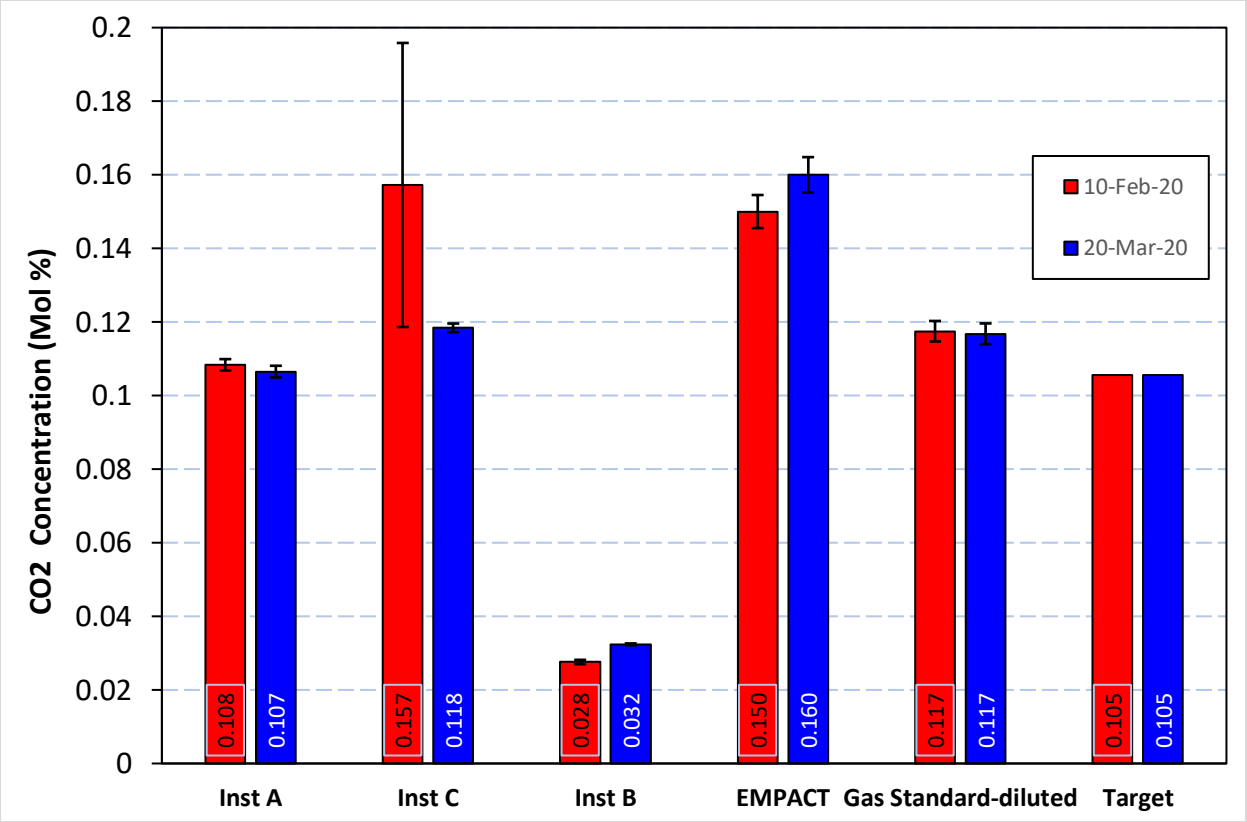


Figure A-12. Low Contaminant Blend CO_2 lab test results.

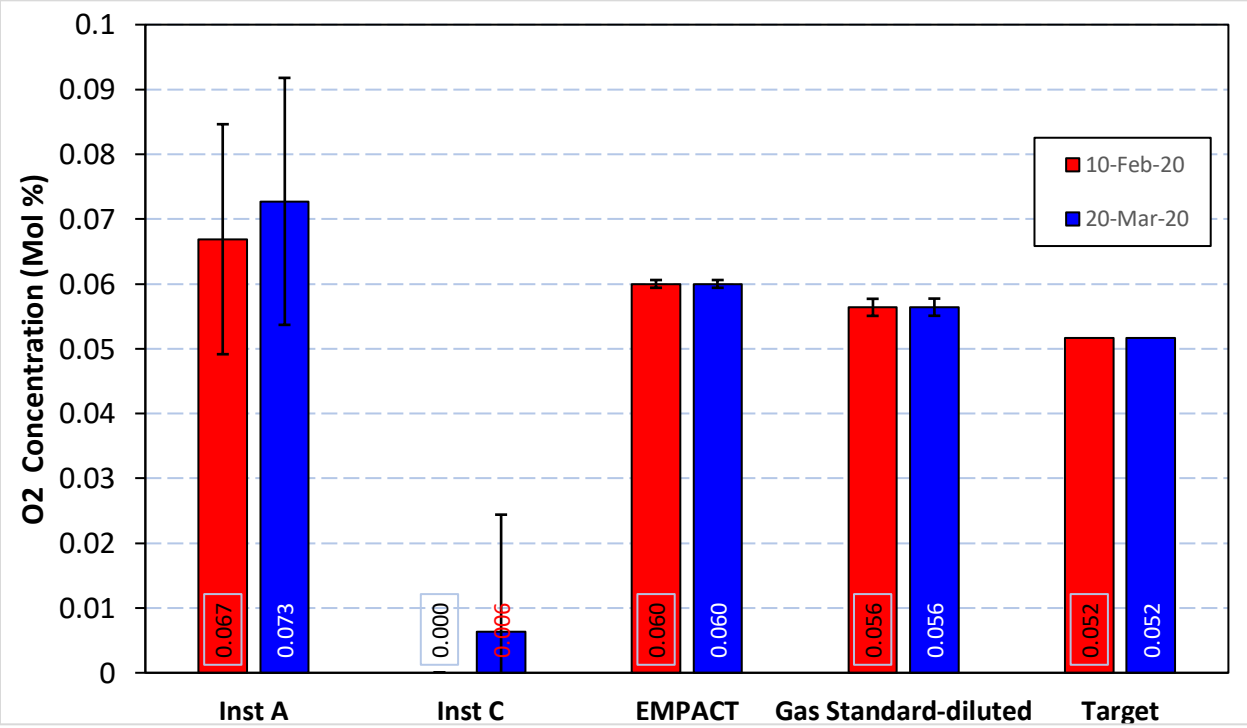


Figure A-13. Low Contaminant Blend O_2 lab test results; Instrument B non-detect.

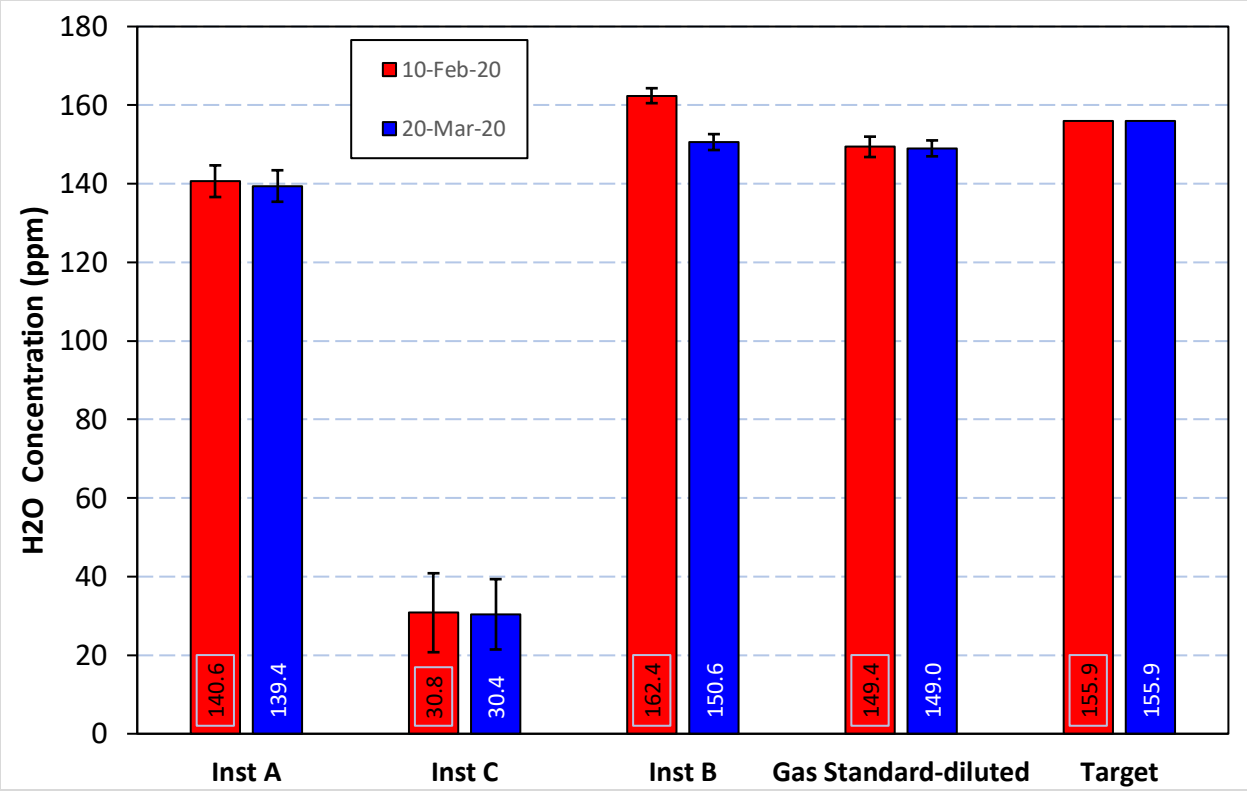


Figure A-14. Mid-B Contaminant Blend H_2O lab test results; EMPACT non-detect.

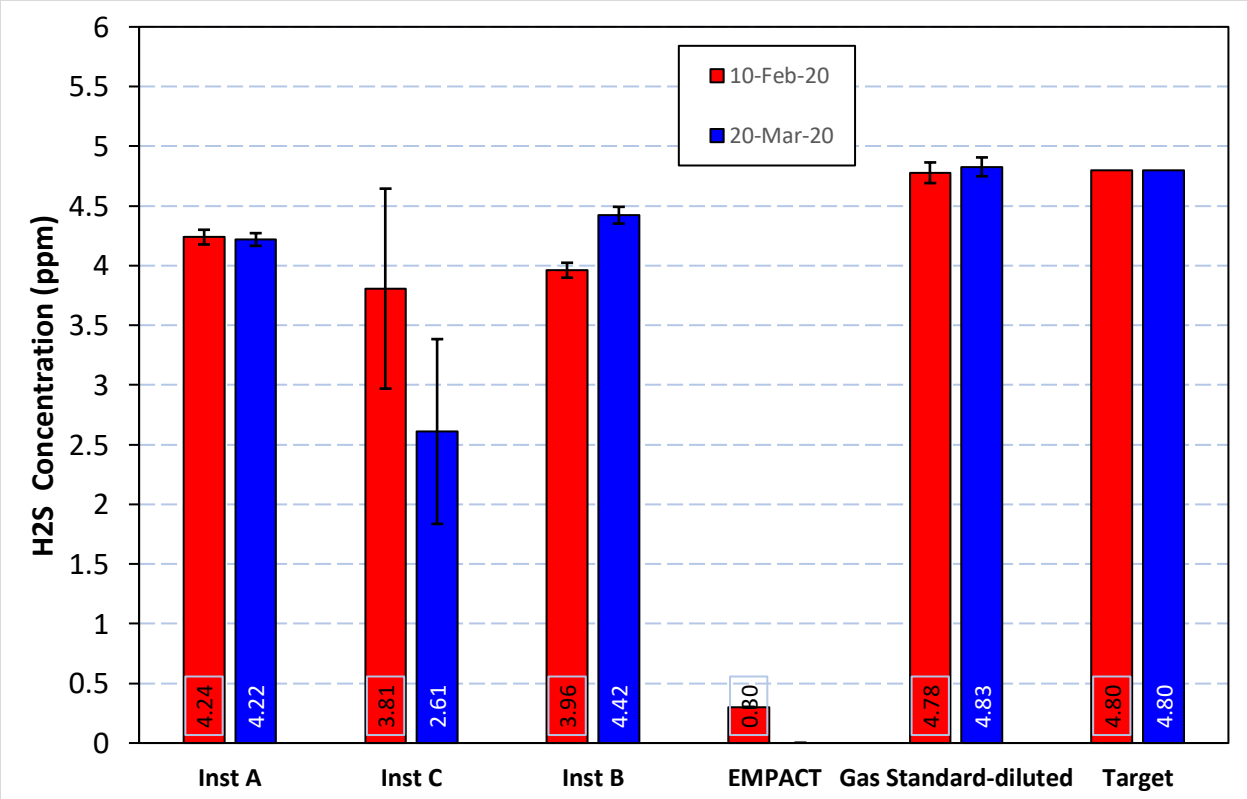


Figure A-15. Mid-B Contaminant Blend H_2S lab test results.

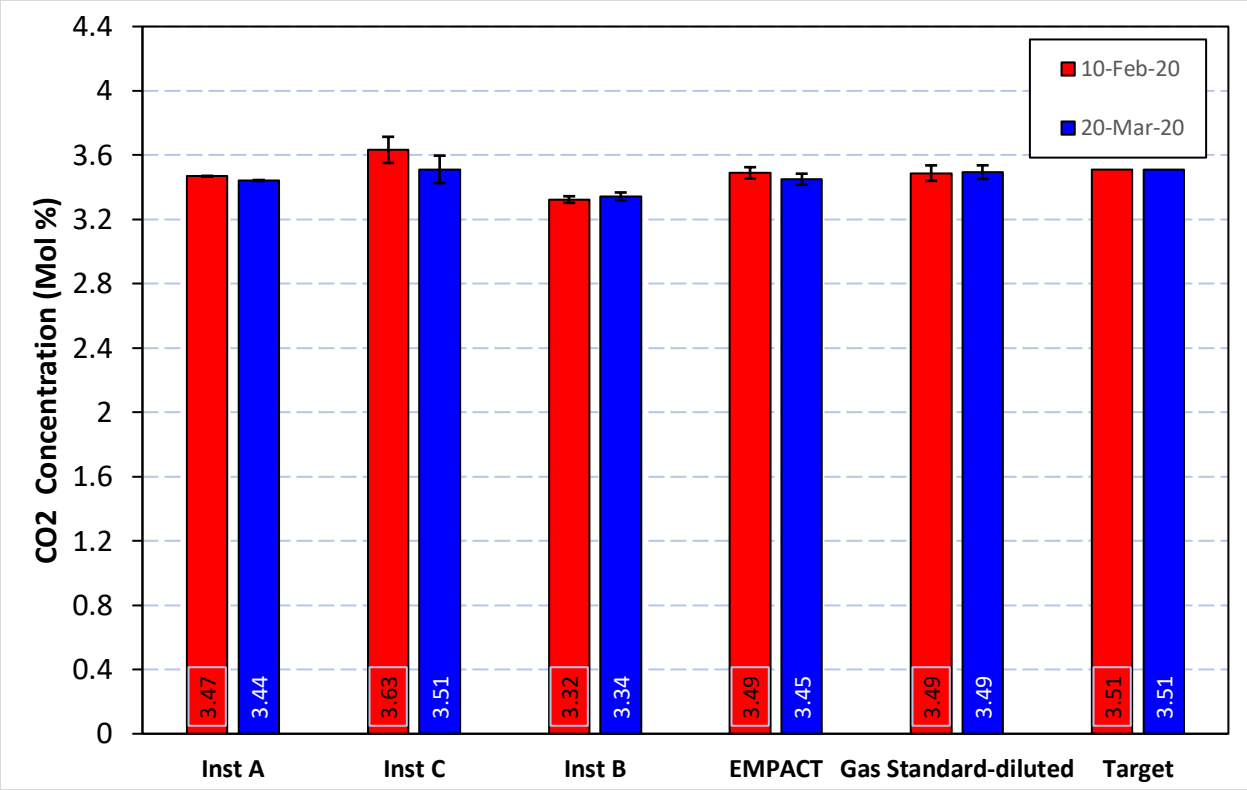


Figure A-16. Mid-B Contaminant Blend CO_2 lab test results.

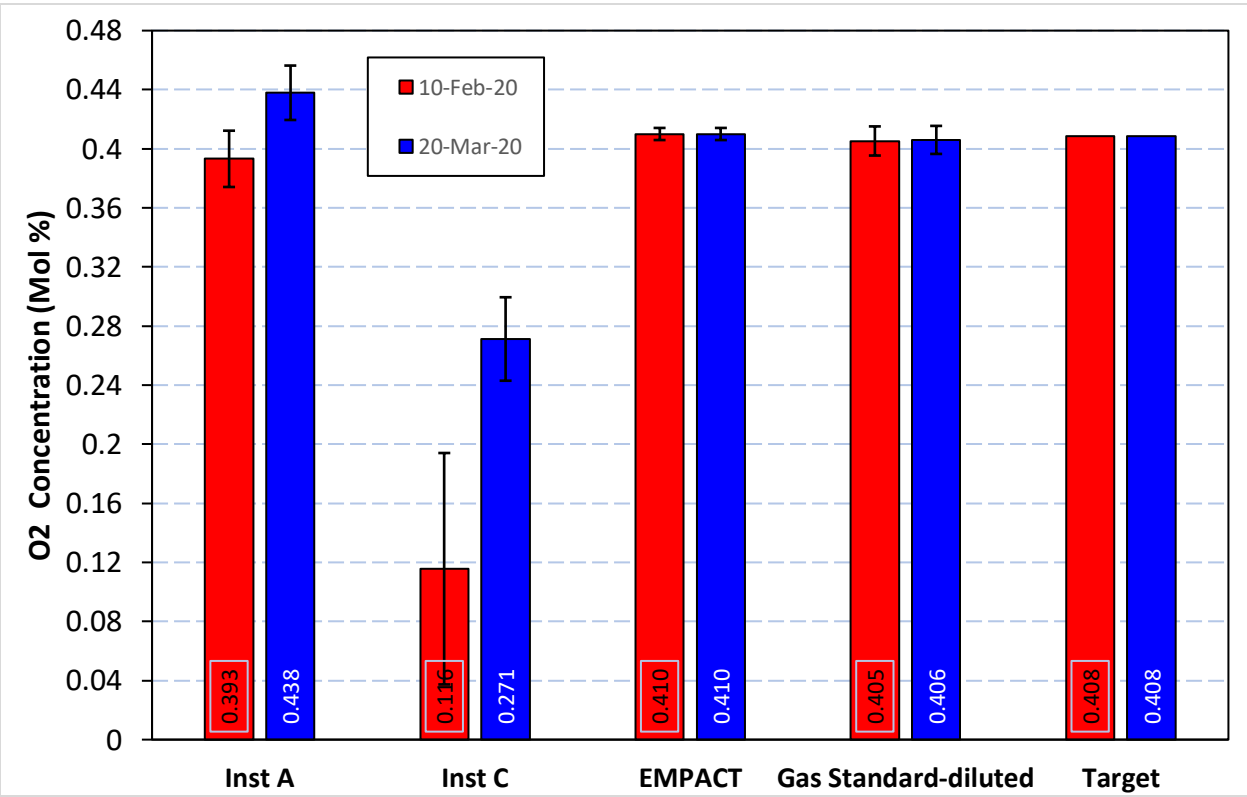


Figure A-17. Mid-B Contaminant Blend O_2 lab test results; Instrument B non-detect.

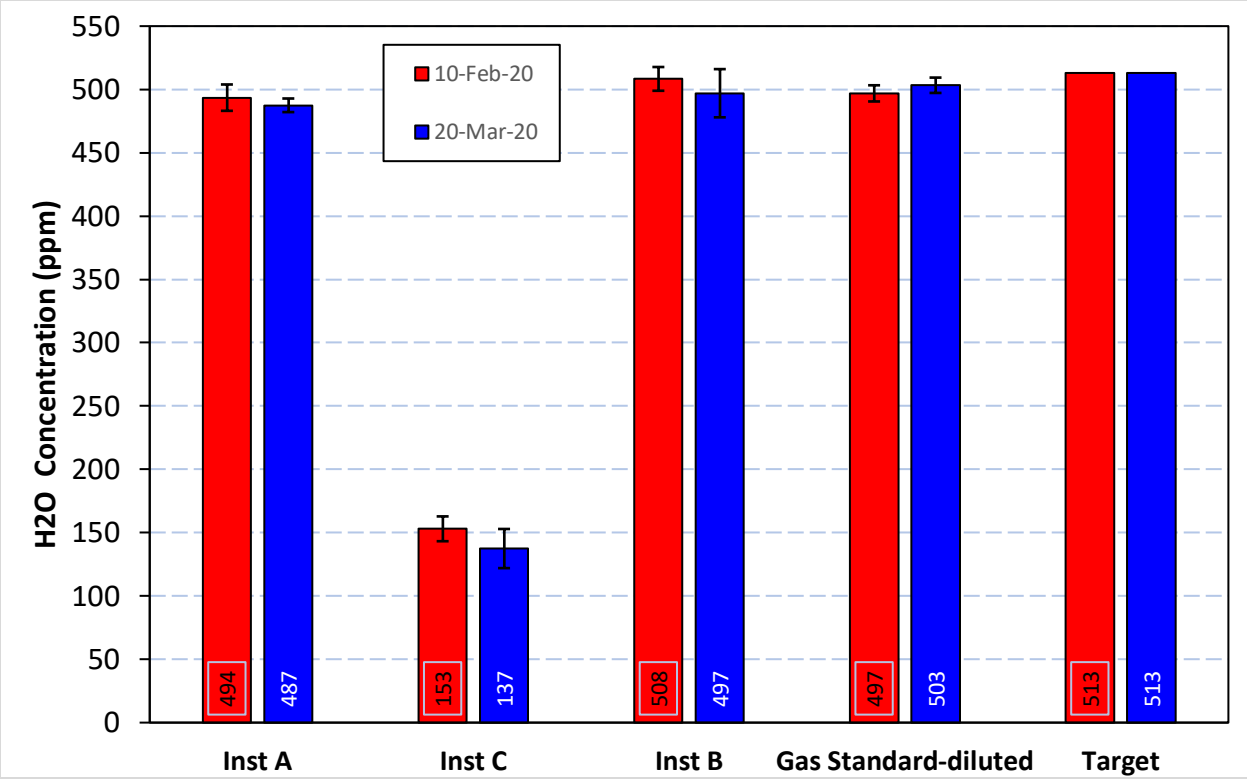


Figure A-18. High Contaminant Blend H_2O lab test results; EMPACT non-detect.

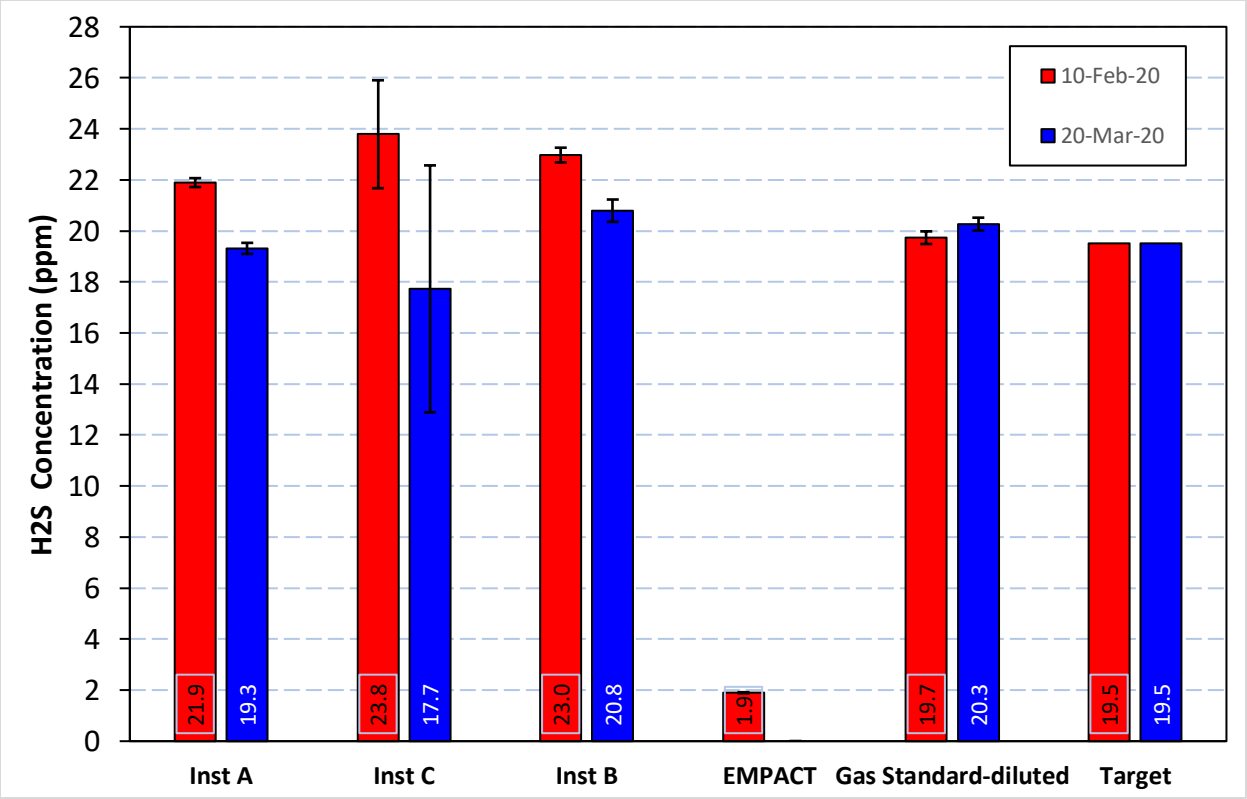


Figure A-19. High Contaminant Blend H_2S lab test results.

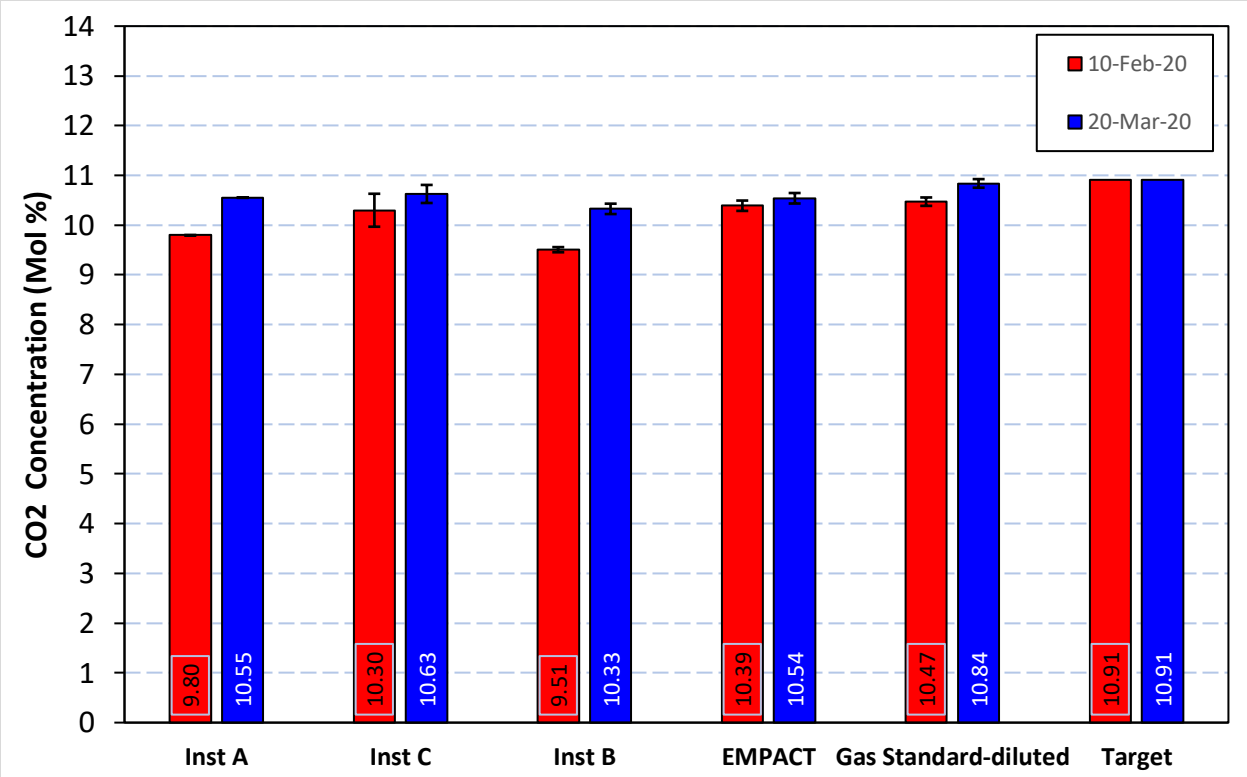


Figure A-20. High Contaminant Blend CO_2 lab test results.

APPENDIX B: THIRD-PARTY LABORATORY RESULTS



NATURAL GAS ANALYSIS

CUSTOMER PROJECT #:		NAME/DESCRIP :	**CNG DCP MIDSTREAM**
SN/PRIMARY DB KEY:			**MEWBOURN #2**
FIELD/AREA:			
PROJECT NO. :	**202001019**	ANALYSIS NO. :	**01**
COMPANY NAME :	**COLORADO STATE UNIVERSITY**	ANALYSIS DATE:	JANUARY 07, 2020 10:41
OFFICE / BRANCH:	FT. COLLINS, CO	SAMPLE DATE :	JANUARY 4, 2020
CUSTOMER REF:		TO:	
PRODUCER :		EFFECTIVE DATE:	
FIELD DATA			
SAMPLE CYCLE:		SAMPLE TYPE:	
SAMPLE PRES. :	20 psig	PROBE :	NO
FLOW PRES. :	psig	CYLINDER NO. :	S115
LAB PRES:	psig	SAMPLED BY :	KHALID ZINEDDIN
SAMPLE TEMP. :	60 °f	SAMPLING COMPANY:	CSU
AMBIENT TEMP.:	°f	H2S BY STAIN TUBE:	- ppm
H2O BY STAIN TUBE:	- #/mmcf	CO2 BY STAIN TUBE:	- Mol %
FIELD COMMENTS:			
LAB COMMENTS:			

COMPONENTS	NORM. MOLE%	GPM @ **14.696**	GPM @ **14.73**
HELIUM	0.01	-	-
HYDROGEN	0.00	-	-
OXYGEN/ARGON	0.00	-	-
NITROGEN	0.29	-	-
CARBON DIOXIDE	0.01	-	-
METHANE	91.37	-	-
ETHANE	8.15	2.179	2.184
PROPANE	0.17	0.047	0.047
ISOBUTANE	0.00	0.000	0.000
N-BUTANE	0.00	0.000	0.000
ISOPENTANE	0.00	0.000	0.000
N-PENTANE	0.00	0.000	0.000
HEXANES PLUS	0.00	0.000	0.000
TOTAL	100.00	2.226	2.231

	BTU @ 60 DEG F	**14.696**	**14.73**
LHV	NET DRY REAL=	968.9 **/scf**	971.1 **/scf**
	NET SATURATED REAL=	952.0 **/scf**	954.2 **/scf**
HHV	GROSS DRY REAL =	1073.7 **/scf**	1076.2 **/scf**
	GROSS SATURATED REAL =	1055.0 **/scf**	1057.5 **/scf**
	NET DRY REAL :	21302.5 **/lb**	21351.7 **/lb**
	GROSS DRY REAL :	23607.4 **/lb**	23662.0 **/lb**

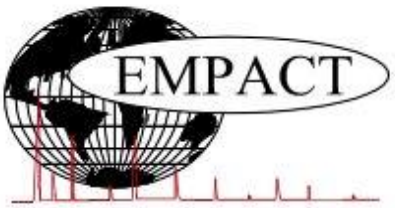
SPECIFIC GRAVITY (AIR=1 @14.696 PSIA 60F) :	0.5962
DENSITY (lb/scf)	0.04550
COMPRESSIBILITY FACTOR :	0.99765
REGULAR WOBBE INDEX (14.696)	1390.6

NOTE: REFERENCE GPA 2261(ASTM D1945 & ASME-PTC), 2145, & 2172 CURRENT PUBLICATIONS

Reference: Per GPA 2172-14 sec 9 ***The C6+ is derived from the following ratios of C6, C7 & C8+ respectively:*** **60% 30% 10%**

The data presented herein has been acquired by means of current analytical techniques and represents the judicious conclusion EMPACT Analytical Systems, Inc. Results of the analysis can be affected by the sampling conditions, therefore, are only warranted through proper lab protocol. EMPACT assumes no responsibility for interpretation or any consequences from application of the reported information and is the sole liability of the user. The reproduction in any media of this reported information may not be made, in portion or as a whole, without the written permission of EMPACT Analytical Systems, Inc.

Figure B-1. EMPACT third-party lab test results for Field Gas 1 used for '10-Feb-20' analyzer testing.



NATURAL GAS ANALYSIS

CUSTOMER PROJECT #: NAME/DESCRIP : **FIELD SAMPLE #1**
SN/PRIMARY DB KEY:
FIELD/AREA:

PROJECT NO. :	**202003106**		ANALYSIS NO. :	**05**
COMPANY NAME :	**COLORADO STATE UNIVERSITY**		ANALYSIS DATE:	MARCH 25, 2020 10:52
OFFICE / BRANCH:	FT. COLLINS, CO		SAMPLE DATE :	MARCH 19, 2020
CUSTOMER REF:	CLIENT PROJECT #201911025		TO:	
PRODUCER :			EFFECTIVE DATE:	
*****FIELD DATA*****				
SAMPLE CYCLE:			SAMPLE TYPE:	
SAMPLE PRES. :	20	psig	PROBE :	
FLOW PRES. :		psig	CYLINDER NO. :	1117
LAB PRES:		psig	SAMPLED BY :	TIM VAUGHN
SAMPLE TEMP. :	70	°f	SAMPLING COMPANY:	CSU
AMBIENT TEMP.:		°f	H2S BY STAIN TUBE: -	ppm
H2O BY STAIN TUBE: -		#/mmcf	CO2 BY STAIN TUBE: -	Mol %
FIELD COMMENTS:				
LAB COMMENTS:				

COMPONENTS	NORM. MOLE%	GPM @ **14.696**	GPM @ **14.73**
HELIUM	0.01	-	-
HYDROGEN	0.00	-	-
OXYGEN/ARGON	0.00	-	-
NITROGEN	0.29	-	-
CARBON DIOXIDE	0.01	-	-
METHANE	91.40	-	-
ETHANE	8.12	2.171	2.176
PROPANE	0.17	0.047	0.047
ISOBUTANE	0.00	0.000	0.000
N-BUTANE	0.00	0.000	0.000
ISOPENTANE	0.00	0.000	0.000
N-PENTANE	0.00	0.000	0.000
HEXANES PLUS	0.00	0.000	0.000
TOTAL	100.00	2.218	2.223

	BTU @ 60 DEG F	**14.696**	**14.73**
LHV	NET DRY REAL=	968.9 **/scf**	971.1 **/scf**
	NET SATURATED REAL=	952.0 **/scf**	954.2 **/scf**
HHV	GROSS DRY REAL =	1073.6 **/scf**	1076.1 **/scf**
	GROSS SATURATED REAL =	1054.9 **/scf**	1057.4 **/scf**
	NET DRY REAL :	21303.0 **/lb**	21352.2 **/lb**
	GROSS DRY REAL :	23608.1 **/lb**	23662.7 **/lb**

SPECIFIC GRAVITY (AIR=1 @14.696 PSIA 60F) :	0.5962
DENSITY (lb/scf)	0.04549
COMPRESSIBILITY FACTOR :	0.99765
REGULAR WOBBE INDEX (14.696)	1390.5

NOTE: REFERENCE GPA 2261(ASTM D1945 & ASME-PTC), 2145, & 2172 CURRENT PUBLICATIONS

Reference: Per GPA 2172-14 sec 9 *The C6+ is derived from the following ratios of C6, C7 & C8+ respectively:* **60% 30% 10%**

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Figure B-2. EMPACT third-party lab test results for Field Gas 1 used for ’20-Mar-20’ analyzer testing.



NATURAL GAS ANALYSIS

CUSTOMER PROJECT #:		NAME/DESCRIP :	**CNG DCP MIDSTREAM**
SN/PRIMARY DB KEY:			**MEWBOURN #3**
FIELD/AREA:			
PROJECT NO. :	**202001019**	ANALYSIS NO. :	**02**
COMPANY NAME :	**COLORADO STATE UNIVERSITY**	ANALYSIS DATE:	JANUARY 07, 2020 11:06
OFFICE / BRANCH:	FT. COLLINS, CO	SAMPLE DATE :	JANUARY 4, 2020
CUSTOMER REF:		TO:	
PRODUCER :		EFFECTIVE DATE:	
FIELD DATA			
SAMPLE CYCLE:		SAMPLE TYPE:	
SAMPLE PRES. :	20 psig	PROBE :	
FLOW PRES. :	psig	CYLINDER NO. :	S116
LAB PRES:	psig	SAMPLED BY :	KHALID ZINEDDIN
SAMPLE TEMP. :	60 °f	SAMPLING COMPANY:	CSU
AMBIENT TEMP.:	°f	H2S BY STAIN TUBE:	- ppm
H2O BY STAIN TUBE:	- #/mmcf	CO2 BY STAIN TUBE:	- Mol %
FIELD COMMENTS:			
LAB COMMENTS:	***Insufficient sample to fill line***		

COMPONENTS	NORM. MOLE%	GPM @ **14.696**	GPM @ **14.73**
HELIUM	0.01	-	-
HYDROGEN	0.00	-	-
OXYGEN/ARGON	0.00	-	-
NITROGEN	0.39	-	-
CARBON DIOXIDE	2.34	-	-
METHANE	79.49	-	-
ETHANE	14.20	3.800	3.808
PROPANE	2.79	0.769	0.771
ISOBUTANE	0.18	0.059	0.059
N-BUTANE	0.39	0.123	0.124
ISOPENTANE	0.07	0.026	0.026
N-PENTANE	0.08	0.029	0.029
HEXANES PLUS	0.06	0.026	0.026
TOTAL	100.00	4.833	4.844

	BTU @ 60 DEG F	**14.696**	**14.73**
LHV	NET DRY REAL=	1046.0 **/scf**	1048.4 **/scf**
	NET SATURATED REAL=	1027.7 **/scf**	1030.2 **/scf**
HHV	GROSS DRY REAL =	1155.3 **/scf**	1158.0 **/scf**
	GROSS SATURATED REAL =	1135.2 **/scf**	1137.8 **/scf**
	NET DRY REAL :	19959.9 **/lb**	20006.1 **/lb**
	GROSS DRY REAL :	22049.0 **/lb**	22100.0 **/lb**

SPECIFIC GRAVITY (AIR=1 @14.696 PSIA 60F) :	0.6865
DENSITY (lb/scf)	0.05239
COMPRESSIBILITY FACTOR :	0.99698
REGULAR WOBBE INDEX (14.696)	1394.4

NOTE: REFERENCE GPA 2261(ASTM D1945 & ASME-PTC), 2145, & 2172 CURRENT PUBLICATIONS

Reference: Per GPA 2172-14 sec 9 ***The C6+ is derived from the following ratios of C6, C7 & C8+ respectively:*** **60% 30% 10%**

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Figure B-3. EMPACT third-party lab test results for Field Gas 2 used in ’10-Feb-20’ analyzer testing.



NATURAL GAS ANALYSIS

CUSTOMER PROJECT #: NAME/DESCRIP : **FIELD SAMPLE #2**
SN/PRIMARY DB KEY:
FIELD/AREA:

PROJECT NO. :	**202003106**		ANALYSIS NO. :	**02**
COMPANY NAME :	**COLORADO STATE UNIVERSITY**		ANALYSIS DATE:	MARCH 25, 2020 09:41
OFFICE / BRANCH:	FT. COLLINS, CO		SAMPLE DATE :	MARCH 19, 2020
CUSTOMER REF:	CLIENT PROJECT #201911025		TO:	
PRODUCER :			EFFECTIVE DATE:	
*****FIELD DATA*****				
SAMPLE CYCLE:			SAMPLE TYPE:	
SAMPLE PRES. :	20	psig	PROBE :	
FLOW PRES. :		psig	CYLINDER NO. :	1949
LAB PRES:		psig	SAMPLED BY :	TIM VAUGHN
SAMPLE TEMP. :	70	°f	SAMPLING COMPANY:	CSU
AMBIENT TEMP.:		°f	H2S BY STAIN TUBE:	- ppm
H2O BY STAIN TUBE:	-	#/mmcf	CO2 BY STAIN TUBE:	- Mol %

FIELD COMMENTS:
LAB COMMENTS:

COMPONENTS	NORM. MOLE%	GPM @ **14.696**	GPM @ **14.73**
HELIUM	0.01	-	-
HYDROGEN	0.00	-	-
OXYGEN/ARGON	0.01	-	-
NITROGEN	0.39	-	-
CARBON DIOXIDE	2.35	-	-
METHANE	79.49	-	-
ETHANE	14.18	3.795	3.803
PROPANE	2.78	0.766	0.768
ISOBUTANE	0.18	0.059	0.059
N-BUTANE	0.39	0.123	0.124
ISOPENTANE	0.08	0.029	0.029
N-PENTANE	0.08	0.029	0.029
HEXANES PLUS	0.06	0.026	0.026
TOTAL	100.00	4.828	4.839

	BTU @ 60 DEG F	**14.696**	**14.73**
LHV	NET DRY REAL=	1046.0 **/scf**	1048.4 **/scf**
	NET SATURATED REAL=	1027.7 **/scf**	1030.2 **/scf**
HHV	GROSS DRY REAL =	1155.1 **/scf**	1157.8 **/scf**
	GROSS SATURATED REAL =	1135.0 **/scf**	1137.6 **/scf**
	NET DRY REAL :	19959.5 **/lb**	20005.7 **/lb**
	GROSS DRY REAL :	22048.3 **/lb**	22099.3 **/lb**

SPECIFIC GRAVITY (AIR=1 @14.696 PSIA 60F) :	0.6866
DENSITY (lb/scf)	0.05241
COMPRESSIBILITY FACTOR :	0.99698
REGULAR WOBBE INDEX (14.696)	1394.0

NOTE: REFERENCE GPA 2261(ASTM D1945 & ASME-PTC), 2145, & 2172 CURRENT PUBLICATIONS

Reference: Per GPA 2172-14 sec 9 *The C6+ is derived from the following ratios of C6, C7 & C8+ respectively:* **60% 30% 10%**

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Figure B-4. EMPACT third-party lab test results for Field Gas 2 used in ’20-Mar-20’ analyzer testing.



NATURAL GAS ANALYSIS

CUSTOMER PROJECT #:		NAME/DESCRIP :	**UTILITY NATURAL GAS**
SN/PRIMARY DB KEY:			
FIELD/AREA:			
PROJECT NO. :	**202001015**	ANALYSIS NO. :	**01**
COMPANY NAME :	**COLORADO STATE UNIVERSITY**	ANALYSIS DATE:	JANUARY 07, 2020 10:04
OFFICE / BRANCH:	FT. COLLINS, CO	SAMPLE DATE :	JANUARY 3, 2020
CUSTOMER REF:		TO:	
PRODUCER :		EFFECTIVE DATE:	
FIELD DATA			
SAMPLE CYCLE:		SAMPLE TYPE:	
SAMPLE PRES. :	20 psig	PROBE :	NO
FLOW PRES. :	psig	CYLINDER NO. :	S117
LAB PRES:	psig	SAMPLED BY :	KHALID ZINEDDIN
SAMPLE TEMP. :	60 °f	SAMPLING COMPANY:	CSU
AMBIENT TEMP.:	°f	H2S BY STAIN TUBE:	- ppm
H2O BY STAIN TUBE:	- #/mmcf	CO2 BY STAIN TUBE:	- Mol %
FIELD COMMENTS:			
LAB COMMENTS:			

COMPONENTS	NORM. MOLE%	GPM @ **14.696**	GPM @ **14.73**
HELIUM	0.01	-	-
HYDROGEN	0.00	-	-
OXYGEN/ARGON	0.00	-	-
NITROGEN	0.21	-	-
CARBON DIOXIDE	2.56	-	-
METHANE	84.17	-	-
ETHANE	10.65	2.849	2.855
PROPANE	1.95	0.538	0.539
ISOBUTANE	0.16	0.052	0.052
N-BUTANE	0.23	0.072	0.072
ISOPENTANE	0.03	0.011	0.011
N-PENTANE	0.02	0.007	0.007
HEXANES PLUS	0.01	0.004	0.004
TOTAL	100.00	3.533	3.541

	BTU @ 60 DEG F	**14.696**	**14.73**
LHV	NET DRY REAL=	999.6 **/scf**	1001.9 **/scf**
	NET SATURATED REAL=	982.2 **/scf**	984.5 **/scf**
HHV	GROSS DRY REAL =	1105.9 **/scf**	1108.5 **/scf**
	GROSS SATURATED REAL =	1086.6 **/scf**	1089.2 **/scf**
	NET DRY REAL :	19939.4 **/lb**	19985.6 **/lb**
	GROSS DRY REAL :	22056.9 **/lb**	22107.9 **/lb**

SPECIFIC GRAVITY (AIR=1 @14.696 PSIA 60F) :	0.6567
DENSITY (lb/scf)	0.05013
COMPRESSIBILITY FACTOR :	0.99727
REGULAR WOBBE INDEX (14.696)	1364.7

NOTE: REFERENCE GPA 2261(ASTM D1945 & ASME-PTC), 2145, & 2172 CURRENT PUBLICATIONS

Reference: Per GPA 2172-14 sec 9 ***The C6+ is derived from the following ratios of C6, C7 & C8+ respectively:*** **60% 30% 10%**

The data presented herein has been acquired by means of current analytical techniques and represents the judicious conclusion EMPACT Analytical Systems, Inc. Results of the analysis can be affected by the sampling conditions, therefore, are only warranted through proper lab protocol. EMPACT assumes no responsibility for interpretation or any consequences from application of the reported information and is the sole liability of the user. The reproduction in any media of this reported information may not be made, in portion or as a whole, without the written permission of EMPACT Analytical Systems, Inc.

Figure B-5. EMPACT third-party lab test results for Utility Gas used in ’10-Feb-20’ analyzer testing.



NATURAL GAS ANALYSIS

CUSTOMER PROJECT #:		NAME/DESCRIP :	**UTILITY GAS SAMPLE**
SN/PRIMARY DB KEY:			
FIELD/AREA:			
PROJECT NO. :	**202003106**	ANALYSIS NO. :	**03**
COMPANY NAME :	**COLORADO STATE UNIVERSITY**	ANALYSIS DATE:	MARCH 25, 2020 10:05
OFFICE / BRANCH:	FT. COLLINS, CO	SAMPLE DATE :	MARCH 19, 2020
CUSTOMER REF:	CLIENT PROJECT #201911025	TO:	
PRODUCER :		EFFECTIVE DATE:	
*****FIELD DATA*****			
SAMPLE CYCLE:		SAMPLE TYPE:	
SAMPLE PRES. :	20 psig	PROBE :	
FLOW PRES. :	psig	CYLINDER NO. :	1190
LAB PRES:	psig	SAMPLED BY :	TIM VAUGHN
SAMPLE TEMP. :	70 °f	SAMPLING COMPANY:	CSU
AMBIENT TEMP.:	°f	H2S BY STAIN TUBE:	- ppm
H2O BY STAIN TUBE:	- #/mmcf	CO2 BY STAIN TUBE:	- Mol %
FIELD COMMENTS:			
LAB COMMENTS:			

COMPONENTS	NORM. MOLE%	GPM @ **14.696**	GPM @ **14.73**
HELIUM	0.01	-	-
HYDROGEN	0.00	-	-
OXYGEN/ARGON	0.00	-	-
NITROGEN	0.21	-	-
CARBON DIOXIDE	2.56	-	-
METHANE	84.21	-	-
ETHANE	10.61	2.838	2.844
PROPANE	1.95	0.538	0.539
ISOBUTANE	0.16	0.052	0.052
N-BUTANE	0.23	0.072	0.072
ISOPENTANE	0.03	0.011	0.011
N-PENTANE	0.02	0.007	0.007
HEXANES PLUS	0.01	0.004	0.004
TOTAL	100.00	3.522	3.530

	BTU @ 60 DEG F	**14.696**	**14.73**
LHV	NET DRY REAL=	999.4 **/scf**	1001.7 **/scf**
	NET SATURATED REAL=	982.0 **/scf**	984.3 **/scf**
HHV	GROSS DRY REAL =	1105.6 **/scf**	1108.2 **/scf**
	GROSS SATURATED REAL =	1086.3 **/scf**	1088.9 **/scf**
	NET DRY REAL :	19939.7 **/lb**	19985.9 **/lb**
	GROSS DRY REAL :	22057.4 **/lb**	22108.4 **/lb**

SPECIFIC GRAVITY (AIR=1 @14.696 PSIA 60F) :	0.6565
DENSITY (lb/scf)	0.05011
COMPRESSIBILITY FACTOR :	0.99728
REGULAR WOBBE INDEX (14.696)	1364.5

NOTE: REFERENCE GPA 2261(ASTM D1945 & ASME-PTC), 2145, & 2172 CURRENT PUBLICATIONS

Reference: Per GPA 2172-14 sec 9 ***The C6+ is derived from the following ratios of C6, C7 & C8+ respectively:*** **60% 30% 10%**

The data presented herein has been acquired by means of current analytical techniques and represents the judicious conclusion EMPACT Analytical Systems, Inc. Results of the analysis can be affected by the sampling conditions, therefore, are only warranted through proper lab protocol. EMPACT assumes no responsibility for interpretation or any consequences from application of the reported information and is the sole liability of the user. The reproduction in any media of this reported information may not be made, in portion or as a whole, without the written permission of EMPACT Analytical Systems, Inc.

Figure B-6. EMPACT third-party lab test results for Utility Gas used in ’20-Mar-20’ analyzer testing.



NATURAL GAS ANALYSIS

CUSTOMER PROJECT #:		NAME/DESCRIP :	**CSU POWERHOUSE**
SN/PRIMARY DB KEY:			**"LOW" CONTAMINANT CUSTOM BLEND #2**
FIELD/AREA:			
PROJECT NO. :	**202002046**	ANALYSIS NO. :	**01**
COMPANY NAME :	**COLORADO STATE UNIVERSITY**	ANALYSIS DATE:	FEBRUARY 12, 2020 07:14
OFFICE / BRANCH:	FT. COLLINS, CO	SAMPLE DATE :	FEBRUARY 10, 2020
CUSTOMER REF:		TO:	
PRODUCER :		EFFECTIVE DATE:	
FIELD DATA			
SAMPLE CYCLE:		SAMPLE TYPE:	
SAMPLE PRES. :	20 psig	PROBE :	NO
FLOW PRES. :	psig	CYLINDER NO. :	S092
LAB PRES:	psig	SAMPLED BY :	KHALID ZINEDDIN
SAMPLE TEMP. :	70 °f	SAMPLING COMPANY:	CSU
AMBIENT TEMP.:	°f	H2S BY STAIN TUBE:	- ppm
H2O BY STAIN TUBE:	- #/mmcf	CO2 BY STAIN TUBE:	- Mol %
FIELD COMMENTS:			
LAB COMMENTS:			

COMPONENTS	NORM. MOLE%	GPM @ **14.696**	GPM @ **14.73**
HELIUM	0.00	-	-
HYDROGEN	0.00	-	-
OXYGEN/ARGON	0.06	-	-
NITROGEN	0.01	-	-
CARBON DIOXIDE	0.15	-	-
METHANE	92.62	-	-
ETHANE	7.16	1.914	1.919
PROPANE	0.00	0.000	0.000
ISOBUTANE	0.00	0.000	0.000
N-BUTANE	0.00	0.000	0.000
ISOPENTANE	0.00	0.000	0.000
N-PENTANE	0.00	0.000	0.000
HEXANES PLUS	0.00	0.000	0.000
TOTAL	100.00	1.914	1.919

	BTU @ 60 DEG F	**14.696**	**14.73**
LHV	NET DRY REAL=	960.4 **/scf**	962.6 **/scf**
	NET SATURATED REAL=	943.7 **/scf**	945.9 **/scf**
HHV	GROSS DRY REAL =	1064.6 **/scf**	1067.1 **/scf**
	GROSS SATURATED REAL =	1046.1 **/scf**	1048.6 **/scf**
	NET DRY REAL :	21310.3 **/lb**	21359.6 **/lb**
	GROSS DRY REAL :	23623.8 **/lb**	23678.5 **/lb**

SPECIFIC GRAVITY (AIR=1 @14.696 PSIA 60F) :	0.5904
DENSITY (lb/scf)	0.04506
COMPRESSIBILITY FACTOR :	0.99770
REGULAR WOBBE INDEX (14.696)	1385.6

NOTE: REFERENCE GPA 2261(ASTM D1945 & ASME-PTC), 2145, & 2172 CURRENT PUBLICATIONS

Reference: Per GPA 2172-14 sec 9 ***The C6+ is derived from the following ratios of C6, C7 & C8+ respectively:* 60% 30% 10%**

The data presented herein has been acquired by means of current analytical techniques and represents the judicious conclusion EMPACT Analytical Systems, Inc. Results of the analysis can be affected by the sampling conditions, therefore, are only warranted through proper lab protocol. EMPACT assumes no responsibility for interpretation or any consequences from application of the reported information and is the sole liability of the user. The reproduction in any media of this reported information may not be made, in portion or as a whole, without the written permission of EMPACT Analytical Systems, Inc.

Figure B-7. EMPACT third-party lab test results for Low Contaminant custom gas blend used in ’10-Feb-20’ analyzer testing.



NATURAL GAS ANALYSIS

CUSTOMER PROJECT #: NAME/DESCRIP : **LOW CONT**
SN/PRIMARY DB KEY:
FIELD/AREA:

PROJECT NO. :	**202003106**		ANALYSIS NO. :	**07**
COMPANY NAME :	**COLORADO STATE UNIVERSITY**		ANALYSIS DATE:	MARCH 26, 2020 08:28
OFFICE / BRANCH:	FT. COLLINS, CO		SAMPLE DATE :	MARCH 20, 2020
CUSTOMER REF:	CLIENT PROJECT #201911025		TO:	
PRODUCER :			EFFECTIVE DATE:	
FIELD DATA				
SAMPLE CYCLE:			SAMPLE TYPE:	
SAMPLE PRES. :	20	psig	PROBE :	
FLOW PRES. :		psig	CYLINDER NO. :	1628
LAB PRES:		psig	SAMPLED BY :	TIM VAUGHN
SAMPLE TEMP. :	70	°f	SAMPLING COMPANY:	CSU
AMBIENT TEMP.:		°f	H2S BY STAIN TUBE:	- ppm
H2O BY STAIN TUBE:	-	#/mmcf	CO2 BY STAIN TUBE:	- Mol %

FIELD COMMENTS:
LAB COMMENTS:

COMPONENTS	NORM. MOLE%	GPM @ **14.696**	GPM @ **14.73**
HELIUM	0.00	-	-
HYDROGEN	0.00	-	-
OXYGEN/ARGON	0.06	-	-
NITROGEN	0.01	-	-
CARBON DIOXIDE	0.16	-	-
METHANE	93.41	-	-
ETHANE	6.36	1.701	1.705
PROPANE	0.00	0.000	0.000
ISOBUTANE	0.00	0.000	0.000
N-BUTANE	0.00	0.000	0.000
ISOPENTANE	0.00	0.000	0.000
N-PENTANE	0.00	0.000	0.000
HEXANES PLUS	0.00	0.000	0.000
TOTAL	100.00	1.701	1.705

	BTU @ 60 DEG F	**14.696**	**14.73**
LHV	NET DRY REAL=	954.7 **/scf**	956.9 **/scf**
	NET SATURATED REAL=	938.0 **/scf**	940.2 **/scf**
HHV	GROSS DRY REAL =	1058.4 **/scf**	1060.9 **/scf**
	GROSS SATURATED REAL =	1040.0 **/scf**	1042.4 **/scf**
	NET DRY REAL :	21324.0 **/lb**	21373.3 **/lb**
	GROSS DRY REAL :	23643.9 **/lb**	23698.6 **/lb**

SPECIFIC GRAVITY (AIR=1 @14.696 PSIA 60F) :	0.5866
DENSITY (lb/scf)	0.04477
COMPRESSIBILITY FACTOR :	0.99773
REGULAR WOBBE INDEX (14.696)	1381.9

NOTE: REFERENCE GPA 2261(ASTM D1945 & ASME-PTC), 2145, & 2172 CURRENT PUBLICATIONS

Reference: Per GPA 2172-14 sec 9 *The C6+ is derived from the following ratios of C6, C7 & C8+ respectively:* **60% 30% 10%**

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Figure B-8. EMPACT third-party lab test results for Low Contaminant custom gas blend used in ’20-Mar-20’ analyzer testing.



NATURAL GAS ANALYSIS

CUSTOMER PROJECT #:		NAME/DESCRIP :	**CSU POWERHOUSE**
SN/PRIMARY DB KEY:			**"MID-A" CONTAMINANT CUSTOM BLEND**
FIELD/AREA:			
PROJECT NO. :	**202002046**	ANALYSIS NO. :	**02**
COMPANY NAME :	**COLORADO STATE UNIVERSITY**	ANALYSIS DATE:	FEBRUARY 12, 2020 07:38
OFFICE / BRANCH:	FT. COLLINS, CO	SAMPLE DATE :	FEBRUARY 10, 2020
CUSTOMER REF:		TO:	
PRODUCER :		EFFECTIVE DATE:	
FIELD DATA			
SAMPLE CYCLE:		SAMPLE TYPE:	
SAMPLE PRES. :	20 psig	PROBE :	NO
FLOW PRES. :	psig	CYLINDER NO. :	S090
LAB PRES:	psig	SAMPLED BY :	KHALID ZINEDDIN
SAMPLE TEMP. :	70 °f	SAMPLING COMPANY:	CSU
AMBIENT TEMP.:	°f	H2S BY STAIN TUBE:	- ppm
H2O BY STAIN TUBE:	- #/mmcf	CO2 BY STAIN TUBE:	- Mol %
FIELD COMMENTS:			
LAB COMMENTS:			

COMPONENTS	NORM. MOLE%	GPM @ **14.696**	GPM @ **14.73**
HELIUM	0.00	-	-
HYDROGEN	0.00	-	-
OXYGEN/ARGON	0.20	-	-
NITROGEN	0.01	-	-
CARBON DIOXIDE	2.05	-	-
METHANE	85.05	-	-
ETHANE	12.69	3.394	3.402
PROPANE	0.00	0.000	0.000
ISOBUTANE	0.00	0.000	0.000
N-BUTANE	0.00	0.000	0.000
ISOPENTANE	0.00	0.000	0.000
N-PENTANE	0.00	0.000	0.000
HEXANES PLUS	0.00	0.000	0.000
TOTAL	100.00	3.394	3.402

	BTU @ 60 DEG F	**14.696**	**14.73**
LHV	NET DRY REAL=	981.4 **/scf**	983.7 **/scf**
	NET SATURATED REAL=	964.3 **/scf**	966.6 **/scf**
HHV	GROSS DRY REAL =	1086.4 **/scf**	1088.9 **/scf**
	GROSS SATURATED REAL =	1067.5 **/scf**	1070.0 **/scf**
	NET DRY REAL :	20216.5 **/lb**	20263.2 **/lb**
	GROSS DRY REAL :	22379.4 **/lb**	22431.2 **/lb**

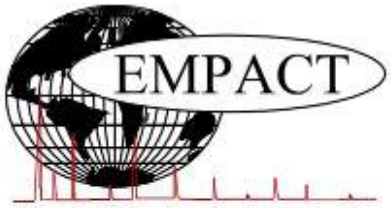
SPECIFIC GRAVITY (AIR=1 @14.696 PSIA 60F) :	0.6362
DENSITY (lb/scf)	0.04856
COMPRESSIBILITY FACTOR :	0.99742
REGULAR WOBBE INDEX (14.696)	1362.1

NOTE: REFERENCE GPA 2261(ASTM D1945 & ASME-PTC), 2145, & 2172 CURRENT PUBLICATIONS

Reference: Per GPA 2172-14 sec 9 *The C6+ is derived from the following ratios of C6, C7 & C8+ respectively:* **60% 30% 10%**

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Figure B-9. EMPACT third-party lab test results for Mid-A Contaminant custom gas blend used in ’10-Feb-20’ analyzer testing.



NATURAL GAS ANALYSIS

CUSTOMER PROJECT #: NAME/DESCRIP : **MID-CONT A**
SN/PRIMARY DB KEY:
FIELD/AREA:

PROJECT NO. :	**202003106**		ANALYSIS NO. :	**01**
COMPANY NAME :	**COLORADO STATE UNIVERSITY**		ANALYSIS DATE:	MARCH 25, 2020 09:13
OFFICE / BRANCH:	FT. COLLINS, CO		SAMPLE DATE :	MARCH 19, 2020
CUSTOMER REF:	CLIENT PROJECT #201911025		TO:	
PRODUCER :			EFFECTIVE DATE:	
*****FIELD DATA*****				
SAMPLE CYCLE:			SAMPLE TYPE:	
SAMPLE PRES. :	20	psig	PROBE :	
FLOW PRES. :		psig	CYLINDER NO. :	1509
LAB PRES:		psig	SAMPLED BY :	TIM VAUGHN
SAMPLE TEMP. :	70	°f	SAMPLING COMPANY:	CSU
AMBIENT TEMP.:		°f	H2S BY STAIN TUBE:	- ppm
H2O BY STAIN TUBE:	-	#/mmcf	CO2 BY STAIN TUBE:	- Mol %

FIELD COMMENTS:
LAB COMMENTS:

COMPONENTS	NORM. MOLE%	GPM @ 14.696	GPM @ 14.73
HELIUM	0.00	-	-
HYDROGEN	0.00	-	-
OXYGEN/ARGON	0.20	-	-
NITROGEN	0.01	-	-
CARBON DIOXIDE	2.04	-	-
METHANE	85.06	-	-
ETHANE	12.69	3.394	3.402
PROPANE	0.00	0.000	0.000
ISOBUTANE	0.00	0.000	0.000
N-BUTANE	0.00	0.000	0.000
ISOPENTANE	0.00	0.000	0.000
N-PENTANE	0.00	0.000	0.000
HEXANES PLUS	0.00	0.000	0.000
TOTAL	100.00	3.394	3.402

	BTU @ 60 DEG F	14.696	14.73
LHV	NET DRY REAL=	981.5 /scf	983.8 /scf
	NET SATURATED REAL=	964.4 /scf	966.7 /scf
HHV	GROSS DRY REAL =	1086.5 /scf	1089.0 /scf
	GROSS SATURATED REAL =	1067.6 /scf	1070.1 /scf
	NET DRY REAL :	20218.5 /lb	20265.2 /lb
	GROSS DRY REAL :	22381.7 /lb	22433.5 /lb

SPECIFIC GRAVITY (AIR=1 @14.696 PSIA 60F) :	0.6361
DENSITY (lb/scf)	0.04855
COMPRESSIBILITY FACTOR :	0.99743
REGULAR WOBBE INDEX (14.696)	1362.3

NOTE: REFERENCE GPA 2261(ASTM D1945 & ASME-PTC), 2145, & 2172 CURRENT PUBLICATIONS

Reference: Per GPA 2172-14 sec 9 *The C6+ is derived from the following ratios of C6, C7 & C8+ respectively:* **60% 30% 10%**

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Figure B-10. EMPACT third-party lab test results for Mid-A Contaminant custom gas blend used in ’20-Mar-20’ analyzer testing.



NATURAL GAS ANALYSIS

CUSTOMER PROJECT #:		NAME/DESCRIP :	**CSU POWERHOUSE**
SN/PRIMARY DB KEY:			**"MID-B" CONTAMINANT CUSTOM BLEND**
FIELD/AREA:			
PROJECT NO. :	**202002046**	ANALYSIS NO. :	**03**
COMPANY NAME :	**COLORADO STATE UNIVERSITY**	ANALYSIS DATE:	FEBRUARY 12, 2020 08:01
OFFICE / BRANCH:	FT. COLLINS, CO	SAMPLE DATE :	FEBRUARY 10, 2020
CUSTOMER REF:		TO:	
PRODUCER :		EFFECTIVE DATE:	
FIELD DATA			
SAMPLE CYCLE:		SAMPLE TYPE:	
SAMPLE PRES. :	20 psig	PROBE :	NO
FLOW PRES. :	psig	CYLINDER NO. :	S096
LAB PRES:	psig	SAMPLED BY :	KHALID ZINEDDIN
SAMPLE TEMP. :	70 °f	SAMPLING COMPANY:	CSU
AMBIENT TEMP.:	°f	H2S BY STAIN TUBE:	- ppm
H2O BY STAIN TUBE:	- #/mmcf	CO2 BY STAIN TUBE:	- Mol %
FIELD COMMENTS:			
LAB COMMENTS:			

COMPONENTS	NORM. MOLE%	GPM @ **14.696**	GPM @ **14.73**
HELIUM	0.00	-	-
HYDROGEN	0.00	-	-
OXYGEN/ARGON	0.41	-	-
NITROGEN	0.01	-	-
CARBON DIOXIDE	3.49	-	-
METHANE	84.48	-	-
ETHANE	11.61	3.105	3.112
PROPANE	0.00	0.000	0.000
ISOBUTANE	0.00	0.000	0.000
N-BUTANE	0.00	0.000	0.000
ISOPENTANE	0.00	0.000	0.000
N-PENTANE	0.00	0.000	0.000
HEXANES PLUS	0.00	0.000	0.000
TOTAL	100.00	3.105	3.112

	BTU @ 60 DEG F	**14.696**	**14.73**
LHV	NET DRY REAL=	958.7 **/scf**	961.0 **/scf**
	NET SATURATED REAL=	942.0 **/scf**	944.2 **/scf**
HHV	GROSS DRY REAL =	1061.4 **/scf**	1063.9 **/scf**
	GROSS SATURATED REAL =	1042.9 **/scf**	1045.4 **/scf**
	NET DRY REAL :	19440.2 **/lb**	19485.2 **/lb**
	GROSS DRY REAL :	21525.0 **/lb**	21574.8 **/lb**

SPECIFIC GRAVITY (AIR=1 @14.696 PSIA 60F) :	0.6460
DENSITY (lb/scf)	0.04931
COMPRESSIBILITY FACTOR :	0.99746
REGULAR WOBBE INDEX (14.696)	1320.6

NOTE: REFERENCE GPA 2261(ASTM D1945 & ASME-PTC), 2145, & 2172 CURRENT PUBLICATIONS

Reference: Per GPA 2172-14 sec 9 ***The C6+ is derived from the following ratios of C6, C7 & C8+ respectively:*** **60% 30% 10%**

The data presented herein has been acquired by means of current analytical techniques and represents the judicious conclusion EMPACT Analytical Systems, Inc. Results of the analysis can be affected by the sampling conditions, therefore, are only warranted through proper lab protocol. EMPACT assumes no responsibility for interpretation or any consequences from application of the reported information and is the sole liability of the user. The reproduction in any media of this reported information may not be made, in portion or as a whole, without the written permission of EMPACT Analytical Systems, Inc.

Figure B-11. EMPACT third-party lab test results for Mid-B Contaminant custom gas blend used in ’10-Feb-20’ analyzer testing.



NATURAL GAS ANALYSIS

CUSTOMER PROJECT #: NAME/DESCRIP : **MID CONT B**
SN/PRIMARY DB KEY:
FIELD/AREA:

PROJECT NO. :	**202003106**		ANALYSIS NO. :	**06**
COMPANY NAME :	**COLORADO STATE UNIVERSITY**		ANALYSIS DATE:	MARCH 26, 2020 08:01
OFFICE / BRANCH:	FT. COLLINS, CO		SAMPLE DATE :	MARCH 19, 2020
CUSTOMER REF:	CLIENT PROJECT #201911025		TO:	
PRODUCER :			EFFECTIVE DATE:	
FIELD DATA				
SAMPLE CYCLE:			SAMPLE TYPE:	
SAMPLE PRES. :	20	psig	PROBE :	
FLOW PRES. :		psig	CYLINDER NO. :	1969
LAB PRES:		psig	SAMPLED BY :	TIM VAUGHN
SAMPLE TEMP. :	70	°f	SAMPLING COMPANY:	CSU
AMBIENT TEMP.:		°f	H2S BY STAIN TUBE:	- ppm
H2O BY STAIN TUBE:	-	#/mmcf	CO2 BY STAIN TUBE:	- Mol %

FIELD COMMENTS:
LAB COMMENTS: ***Possible moisture in sample***

COMPONENTS	NORM. MOLE%	GPM @ **14.696**	GPM @ **14.73**
HELIUM	0.00	-	-
HYDROGEN	0.00	-	-
OXYGEN/ARGON	0.41	-	-
NITROGEN	0.01	-	-
CARBON DIOXIDE	3.45	-	-
METHANE	84.36	-	-
ETHANE	11.77	3.148	3.155
PROPANE	0.00	0.000	0.000
ISOBUTANE	0.00	0.000	0.000
N-BUTANE	0.00	0.000	0.000
ISOPENTANE	0.00	0.000	0.000
N-PENTANE	0.00	0.000	0.000
HEXANES PLUS	0.00	0.000	0.000
TOTAL	100.00	3.148	3.155

	BTU @ 60 DEG F	**14.696**	**14.73**
LHV	NET DRY REAL=	960.1 **/scf**	962.4 **/scf**
	NET SATURATED REAL=	943.4 **/scf**	945.6 **/scf**
HHV	GROSS DRY REAL =	1062.9 **/scf**	1065.4 **/scf**
	GROSS SATURATED REAL =	1044.4 **/scf**	1046.8 **/scf**
	NET DRY REAL :	19461.4 **/lb**	19506.5 **/lb**
	GROSS DRY REAL :	21547.4 **/lb**	21597.3 **/lb**

SPECIFIC GRAVITY (AIR=1 @14.696 PSIA 60F) :	0.6464
DENSITY (lb/scf)	0.04934
COMPRESSIBILITY FACTOR :	0.99745
REGULAR WOBBE INDEX (14.696)	1322.0

NOTE: REFERENCE GPA 2261(ASTM D1945 & ASME-PTC), 2145, & 2172 CURRENT PUBLICATIONS

Reference: Per GPA 2172-14 sec 9 ***The C6+ is derived from the following ratios of C6, C7 & C8+ respectively:*** **60% 30% 10%**

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Figure B-12. EMPACT third-party lab test results for Mid-B Contaminant custom gas blend used in ’20-Mar-20’ analyzer testing.



NATURAL GAS ANALYSIS

CUSTOMER PROJECT #:		NAME/DESCRIP :	**CSU POWERHOUSE**
SN/PRIMARY DB KEY:			**HIGH CONTAMINANT CUSTOM BLEND**
FIELD/AREA:			
PROJECT NO. :	**202002042**	ANALYSIS NO. :	**01**
COMPANY NAME :	**COLORADO STATE UNIVERSITY**	ANALYSIS DATE:	FEBRUARY 11, 2020 07:17
OFFICE / BRANCH:	FT. COLLINS	SAMPLE DATE :	FEBRUARY 5, 2020
CUSTOMER REF:		TO:	
PRODUCER :		EFFECTIVE DATE:	
FIELD DATA			
SAMPLE CYCLE:		SAMPLE TYPE:	
SAMPLE PRES. :	20 psig	PROBE :	
FLOW PRES. :	psig	CYLINDER NO. :	S101
LAB PRES:	psig	SAMPLED BY :	KHALID ZINEDDIN
SAMPLE TEMP. :	70 °f	SAMPLING COMPANY:	CSU
AMBIENT TEMP.:	°f	H2S BY STAIN TUBE:	- ppm
H2O BY STAIN TUBE:	- #/mmcf	CO2 BY STAIN TUBE:	- Mol %
FIELD COMMENTS:			
LAB COMMENTS:			

COMPONENTS	NORM. MOLE%	GPM @ **14.696**	GPM @ **14.73**
HELIUM	0.00	-	-
HYDROGEN	0.00	-	-
OXYGEN/ARGON	1.07	-	-
NITROGEN	0.01	-	-
CARBON DIOXIDE	10.39	-	-
METHANE	82.15	-	-
ETHANE	6.38	1.706	1.710
PROPANE	0.00	0.000	0.000
ISOBUTANE	0.00	0.000	0.000
N-BUTANE	0.00	0.000	0.000
ISOPENTANE	0.00	0.000	0.000
N-PENTANE	0.00	0.000	0.000
HEXANES PLUS	0.00	0.000	0.000
TOTAL	100.00	1.706	1.710

	BTU @ 60 DEG F	**14.696**	**14.73**
LHV	NET DRY REAL=	852.4 **/scf**	854.4 **/scf**
	NET SATURATED REAL=	837.6 **/scf**	839.6 **/scf**
HHV	GROSS DRY REAL =	944.9 **/scf**	947.1 **/scf**
	GROSS SATURATED REAL =	928.4 **/scf**	930.6 **/scf**
	NET DRY REAL :	16167.4 **/lb**	16204.8 **/lb**
	GROSS DRY REAL :	17922.4 **/lb**	17963.9 **/lb**

SPECIFIC GRAVITY (AIR=1 @14.696 PSIA 60F) :	0.6910
DENSITY (lb/scf)	0.05274
COMPRESSIBILITY FACTOR :	0.99760
REGULAR WOBBE INDEX (14.696)	1136.7

NOTE: REFERENCE GPA 2261(ASTM D1945 & ASME-PTC), 2145, & 2172 CURRENT PUBLICATIONS

Reference: Per GPA 2172-14 sec 9 ***The C6+ is derived from the following ratios of C6, C7 & C8+ respectively:*** **60% 30% 10%**

The data presented herein has been acquired by means of current analytical techniques and represents the judicious conclusion EMPACT Analytical Systems, Inc. Results of the analysis can be affected by the sampling conditions, therefore, are only warranted through proper lab protocol. EMPACT assumes no responsibility for interpretation or any consequences from application of the reported information and is the sole liability of the user. The reproduction in any media of this reported information may not be made, in portion or as a whole, without the written permission of EMPACT Analytical Systems, Inc.

Figure B-13. EMPACT third-party lab test results for High Contaminant custom gas blend used in ’10-Feb-20’ analyzer testing.



NATURAL GAS ANALYSIS

CUSTOMER PROJECT #: NAME/DESCRIP : **HIGH CONT**
SN/PRIMARY DB KEY:
FIELD/AREA:

PROJECT NO. :	**202003106**	ANALYSIS NO. :	**04**
COMPANY NAME :	**COLORADO STATE UNIVERSITY**	ANALYSIS DATE:	MARCH 25, 2020 10:29
OFFICE / BRANCH:	FT. COLLINS, CO	SAMPLE DATE :	MARCH 20, 2020
CUSTOMER REF:	CLIENT PROJECT #201911025	TO:	
PRODUCER :		EFFECTIVE DATE:	
FIELD DATA			
SAMPLE CYCLE:		SAMPLE TYPE:	
SAMPLE PRES. :	20 psig	PROBE :	
FLOW PRES. :	psig	CYLINDER NO. :	0104
LAB PRES:	psig	SAMPLED BY :	TIM VAUGHN
SAMPLE TEMP. :	70 °f	SAMPLING COMPANY:	CSU
AMBIENT TEMP.:	°f	H2S BY STAIN TUBE:	- ppm
H2O BY STAIN TUBE:	- #/mmcf	CO2 BY STAIN TUBE:	- Mol %

FIELD COMMENTS:
LAB COMMENTS:

COMPONENTS	NORM. MOLE%	GPM @ **14.696**	GPM @ **14.73**
HELIUM	0.00	-	-
HYDROGEN	0.00	-	-
OXYGEN/ARGON	1.10	-	-
NITROGEN	0.01	-	-
CARBON DIOXIDE	10.54	-	-
METHANE	81.99	-	-
ETHANE	6.36	1.701	1.705
PROPANE	0.00	0.000	0.000
ISOBUTANE	0.00	0.000	0.000
N-BUTANE	0.00	0.000	0.000
ISOPENTANE	0.00	0.000	0.000
N-PENTANE	0.00	0.000	0.000
HEXANES PLUS	0.00	0.000	0.000
TOTAL	100.00	1.701	1.705

	BTU @ 60 DEG F	**14.696**	**14.73**
LHV	NET DRY REAL=	850.7 **/scf**	852.7 **/scf**
	NET SATURATED REAL=	835.9 **/scf**	837.9 **/scf**
HHV	GROSS DRY REAL =	943.1 **/scf**	945.2 **/scf**
	GROSS SATURATED REAL =	926.6 **/scf**	928.8 **/scf**
	NET DRY REAL :	16092.6 **/lb**	16129.9 **/lb**
	GROSS DRY REAL :	17839.6 **/lb**	17880.9 **/lb**

SPECIFIC GRAVITY (AIR=1 @14.696 PSIA 60F) :	0.6927
DENSITY (lb/scf)	0.05286
COMPRESSIBILITY FACTOR :	0.99760
REGULAR WOBBE INDEX (14.696)	1133.1

NOTE: REFERENCE GPA 2261(ASTM D1945 & ASME-PTC), 2145, & 2172 CURRENT PUBLICATIONS

Reference: Per GPA 2172-14 sec 9 ***The C6+ is derived from the following ratios of C6, C7 & C8+ respectively:*** **60% 30% 10%**

The data presented herein has been acquired by means of current analytical techniques and represents the judicious conclusion EMPACT Analytical Systems, Inc. Results of the analysis can be affected by the sampling conditions, therefore, are only warranted through proper lab protocol. EMPACT assumes no responsibility for interpretation or any consequences from application of the reported information and is the sole liability of the user. The reproduction in any media of this reported information may not be made, in portion or as a whole, without the written permission of EMPACT Analytical Systems, Inc.

Figure B-14. EMPACT third-party lab test results for High Contaminant custom gas blend used in ’20-Mar-20’ analyzer testing.

APPENDIX C: UNCERTAINTY CALCULATIONS

G	H	I	J	K	L	M	N	O	P
1		Perm-tubes	ng/min	T (C)		COV H2S press	COV H2O press	mol/L=	0.041418095
2		H2O	473345	80		0.002583563	0.006046009		
3		H2S	63365	30					
4		Reg1-CH4 (slpn	Reg2-C2H6 (slp	Reg3-CO2/CH4	Reg4-O2/CH4 (s	H2S perm blen	H2O perm blen	H2S perm total	H2O perm total
5	Avg	5.820495044	0.651278029	0.473276893	1.35319161	0.025740048	0.024148054	0.100399119	0.101470678
6	stdev	0.006601138	0.000475731	0.000552931	0.001426428	0.0000665010	0.000145999	0.000168392	0.000161041
7	DryCal device	0.05820495	0.00651278	0.004732769	0.013531916	0.0002574	0.000241481	0.001003991	0.001014707
8	Gas bottle cal	0.00058205	6.51278E-05						
9	Water bath temp								
10									
11								0.00415834	0.004202722
12									
13	delXn	0.065388138	0.007053639	0.0052857	0.014958344	0.000323902	0.00038748	0.001172383	0.001175748
14	dCO2/dXn	141.72	141.72	-2356.99	141.72	140.5797101	140.5797101		
15	CO2 term	85.87371096	0.999283546	155.2102647	4.493961436	0.002073343	0.002967178		
16	dO2/dXn	68.46	68.46	68.46	-353.66	68.11594203	68.11594203		
17	O2 term	20.03880104	0.233184801	0.130941933	27.98587817	0.00048677	0.00069662		
18	dH2S/dXn	0.1495	0.1495	0.1495	0.1495	-53.43478261	0.15942029		
19	H2S term	9.55609E-05	1.11201E-06	6.24435E-07	5.00091E-06	0.000299553	3.8158E-09		
20	dH2O/dXn	2.09	2.09	2.09	2.09	2.028985507	-747.2173913		
21	H2O term	0.018676286	0.00021733	0.000122039	0.000977371	4.31901E-07	0.083828613		
22									
23									
24									
25	CH4 ppm			979280	9.97E+05	999431	993577		
26	other ppm					447.1259043	6251.911829		
27									
28	vol frac	0.697221446	0.078014843	0.056692566	0.162095183	0.003083331	0.00289263		
29									
30	CH4 ppm	697221.4459		55517.89609	161531.092	3081.576709	2874.051024		
31	CO2 ppm			1167.866861					
32	O2 ppm				564.0912376				
33	C2H6 ppm		78014.84333						
34	H2S ppm					1.378637217			
35	H2O ppm						18.08447015		

Figure C-1. Left-hand portion of spreadsheet used in calculating uncertainties in Gas Standard-diluted concentrations.

Uncertainty calculations for the blending cart flows were approached on an individual gas mixture component basis; the following description is based on the spreadsheets shown in Figures C-1 and C-2. The first step was to find the total flow of gases through the entire system by summing the calculated flow rates from each source (I5:N5, total in Q5). From the total flow the component flow volume fractions were then calculated by dividing each component flow by the total (I28:N28). These values were then converted into parts per million (ppm) by multiplying by a factor of 10^6 (I30:N35). For individual flows which contained pre-mixed gases (columns K

	Q	R	S	T	U	V	W
1							
2				104.4	618		
3							
4	TOTAL	H2O ng/min	H2S ng/min	O2 bottle ppm	CO2 bottle ppm	FINAL Uncertainty (±ppm)	Uncertainty (±%)
5	8.348129677	473345	63365	3480	20600		
6							
7							
8				69.6	412		
9		9466.9	1267.3				
10							
11		2.6275E-05	1.8593E-06				
12							
13				69.6	412		
14					-0.056718447		
15					546.063424	28.15396393	2.410716913
16				-0.16217433			
17				127.4038938		13.25872856	2.350458167
18							
19			0.00235629			0.052518076	3.809419582
20							
21		0.248743257				0.593772118	3.283326041
22							
23							
24							
25							
26							
27							
28							
29							
30	920226.0617						
31	1167.866861						
32	564.0912376						
33	78014.84333						
34	1.378637217						
35	18.08447015						

Figure C-2. Remaining right-hand portion of spreadsheet used in calculating uncertainties in Gas Standard-diluted concentrations.

through N) the published concentration percentages were multiplied by the channel flow to give the ppm of each component; for example, total ppm of CO2 (Q31) was determined by multiplying the channel volume flow fraction (K28) by the rated CO2 concentration in the gas bottle (U5). Since the primary component of every pre-mixed gas blend was CH4, the CH4 concentration for each channel was also calculated (I30:N30) and summed to give the total concentration of CH4 in the overall system gas flow (Q30). Total ppm concentrations for each component are provided in cells Q30:Q35.

To begin the uncertainty calculations, first the flow rates, calculated by the DAQ program based off calibrated flow curves, were averaged for each gas component on Regulators 1 through 4 (Cells I5:L5). The standard deviation of the selected data range (I6:L6) was also computed along with the uncertainty due to the DryCal devices used to calibrate the gas flows (I7:L7). For the pure gases used on Regulators 1 and 2 the uncertainty due to gas purity (99.99% rated) was computed (I8:J8). These uncertainty sources were then summed, labeled "delXn" and displayed in cells I13-N13. Next the differential change in component concentration was calculated based on a reduction of 0.1 slpm of flow from each regulator (I14:N14, I16:N16, I18:N18, I20:N20). For the pre-mixed gases used on Regulators 3 and 4 the uncertainty provided by the bottling company was used (±2%, cells T5:U5). The differential change in ppm was calculated based on a 3% change (T2:U2) and entered in cells T16 and U14. This was then multiplied by the uncertainty values in T13:U13 to give the total uncertainty in ppm (T17, U15) which was added into the overall uncertainty calculation for the CO2 and O2 components (V15 and V17 respectively).

Calculating uncertainty for the contaminants introduced through the permeation tube cylinders (H2O and H2S) was done by first finding the average pressure of the back-pressure regulator at each perm tube outlet and calculating the flow rate based off calibrated flow curves (cells M5:N5). Then the Coefficient of Variance of each back-pressure regulator was used to compute the standard deviation of the H2S and H2O flows (cells M6:N6). Uncertainty from the DryCal devices was also taken into account (M7:N7). Similar to the flows on Regulators 1 through 4 the "delXn" was summed from the different sources of uncertainty (M13:N13) and subsequent differential changes in flow for each component were computed. These differential flow changes were multiplied by delXn then squared (M14:N21). For the overall Uncertainty equation, the

square of each component term was summed (I14:N14, I16:N16, etc.) then the total square-rooted to determine the total uncertainty in ppm (V15:V21); each of these values was then divided by the total calculated ppm of each gas component (Q30:Q35) to find the total uncertainty as a percentage of flow (W15:W21).

Uncertainty due to changes in the permeation tube emission rates was performed in a different manner. The manufacturer of the permeation tube cylinders provided a change in emission rate of 10% for every 1°C temperature change. The literature for the water baths used to keep the perm tube cylinders at a constant temperature gave a rated ±0.2°C temperature fluctuation which was multiplied by the change in emission rate function. Using the published emission rates for the H2S and H2O cylinders (R5:S5) and multiplying those by the change in emission rate due to temperature fluctuation (R9:S9) gave the total uncertainty in ng/min. This figure was then converted from ng/min by dividing by the molecular weight and a factor of 10^9 (R11:S11) to give the uncertainty in ppm (R21, S19).

APPENDIX D: CIG NATURAL GAS TARIFF

3. QUALITY

3.1 Specifications. Unless otherwise agreed pursuant to Sections 3.2 and 3.3 below, Shipper warrants that Gas Tendered hereunder at each Point of Receipt and Point of Delivery will comply with the following quality specifications:

(a) At a pressure of 14.73 p.s.i.a. and a temperature of 60 degrees Fahrenheit, such Gas shall not contain more than:

(i) .25 grain of hydrogen sulphide per 100 cubic feet,

(ii) 5 grains of total sulphur per 100 cubic feet,

(iii) 10 parts per million (0.001 percent) by volume of oxygen; however, this oxygen quality specification shall not apply at Point(s) of Delivery on the Valley Line and its supporting blending operations (see Section 3.5 below for oxygen specifications applicable to the Valley Line and its supporting blending operations,)

(iv) 3.0 percent by volume of carbon dioxide,

(v) 7 pounds of water vapor per million cubic feet at Point(s) of Receipt and Point(s) of Delivery within the states of Kansas, Oklahoma, and Texas and 5 pounds of water vapor per million cubic feet in all other states.

(b) Shipper warrants that all Gas Tendered will be commercial in quality and shall be free from any foreign material such as solids, lubricating oils, sand, dirt, dust, gums, crude oil, water or hydrocarbons in the liquid phase, metal particles, and other objectionable substances, including, but not limited to, polychlorinated biphenyls, which may be injurious to pipelines, people, property, or the environment which may interfere with its Transportation or makes the Gas unmarketable or unacceptable for Delivery from Transporter's transmission system.

(c) Shipper warrants that all Gas Tendered will have a Gross Heating Value of not more than 1,235 Btu's nor less than 968 Btu's per cubic foot at a pressure of 14.73 p.s.i.a. and a temperature of 60 degrees Fahrenheit.

(d) Shipper warrants that the temperature of the Gas Tendered will not exceed 120 degrees Fahrenheit; provided, however, if Transporter is required to dehydrate the Gas at the Point(s) of Receipt, then the temperature of such Gas shall not exceed 90 degrees Fahrenheit.

Figure D-1. Page 232 of GIG Tariff of 2013 outlining natural gas quality specifications.

3.1 Specifications (continued)

(e) Shipper warrants that the hydrocarbon dew point of all Gas Tendered will not exceed a temperature of 25 degrees Fahrenheit at any pressure between 100 p.s.i.a. and 1,480 p.s.i.a. as calculated from the Gas composition.

Notwithstanding Sections 3.1 through 3.3, Transporter shall not be required to receive Gas at any Point of Receipt which is of a quality inferior to that required by Shipper or a third Party at any Point of Delivery under the Agreement. Transporter shall not be liable to Shipper or any third Party for any damages incurred as a result of Transporter's refusal to receive Gas as a result of this provision.

3.2 Specification Exemptions. Transporter, in its reasonable discretion and judgment, may accept Gas that does not conform to the quality specifications in Section 3.1 but meets the conditions set forth below, provided Transporter determines that such acceptance will not interfere with Transporter's ability to: (1) maintain prudent and safe operation of Transporter's pipeline system and storage facilities, (2) ensure that such Gas does not adversely affect Transporter's ability to provide service to others, and (3) ensure that such Gas does not adversely affect Transporter's ability to Tender Gas for Delivery to a downstream pipeline or end-user.

(a) Transporter may accept Gas with no more than 2000 parts per million (.200 percent) by volume of oxygen at a pressure of 14.73 p.s.i.a. and a temperature of 60 degrees Fahrenheit at any Point(s) of Receipt.

(b) Transporter may accept Gas with a hydrocarbon dew point in excess of 25 degrees Fahrenheit at any pressure between 100 p.s.i.a. and 1,480 p.s.i.a. as calculated from the Gas composition; provided that the Gas is subsequently processed at the BP Wattenberg, Regency Lakin, Mocane, CIG Rawlins, Williams Field Service Echo Springs or DCP Roggen plants. However, the Gas must meet the Section 3.1(e) specification after processing at these plants and upon reintroduction into CIG's mainline facilities.

(c) Transporter may accept Gas with a water vapor content in excess of 7 pounds per million cubic feet; provided that the Gas is subsequently processed within the Regency Lakin and Mocane plant. However, the Gas must meet the Section 3.1(a)(v) specification after processing at this plant and before reintroduction into CIG's mainline facilities.

(d) Transporter may accept Gas with a hydrocarbon dew point in excess of 25 degrees Fahrenheit at any pressure between 100 p.s.i.a. and 1,480 p.s.i.a. as calculated from the Gas composition at the East Dry Creek, Cavalry, Bent-Wagon Trail and Fluke Meter Stations for quantities not to exceed 1,000 Dth/d at each location and at the Kiowa Meter Station for quantities not to exceed 4,000 Dth/d.

Figure D-2. Page 233 of CIG Tariff with continued natural gas quality specifications as well as specification exemptions.