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FINAL PROJECT REPORT

Evaluation and Identification of Constituents in Pipeline Natural Gas, Biogas, and Biomethane in California: Wastewater Treatment, Green Waste, and Landfills

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Natural Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with RD&D entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater natural gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency.
- Industrial, Agriculture and Water Efficiency
- Renewable Energy and Advanced Generation
- Natural Gas Infrastructure Safety and Integrity.
- Energy-Related Environmental Research
- Natural Gas-Related Transportation.

Evaluation and Identification of Constituents in Pipeline Natural Gas, Biogas, and Biomethane in California is the final report for the Evaluation and Identification of Constituents Found in Common Carrier Pipeline Natural Gas, Biogas and Upgraded Biomethane in California: Phase 2 project, Contract Number 500-13-006, conducted by the University of California at Davis. The information from this project contributes to Energy Research and Development Division's Natural Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at 916-327-1551.

ABSTRACT

This project characterized the composition of biogas and biomethane in California based on measurements from 13 sample streams derived from 7 different production sources: 2 wastewater treatment plants, 2 dry green waste and solid waste facilities, 1 ne wet green waste and solid waste facility, and 2 landfills.

Methane content in the raw biogas varied from 48 to 65 percent. Methane content in upgraded biomethane ranged from 87.7 to 98.3 percent. The cleanest biomethane met the composition requirements for pipeline injection.

Biogas produced from landfills had notably higher concentrations of halocarbons and polychlorinated biphenyls compared to other sources of biogas. Halocarbons are molecules containing carbon atoms bonded to fluorine, chlorine, bromine, or iodine, and many halocarbons are toxic to humans and animals. Polychlorinated biphenyls are a subset of halocarbons, widely used in electrical equipment, and may accumulate in the food chain causing developmental problems. Biogas also had higher concentrations than natural gas of many organic sulfur species that can react to form acids that damage pipelines or airborne particulate matter that affects human health. Facilities that upgraded biogas to pipeline quality biomethane removed the majority of these sulfur compounds. Conversely, natural gas has substantially higher concentrations of complex hydrocarbons compared with biogas. These additional hydrocarbons increased the heating value of natural gas. Chromium, manganese, nickel and zinc concentrations were detected sporadically, sometimes at levels that may raise health concerns depending on the oxidation state which affects their reactivity and toxicity.

The research found cultivable aerobic and anaerobic bacteria at multiple sites, but none were pathogens or likely to cause pipeline corrosion. Upgrading biogas to biomethane did not completely remove the bacteria from the gas stream, suggesting that new technologies would need to be developed if bacteria control is desired in the future.

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Introduction

Renewable energy sources are essential in California to meet state goals for reducing greenhouse gas emissions. Biogas is a source of renewable energy with great potential in California, and is produced by converting organic waste materials into a gaseous mixture of carbon dioxide and methane. Biogas can be used directly to produce electricity, typically following minimal cleanup to remove sulfur or silicon compounds, or it can be further upgraded to biomethane by removing carbon dioxide and other impurities so that it can potentially be used in all applications that currently use natural gas. California Assembly Bill 1900 (Gatto, Chapter 602, Statutes of 2012) requires the development and periodic review of standards for constituents in biogas to protect human health and pipeline integrity and safety.

Despite the large potential for biogas in California, a major increase in the use of any fuel in the state must consider air quality implications and unintended outcomes for public health and infrastructure such as refining facilities and pipelines. The first step in this process is the thorough characterization of biogas and upgraded biomethane produced by a variety of feedstocks and anaerobic digester approaches.

Project Purpose and Process

The primary purpose of this project is to further understand the composition of biogas and biomethane in California and compare the composition of biomethane to the composition of natural gas. More than 350 analytes were measured across classes of compounds including hydrocarbons, volatile organic compounds, semi-volatile organic compounds, polycyclic aromatic hydrocarbons, sulfur compounds, aldehydes and ketones, halocarbons, poly-chlorinated biphenyls, organic silicon compounds, pesticides, and metals. Many of these analytes are present at extremely low concentrations but they still have the potential to affect the toxicity of the raw or upgraded biogas.

Measurements were conducted for thirteen biogas/biomethane sample streams (each consisting of three individual samples collected on different days) and a single natural gas stream (consisting of three samples). Biogas/biomethane sample streams were derived from seven production sources: two wastewater treatment plants, two dry green waste, and solid waste facilities, one wet green waste and solid waste facility, and two landfills. One wastewater treatment plant used the biogas on-site to produce electricity while the other upgraded the gas to pipeline quality. One green and solid waste facility burned gas on-site for electricity, one facility in this class upgraded gas for transportation fuel, and one facility upgraded gas for either transportation fuel or pipeline injection. Both landfills burned the gas on-site to produce electricity. The diverse nature of the gas feedstock and upgrading techniques helps characterize the range of California biogas composition. Natural gas samples for comparison to biogas were obtained from Pacific Gas and Electric (PG&E) in northern California.

Project Results

Measurements are reported for approximately 350 identified and measured substances spanning 11 major compound classes. The methane content of raw biogas fell into the expected range, with concentrations between 47.9 percent to 65.4 percent; the CO2 content ranged from 30.8 percent to 40.6 percent; the nitrogen content ranged from 0.8 percent to 18.1 percent, and the oxygen content ranged from below quantification limits to 3.2 percent. Nitrogen and oxygen were present in the biogas likely due to air entrainment. Upgraded biomethane had methane content between about 87.7 percent to 98.3 percent, depending on the technology employed, which compared favorably with the ~93.5 percent methane content of natural gas. Commercial natural gas contained an additional about 4.8 percent ethane which yielded higher heating value (energy content) than biomethane.

Biogas produced from landfills had notably higher concentrations of halocarbons and polychlorinated biphenyls compared to other sources of biogas. Halocarbons are molecules containing carbon atoms bonded to fluorine, chlorine, bromine, or iodine. Many halocarbons are toxic to humans and animals and may accumulate in the food chain and cause developmental problems for fetuses, babies, and children. Biogas and biomethane samples have substantially higher total concentrations of many organic sulfur species than the natural gas. Organic sulfur species are molecules composed of carbon, hydrogen, oxygen, and sulfur. Organic sulfur species can react to form acids that damage pipelines or they can react to form airborne particulate matter that impacts human health. Facilities upgrading biogas to pipeline quality biomethane removed the majority of these sulfur compounds. Aldehyde and ketone concentrations measured in the biogas collected in the current project were substantially higher than corresponding concentrations measured previously in food waste digesters and landfills, possibly due to saturation of the collection media in those previous measurements. Aldehydes and ketones are oxygenated hydrocarbons that are often toxic in their unburned state; their presence in biogas emphasizes the importance of limiting fugitive emissions from biogas production facilities. Natural gas has substantially higher concentrations of numerous aromatic (for example, benzene, toluene, and xylenes) and aliphatic (such as hexanes and octanes) hydrocarbons compared with biogas sources of all types. These additional hydrocarbons increased the heating value of natural gas.

The researchers detected chromium, manganese, nickel, and zinc concentrations sporadically in biogas, sometimes at levels that may raise health concerns depending on the oxidation state which affects their reactivity and toxicity. In response, the California Air Resources Board has contracted to collect and analyze new samples for metal content, including chromium levels at three test sites.

Cultivable (spore-forming) aerobic bacteria were found at all sites except the wastewater treatment facilities. Cultivable anaerobic bacteria were consistently detected at two sites. None of the bacteria detected in the current study were pathogens or likely to cause pipeline corrosion. The numbers of cultivable bacteria found in this project were comparable to those from previous studies reporting cultivable bacteria concentrations in biogas, around 10 to 100 colony forming units per cubic meters. Upgrading biogas to biomethane did not completely remove the bacteria from the gas stream, suggesting that new removal techniques will need to be developed if bacteria control is desired in the future. DNA sequencing revealed that the

most common cultivable bacteria detected were Bacillus. These natural bacteria are ubiquitous and their spores are resistant to adverse conditions such as heat, cold, desiccation, and radiation. Most Bacillus species are harmless.

The current study adds to the database of biogas composition in California and confirms the unique characteristics of gas produced from different feedstocks using different digestion approaches. Once complete, this dataset will help define typical biogas quality guidelines and identify best practices for future biogas production in California.

Technology and Knowledge Transfer

Project results have been published in peer-reviewed journal articles and presented at multiple scientific conferences.

Benefits to California

The research in this report shows that biogas/biomethane has different trace chemical composition than traditional natural gas, but these differences can be understood to aid in the development of biogas/biomethane as a safe energy resource in California. The results of this report contribute to compliance with Assembly Bill 1900 and will be reported to the California Air Resources Board. Future studies should continue to develop the database of biogas composition from different sources to better understand how to fully use this energy resource in California.

CHAPTER 1:
Introduction

Motivation

Renewable resources are essential for reducing greenhouse gas emissions and reaching state energy goals (Colbertaldo et al. 2019; Wang et al. 2019; Yang et al. 2014). Bioenergy is renewable energy produced from organic waste materials such as organic urban waste, agriculture, and food processing wastes, waste from sewage treatment facilities, landfills and other organic waste sources such as forest and other wood waste. Biogas is a source of renewable energy and is produced by converting organic waste materials into a gaseous mixture of carbon dioxide and methane. Biogas can be used directly to produce electricity or can be cleaned and upgraded to biomethane by removing carbon dioxide and other impurities. If biogas is upgraded to meet natural gas tariff standards or other tariffs specifically crafted for biomethane, it can be injected into the common carrier natural gas pipeline and become a replacement for fossil sources of natural gas in homes and factories. Because of this, the development of renewable natural gases is a high priority for the California Air Resources Board (CARB), the California Energy Commission (CEC) and other state agencies.

California is taking several actions to support the development of bioenergy from organic waste materials. The *2011 Bioenergy Action Plan* (O'Neill 2011) prepared by the Bioenergy Interagency Working Group and the more recent 2012 update (O'Neill 2012) acknowledges that organic waste materials are a sustainable and dependable resource that not only can help California achieve the state's renewable energy goals, but waste reduction and climate change goals as well. However, aggressive actions must be taken to increase its use. To support bioenergy development and the use of renewable energy, the CEC funds natural gas research based on the California Public Utilities Commission (CPUC)-approved annual research plan. The Natural Gas Research, Development, and Demonstration Program Proposed Program Plan and Funding Request for the Fiscal Year 2013-14 (Schrupp and California Energy Commission 2013) follows the state's "loading order." Increased use of renewable energy options is second on the loading order list. Thus, the fiscal year 2013/2014 budget identifies pipeline safety and renewable energy research that address the barriers to increased market penetration of renewable energy as high priority areas for natural gas research.

The California State legislature has also taken action to further advance the use of bioenergy in California by enacting legislation to promote the use of biomethane in the common carrier natural gas pipeline. Assembly Bill (AB) 1900 (Gatto, Chapter 602, Statutes of 2012) requires the CPUC to develop standards for constituents in biogas to protect human health and pipeline integrity and safety, identify impediments that limit procurement of biomethane in California, and adopt policies and programs that promote the in-state production and distribution of biomethane. To support CPUC's standards development efforts, the Office of Environmental Health Hazard Assessment (OEHHA) and CARB were tasked with the evaluation and identification of the health-based constituents of concern in biogas and biomethane in support of developing pipeline-quality renewable natural gas standards and production in California.

CARB and OEHHA staff worked together to fulfill the AB 1900 requirements and develop recommendations to inform the CPUC rulemaking process. The evaluation and identification of the constituents of concern in biogas, detailed in the May 15, 2013 report to the CPUC, relied on existing data and focused on the larger sources of biogas – landfills, dairies, and wastewater treatment plants (POTWs). The sites and sources evaluated were located all over the United States and were not specific to California. In future updates and as additional data becomes available, CARB and OEHHA staff will address other sources of biogas (i.e., food waste, food waste co-generation, crop residuals, energy crops, and/or woody biomass).

This report focuses on adding to the emerging data on the constituents (both major and trace compounds) found in natural gas, biogas, and biomethane from California sites or sources. This data will be useful to further evaluate constituents in biogas/biomethane that may pose health risks and provide critical technical support for the periodic updates mandated by AB 1900.

Research Objectives

The primary objective of this project is to further understand the composition of biogas and biomethane in California and to compare the composition of biomethane to the composition of natural gas.

Project Tasks

The project was organized around the following major tasks:

Task 1a: Seek Feedback From Project Advisory Group (PAC or Advisory Group).

The purpose of this task was to facilitate and conduct advisory group meetings and work with the group to identify candidate facilities that were currently producing or were nearly ready to produce biomethane/biogas in California. The final selection of gas streams was based on the recommendations of the advisory group. All candidate facilities and gas streams that were selected for inclusion in the project were approved by CARB and CEC to ensure that the selections met the project goals. Selection criteria included the feedstock, digestion process, location, and willingness of the producer to participate in the study. The final members of the advisory group are listed in Table 1.

Table 1: List of Advisory Group Members and Affiliations

Name	Affiliation
Valentino Tiangco	Sacramento Municipal Utility District
Josh Rapport	CleanWorld
Greg Kester	California Association of Sanitation Agencies
Johannes Escudero	Renewable Natural Gas Coalition
Ken Kloc	Office of Environmental Health Hazard Assessment
Frank Mitloehner	UC Davis
John Shears	Center for Energy Efficiency and Renewable Technologies
Brian Helmowski	CalRecycle
May Lew	SoCalGas

Source: University of California, Davis

Task 1b: Coordinate With Producers

The contractor, based on recommendations of the advisory group and approval of the selected sources by CARB/CEC, contacted and coordinated with the following producers to obtain permission to sample and evaluate gas streams. Producers were selected based on their feedstock, digestion process, location, and willingness to participate in the study.

Table 2: Producers Participating in Project

Name	Feedstock
Point Loma Biofuels	Wastewater
East Bay Municipal Utility District	Wastewater
Blue Line Energy	Solid Waste and Green Waste
Zero Waste Energy Development	Solid Waste and Green Waste
CR&R	Solid Waste and Green Waste
Brea Power	Solid Waste
Yolo County Landfill	Solid Waste

Source: University of California, Davis

Task 1c. Obtain Gas Samples

The original contract specified 11 gas streams for sampling. The contractor sampled 14 gas streams in preparation for analytical testing using approved methods. Samples of natural gas, biogas, and upgraded biomethane were obtained.

Table 3: Gas Samples Obtained for the Project

Source	Raw Gas	Treated Gas	Comments
Natural gas from Common Carrier Pipeline: California utility pipelines, Northern CA		1 (1)	Either different gas sources or at different times of the year
Natural gas from Common Carrier Pipeline: California utility pipelines, Southern CA		2	Either different gas sources or at different times of the year
Biogas/biomethane produced from POTWs - in CA	1 (2)	1 (2)	
Biogas/biomethane produced from landfills (non-hazardous) - in CA	1 (2)	1 (2)	Testing over a period of time (2 different times at one site) or two different sites
Biogas/biomethane produced from food waste and ag waste	1 (0)	1 (0)	The advisory committee directed the collection of samples at other locations
Biogas/biomethane produced from crop residuals	1 (2)	1 (3)	
Total	4 (6)	7 (8)	

Planned values in the original proposal are listed first followed by actual values in parentheses. The original contract specified 11 samples for characterization, and the actual project delivered 14 samples.

Source: University of California, Davis

Task 1d. Gas Analysis

The composition of the gas samples was analyzed using the methods described in the following section. All results from the analysis are provided in Section 3 of this report.

Compositional Dependent and Other Physical Parameters

Compressibility factor, heating value, relative density, Wobbe number, hydrocarbon dewpoint temperature, and temperature were calculated based on the composition of the biogas following standard methods.

The compressibility factor of the total gas was calculated using the weighted average of the individual components. Compressibility factors for major components at their critical points are shown in Table 4. Raw biogas was measured to have a water content of approximately 6 percent while cleaned biomethane was measured to have a water content of approximately 0.05 percent. These values were used in all calculations requiring saturated vs. dry parameters. Biogas and biomethane is predominantly methane and carbon dioxide, and so it is expected that compressibility factors at critical conditions will vary between 0.276 and 0.29.

Table 4: Compressibility Factors for Individual Components of Biogas at Critical Conditions

Component	Compressibility Factor[1]
Methane	0.29
Ethane	0.285
Carbon Dioxide	0.276
Nitrogen	0.291
Oxygen	0.29

Source: Morgan and Shapiro, "Fundamentals of Engineering Thermodynamics"(Moran et al. 2011)

The relative density of the total gas was also calculated using the weighted average of the individual components. Densities for major components are shown in Table 5. Relative density was calculated as the density of the biogas or biomethane divided by the density of air.

Table 5: Density for Individual Components of Biogas and Total Air at Standard Conditions

Component	Density[1] ($kg\ m^{-3}$)
Methane	0.656
Ethane	1.3388
Carbon Dioxide	1.98
Nitrogen	1.251
Oxygen	1.429
Air	1.29

Source: https://www.airproducts.com/products/gases/gas-facts/physical-properties and https://encyclopedia.airliquide.com/ethane.

Heating values of the biogas were calculated based on the methane content using a lower heating value for methane of 910 Btu ft^{-3} and a higher heating value for methane of 1012 Btu ft^{-3}

The dry Wobbe number was calculated as the dry gas higher heating value divided by the square root of the dry gas relative density.

Motor octane number for each gas was calculated using the formula -406.14 +508.04*(H/C)-173.55*(H/C)^{2}+20.17*(H/C)^{3} based on guidance provided on the CARB website (www.arb.ca.gov/regact/cng-lpg/appd.pdf). The hydrogen-to-carbon ratio was dominated by the methane content of the gas and was close to 4 for all gases tested, yielding relatively constant motor octane numbers.

The methane number for each gas was calculated using the formula 1.624*(motor octane number) -119.1 based on guidance provided on the CARB website

(www.arb.ca.gov/regact/cng-lpg/appd.pdf). This value was then checked using an online calculator (www.cumminswestport.com/fuel-quality-calculator). Both values are reported in the Results section of the report.

Major Component Analysis

Major components in biogas and biomethane samples are collected and analyzed using a modified version of ASTM D1945 (ASTM International 2014) that has been optimized based on our sampling techniques and analytical equipment. Biogas or biomethane samples are collected in a Tedlar sample bag (SKC Inc.) using system pressure or a "Vac-U-Chamber" (SKC Inc.) sampling apparatus, to avoid sampling pump contamination of the sample. Tedlar bags are flushed three times before use and are not re-used.

The analysis is conducted using an Agilent Technologies 6850 gas chromatography coupled with a thermal conductivity detector (GC-TCD). A system blank is analyzed before sample analysis to ensure the cleanliness of the instrument. Each sample is connected to a 250 μl sample loop for injection with a split ratio of 20:1. Peak areas are recorded, and relative concentrations are calculated (in percent) using published TCD response factors. The inlet temperature is controlled at 270 °C and the inlet pressure is maintained at 16 psi. The total helium (He) flow rate is 53.7 ml/min with a column flow rate of 2.4 ml/min and a column pressure of 16 psi. Separation is accomplished using an Agilent J&W CP-Sil 5 CB for formaldehyde (60 m x 0.32 mm x 8.00 µm) with an injection volume of 250 μl. The following temperature program is used: hold at −20 °C for 5 minutes, ramp to 150 °C at 10 °C/min, hold at 150 °C for 2 minutes, ramp to 280 °C at 150 °C/min and hold for 2 minutes. The detector temperature is maintained at 250 °C with a reference flow of 20 ml/minute and a detector make-up flow of 4.6 ml/minute. A major component gas standard mixture (Air Liquide) is used to prepare the standard curve and to quantify concentrations.

Extended Hydrocarbon Analysis

Extended hydrocarbons in biogas or biomethane are collected using an 8 x 100 mm 400 mg/200 mg XAD-2 sorbent tube (SKC, Inc.) for 20-60 min, depending on expected concentration levels, at a flow rate of 1 l/minute. Sorbent tubes are kept sealed until just prior to sampling, and flow rate is controlled with a calibrated adjustable flow meter (Dwyer Instruments, Inc.). Negative pressure is created at the back end of the sampling apparatus using an explosion-proof Teflon diaphragm pump. At the conclusion of the sampling time, the sorbent tube is immediately capped, labeled, and placed into a cooler. Once transported back to the lab, it is stored in a 0 °C freezer until extraction. Sorbent tubes may be held at 0 °C for up to 30 days before being extracted.

To extract the sorbent material, tubes are broken open and each section of XAD-2 is transferred separately to appropriately labeled glass vials. Ethyl acetate (1 ml) is added to each vial, which is then capped and sonicated for 30 minutes. Samples are filtered using a 0.45 μm Teflon syringe filter. No concentration step is used, as it is expected that volatile compounds would be lost in the process.

The analysis is performed using an Agilent 7890 gas chromatography coupled with an Agilent 7200 quadrupole time-of-flight mass spectrometer (GC-qTOF-MS). Each sample batch is

analyzed with quality control samples that include a system blank, two sample blanks (1 set of unused sorbent tube extracts), calibration standards, and the samples. The injection volume is 1.0 µl and injector temperature is 250 °C. Separation is accomplished with an Agilent J&W HP5-MS UI Column (30 m x 0.25 mm x 0.25 µm) at a He carrier gas flow rate of 0.8 ml/minute. The temperature program is 35 °C for 3 minute, ramp from 30 °C to 325 °C at 4 °C/minute, hold at 325 °C for 3 minutes.

A multi-point calibration curve generated from the calibration standards is used to quantify the target compounds. Analytical standards used were Sigma 8S61394-U TPH Mix 3, Sigma 29680-10ML cyclopentane, Sigma 66490-10ML methylcyclopentane, Sigma 442630 Isopropylbenzene, Sigma E49401-5G 2-ethyltoluene, Sigma 47324 1,2,4-trimethylbenzene, Sigma 442430 1-methylnaphthalene, Sigma 36943-250MG 1,2-dimethylnaphthalene,

Sulfur Analysis

Depending on their volatility and concentration range, sulfur compounds are collected in two different ways. Samples for hydrogen sulfide and other volatile sulfur species (such as dimethyl sulfide and methyl mercaptan) analysis are collected in Tedlar bags, while the semi-volatile sulfur species (for example thiophenes and benzothiophenes) are collected on adsorbent cartridges.

Volatile sulfur compound analyses are conducted using a modified version of ASTM D6228 (ASTM International 2019), "Standard test method for determination of sulfur compounds in natural gas and gaseous fuels by gas chromatography and flame photometric detection." Biogas or biomethane samples are collected in a Tedlar sample bag (SKC Inc.) using either system pressure or a "Vac-U- Chamber" (SKC Inc.) sampling apparatus, to avoid sampling pump contamination of the sample. Tedlar bags are flushed three times before use and are not re-used. Samples are analyzed within 72 hours. Semi-volatile organic sulfur compounds are collected on XAD-2 adsorbent cartridges following the same procedures described for non-sulfur containing semi-volatile organic compounds.

Analysis for H_2S is performed on an Agilent Technologies 6850 gas chromatograph coupled with a flame photometric detector. Samples are injected on-column in splitless mode through a heated 6-port valve outfitted with a 0.1 ml or a 1 ml sample loop. Tedlar sample bags are connected directly to the inlet port of the sample loop, and negative pressure is created at the back-end of the sample introduction system using a Teflon diaphragm pump. Each sample run includes the following quality control samples: a pure nitrogen system blank, calibration standards (obtained from Air Liquide, Inc.), and the samples. A multi-point calibration curve is generated from the calibration standard using differently-sized sample loops, ranging from 0.1 ml to 1 ml. Peak areas are recorded and calculated concentrations are subtracted by the concentrations of carbonyl sulfide (obtained as part of the volatile organic compound analysis, see below) because of hydrogen sulfide and carbonyl sulfide co-elute. The inlet temperature is maintained at 50 °C and the inlet pressure is controlled at 10.4 psi. The total He flow rate is 53.3 ml/min, while the column flow rate is 2.4 ml/minute. Separation is accomplished using an Agilent J&W HP-1 column (30 m x 0.32 mm x 5.00 µm) at a column pressure of 10.4 psi. The following temperature program is used for H_2S analysis: hold at 35 °C for three minutes, ramp to 260 °C at 50 °C/min, and hold at 260 °C for four minutes. The detector is maintained at a

temperature of 250 °C and has an H_2 flow of 50 ml/minute, and airflow of 60 ml/minute, and a makeup gas (N_2) flow of 57.6 ml/minute. Samples are quantified against an H_2S standard (Praxair).

Volatile sulfur species other than H_2S are analyzed using an Agilent 6890/5973N gas chromatograph (GC)-mass spectrometer system fitted with a Markes "Unity 2" gas sampling/thermal desorption system. Periodic multi-point calibrations are performed to confirm instrument linearity. Prior to analysis, a system blank is analyzed to evaluate the cleanliness of the system. One-Point calibration is then performed using the calibration standard mixture(s) to confirm consistency in instrument response. A sulfur-specific trap material (Markes U-T6SUL-2S) is used to collect the analytes, and the trap is maintained at 25 °C during a 2.0 minute sampling time with a sample flow rate of 50 ml/minute. Analytes are desorbed at 300 °C held for three minutes. The transfer line temperature is maintained at 140 °C. The GC is operated in constant pressure mode (32 bar) with He carrier gas. Separation is achieved using an Agilent J&W DB-VRX column (60 m x 0.25 mm x 1.40 µm). The temperature program is as follows: hold at 45 °C for three minutes, ramp from 45 °C to 190 °C at 10 °C/min, ramp from 190 °C to 250 °C at 20 °C/minute, hold for eight minutes. A custom gas standard mixture (Air Liquide) is used to quantify analyte concentrations.

Semi-volatile organic sulfur compounds are analyzed using GC-qTOF-MS using the same methods and instrument parameters outlined in the next section for non-sulfur containing semi-volatile organic compounds.

Aldehyde and Ketone Analysis

Carbonyl compound concentrations in biogas and biomethane samples are determined using a modified version of the U.S. Environmental Protection Agency (EPA) method TO-11 (U.S. Environmental Protection Agency 1999a), "Determination of formaldehyde in ambient air using adsorbent cartridge followed by high-performance liquid chromatography." The method has been optimized for this analytical equipment and target compounds.

Biogas or biomethane samples are drawn through a pair of 8 x 115 mm dintrophenylhydrazine (DNPH)-treated silica gel sorbent tubes (SKC, Inc.) for 30 sec and 1 minute, respectively, at a flow rate of 1 l/min. Sorbent tubes are not unsealed until just prior to sampling, and flow rate is controlled with a calibrated 1-5 l/minute adjustable flow meter (Dwyer Instruments, Inc.). Negative pressure is created at the back end of the sampling apparatus through the use of an explosion-proof Teflon diaphragm pump. At the conclusion of the sampling time, the sorbent tube is immediately capped, labeled, and placed into a cooler. Once transported back to the lab, it is stored in a 0 °C freezer prior to extraction. Sorbent tubes may be held at 0 °C for up to 30 days before being extracted. To extract the sorbent material, tubes are broken open and each section of the sorbent material is transferred to a labeled glass vial. One ml acetonitrile is added to each vial, which is then capped and allowed to sit for 30 minutes. The supernatant liquid is transferred to a labeled amber glass autosampler vial.

Sample analysis is carried out on an Agilent 1200 liquid chromatography coupled with an Agilent 6530 quadrupole time-of-flight mass spectrometer. Separation is accomplished using a Restek Ultra C_{18} Column (5 µm, 250 x 4.6 mm). The injection volume is 10 µl and the LC

gradient is: 40 percent A (deionized H_2O with 1 mM CH_3COONH_4) and 60 percent B (ACN/H_2O, 95/5 v/v with 1 mM CH_3COONH_4) for 7 minutes, followed by a linear increase to 100 percent B at 20 min, hold at 100 percent B for 0.5 minute. Each sample run includes a system blank, two sample blanks (1 set of sorbent tube extracts), calibration standards, and the samples. A multi-point calibration curve generated from the calibration standards (Sigma 47285-U TO-11 Standard Mix) is used to quantify the target compounds.

Halocarbon and Volatile Organic Compound Analysis

Volatile organic compounds (VOCs) and volatile halocarbons in biogas and biomethane samples are collected and analyzed using a modified version of the U.S. EPA method TO-15 (U.S. Environmental Protection Agency 1999b), "Determination of Volatile Organic Compounds (VOCs) in Air Collected in Specially- Prepared Canisters and Analyzed by Gas Chromatography/Mass Spectrometry (GC/MS)." The method has been optimized for our sampling techniques, analytical equipment, and target compounds. These compounds are analyzed in the same run, and using the same operating parameters, as the non-H_2S volatile sulfur species described above. A custom TO-15 gas standard mixture (Air Liquide) is used to quantify these compounds.

Semi-Volatile Organic Compound and Polycyclic Aromatic Hydrocarbon Analysis

Semi-volatile organic compound (SVOC) and polycyclic aromatic hydrocarbon (PAH) concentrations in biogas and biomethane samples were determined using a modified version of the U.S. EPA method 8270D (U.S. Environmental Protection Agency 1998), "Semivolatile organic compounds by gas chromatography/mass spectrometry (GC/MS)." The method was optimized for this analytical equipment and target compounds.

Biogas or biomethane samples are drawn through an 8 x 110 mm 400 mg/200 mg XAD-2 sorbent tube (SKC, Inc.) for 20-60 minutes, depending on expected concentrations, at a flow rate of 1 l/min. Sorbent tubes are unsealed immediately prior to sampling, and flow rate is controlled with a calibrated 1-5 l/minute adjustable flow meter (Dwyer Instruments, Inc.). Negative pressure is created at the back end of the sampling apparatus using an explosion-proof Teflon diaphragm pump. At the conclusion of the sampling period, the sorbent tube is immediately capped, labeled, and placed into a cooler. Once transported back to the lab, it is stored in a 0 °C freezer until extraction. Sorbent tubes may be held at 0 °C for up to 30 days before being extracted. Sorbent tubes are extracted by breaking open each section and separately transferring the sorbent material to labeled glass vials. Ethyl acetate (1 ml) is added to each vial, which is then capped and sonicated for 30 minutes. The supernatant liquid is transferred to a labeled amber glass autosampler vial.

The analysis is carried out on an Agilent 7890 gas chromatography coupled with an Agilent 7200 GC-qTOF-MS. Each sample run includes a system blank, two sample blanks (1 set of sorbent tube extracts), calibration standards, and the samples. A multi-point calibration curve generated from the calibration standards (Restek 31850 8270 Megamix) is used to quantify the target compounds.

Separation is accomplished using an Agilent J&W HP5-MS UI column (30 m x 0.25 mm x 0.25 μm) with an injection volume of 1.0 μl and a flow rate of 0.8 ml/minute (He). The injector

temperature is 250 °C and the temperature program is: 35 °C for 3 minutes, ramp to 325 °C at 4°C/min, hold at 325°C for 3 minutes.

Total Organic Silicon, Including Siloxanes

Siloxanes in biogas and biomethane samples are collected and analyzed using the same approaches and parameters described above for extended hydrocarbon analysis. Briefly, samples are collected on XAD-2 adsorbent tubes and analyzed using GC-qTOF-MS. Concentrations are quantified using the following external standards: 1,1,3,3-tetramethyldisiloxane (Sigma 235733-25G), pentamethyldisiloxane (Sigma 76840-5ML), hexamethyldisilane (Sigma 217069-5G), hexamethyldisiloxane (Sigma 205389-5ML), octamethyltrisiloxane (Sigma 235709-5ML), octamethylcyclotetrasiloxane (Sigma 43883-100MG), decamethyltetrasiloxane (Sigma 235679-25G), decamethylcyclopentasiloxane (Sigma 43217-250MG), dodecamethylpentasiloxane (Sigma 447269-10ML), and dodecamethylcyclohexasiloxane (Sigma 43216-25MG).

Pesticide and Polychlorinated Biphenyl Analysis

PCBs in biogas and biomethane samples are collected and analyzed using the same procedures and instrument parameters described for SVOCs. Pesticide concentrations are quantified using a pesticide standard mix (Sigma CRM46845 EPA 8081) and PCBs are quantified using a PCB standard mix (Supelco 47330-U PCB Congener Mix 1).

Biologicals

Biogas and biomethane samples were collected on polycarbonate filters (47 mm, 0.4 µm pore-size) using stainless-steel holders (Pall Laboratory) installed on the in-house sampling manifold. Two filters were collected per sample, then individual filters were placed in a 50-ml Falcon tube containing 15 ml sterile phosphate buffered saline (PBS). One of the falcon tubes was placed in an anaerobic pouch (BD GasPak EZ pouch system) to minimize inactivation of anaerobic bacteria. Samples were placed on ice and transported to the laboratory, then stored at 4 ºC in the dark until analyzed.

Filters submerged in PBS were vortexed for 5 s and then manually shaken for 2 minutes to elute microorganisms collected on filters. The filter eluates in (an)aerobically stored samples were pooled in a biosafety cabinet and then split for cultivation tests (7 ml in duplicate) and nucleic acid extraction (13 ml). A single dilution most probable number (MPN) method was used to estimate the concentrations of cultivable and spore-forming bacteria. Filter eluates were incubated in thioglycolate medium for seven days at 37 ºC for cultivable heterogeneous bacteria analyses (Saber 2009a). Spore testing was conducted by NASA Standard assay (NASA 1980). In brief, filter eluate was heat-treated at 80 ºC for 15 min to inactivate vegetative bacteria prior to inoculation in the media, then incubated in tryptic soy broth for three days at 32ºC. Samples were incubated under aerobic and anaerobic conditions. Positive samples for cultivable bacteria in the MPN tests were further characterized by DNA sequence analysis following polymerase chain reaction (PCR) targeting the 16S rRNA gene (Nadkarni et al. 2002). PCR amplicons were purified using the Qiaquick gel extraction kit and submitted for sequencing to the UC DNA Sequencing Facility at UC Davis. The forward and reverse DNA sequence data were analyzed using Geneious software (Biomatters Inc, Newark, NJ), and the

consensus sequences were compared with GenBank reference sequences using the Basic Local Assignment Search Tool (BLAST) (Altschul et al. 1990). For nucleic acid extraction, the eluate was centrifuged to concentrate microbial entities. DNA was extracted from the concentrated eluate using the FAST DNA® SPIN KIT for Soil (MP Biomedicals, Solon OH) according to the manufacturer's instructions. Five quantitative polymerase chain reactions (qPCR) assays targeting total bacteria and corrosion inducing bacteria (one for sulfate reducing bacteria and acid producing bacteria, and two for iron oxidizing bacteria) were selected from publicly available publications (Nadkarni et al. 2002; Li et al. 2010; Johnson et al. 2012; Foti et al. 2007; Vital et al. 2013). Microbial levels at different sources were compared using the Kruskal-Wallis ANOVA on ranks test with a significance level set at $p<0.05$. Statistical analyses were performed using SigmaPlot (Systat Software Inc., San Jose CA).

Metals

Metals (including mercury) were determined via U.S. EPA Method 29 (U.S. Environmental Protection Agency 2017) (modified) "Determination of Metals Emissions from Stationary Sources." Briefly, gas samples flowed through aqueous acid impingers followed by analysis using inductively coupled plasma mass spectrometry (ICP-MS).

During the spring of 2016, continuing through the summer, approximately 20 samples were analyzed for mercury (Hg) by two methods: the traditional gold-coated trap method, and the metals impinger series used for all elements. Results, including detection limit performance, were comparable. Confidence in the ability to exclude incidental signals from outside the sampled gas flow was more reliable with the impinger series. For those two reasons, results from the ICP-MS method are reported.

Task 1e Reporting

The contractor submitted quarterly progress reports and this final report to fulfill the contract deliverables.

Report Structure

This report is comprised of four chapters:

- Chapter 1: Introduction
- Chapter 2 describes each location where biogas or upgraded biomethane was collected. The general process is described and site over-view diagrams are provided for all locations.
- Chapter 3 summarizes the results of all measurements for all target analytes for biogas and upgraded biomethane. Results are provided for the mean and standard deviation of all measurements.
- Chapter 4 provides preliminary conclusions about the biogas composition measurements and makes recommendations for future work.

CHAPTER 2:
Site Descriptions

Introduction

Biogas samples were collected at seven facilities. Two of these facilities (Point Loma Biofuels and East Bay Municipal Utility District) used wastewater sludge as a feedstock with different levels of upgrading for the final gas. Two of the facilities (Blue Line and Zero Waste Energy Development) used general solid waste including food waste and green waste as the feedstock. One facility (CR&R) exclusively used food scraps, yard trimmings, and other green waste. The final two facilities (Brea and Yolo) were traditional landfills that accepted general solid waste. All sites were reviewed and approved by the project advisory committee and project managers at CARB and CEC. A more detailed description of each site is provided.

Point Loma Biofuels

The Point Loma Biofuels facility is located adjacent to the Point Loma Wastewater Treatment Plant on the Point Loma Peninsula in San Diego, California.

Figure 1: Aerial View of Point Loma Biofuels Production Facility
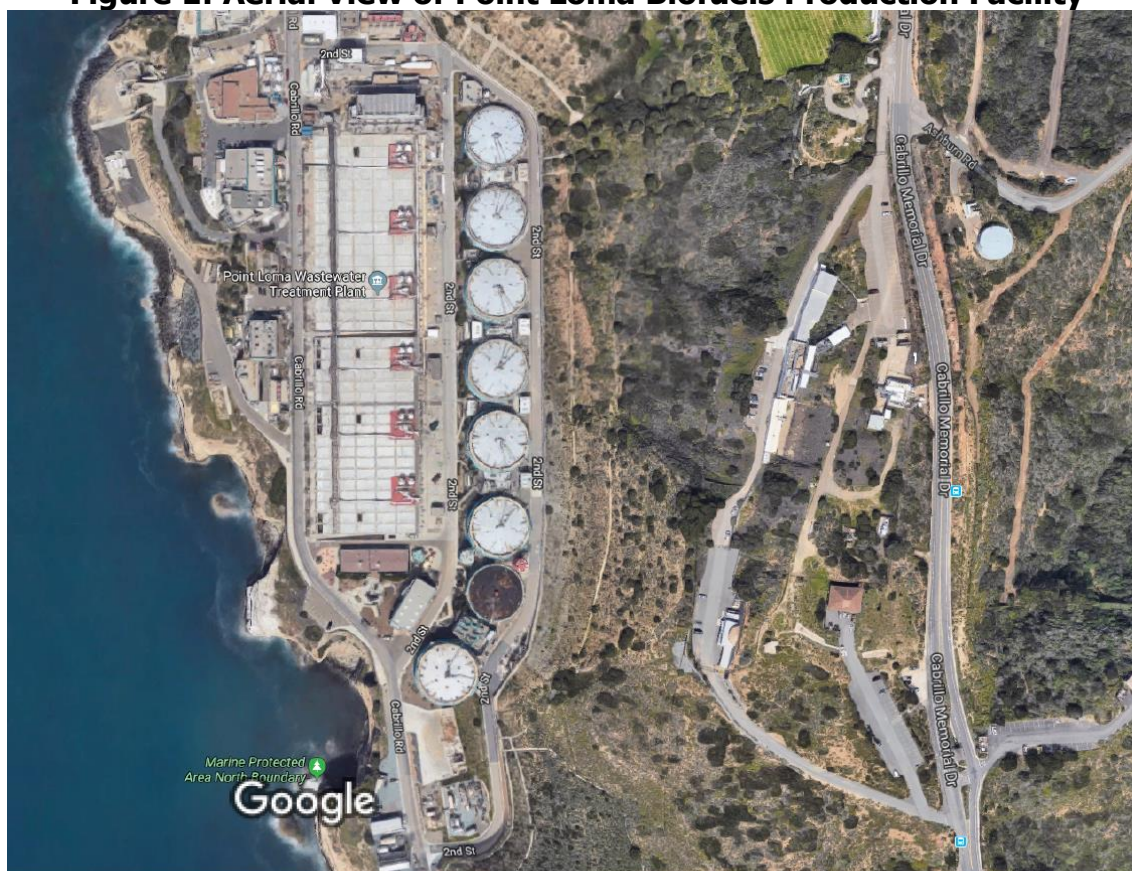
Source:Imagery © 2019 Google, Map data

The plant treats approximately 175 million gallons of wastewater per day from the City of San Diego. The organic material (sludge) that settles to the bottom of collection tanks during the treatment process acts as feedstock to one of eight anaerobic digesters on site. Residence time in each digester is approximately two weeks. Biogas produced by the digester passes through a coalescing filter (water removal), a pressure swing adsorption system (CO_2 removal), activated carbon (VOC, sulfur removal), a two-stage membrane separation system (CO_2 removal), a "Sulfa-Treat" system (H_2S and other sulfur compounds removal), a polishing system with activated carbon (residual compound removal), and a polishing system with silica gel (final moisture removal). Input biogas flow rates to the upgrading facility range between 1,200 and 1,400 thousand cubic feet per day (MCFD) while biomethane production rates range between 600 and 750 MCFD. The upgraded biomethane produced at the treatment facility can be burned on-site to produce electricity that is needed to operate the plant or it can be injected into a pipeline to provide methane for other facilities.

Raw biogas was collected immediately after release from the digester tanks at the piping connections that feed the upgrading facility. Upgraded biogas was either collected immediately after upgrading or it was stored in transportable CNG storage tanks (61 liters) for later analysis in the laboratory. Biomethane was stored at a pressure of 248 bar (3600 psi) using a compressor designed for residential CNG vehicles (PHILL Compressor, BRC Fuel Maker Corporation; Cherasco, Italy).

East Bay Municipal Utility District

The East Bay Municipal Utility District (EBMUD) facility located on Wake Avenue in Oakland, California, can treat up to 320 million gallons of wastewater per day (average dry weather flows of 50-60 million gallons per day) from their 88-square mile service area on the east side of the San Francisco Bay.

Figure 2: Aerial View of East Bay Municipal Utility District Biogas Production Facility

Source: Imagery © 2019 Google, Map data

The sludge from the treatment process is combined with trucked food waste collected from local restaurants and other liquid organics and the resulting feedstock is blended in up to eleven anaerobic digesters with a residence time of approximately three weeks. Sulfur is controlled by adding ferric chloride to the digester sludge. Biogas produced at the facility is cooled to remove moisture and passed through an activated carbon bed to remove siloxanes and residual sulfur compounds before being burned on-site to generate electricity in a 4,500 kW generator (Solar turbines, Mercury 50) or three reciprocating engines (Enterprise, 6DGSR) with a combined output capacity of 2,150 kW. Raw gas samples were collected immediately upstream of the water removal system and clean biogas samples were collected immediately downstream of the activated carbon bed.

Blue Line Energy

Blue Line Energy collects approximately 11,200 tons per year of food waste, green waste, and other solid waste from the adjacent city of South San Francisco to act as feedstock for biogas production.

Figure 3: Aerial View of Blue Line Energy Biogas Production Facility

Source:Imagery © 2019 Google, Map data

Biogas is produced by anaerobic digestion in dry, sealed chambers at 52-55 °C and then upgraded to biomethane using a BioCNG™ upgrading system. Raw biogas is passed through a SulfaTreat system to remove H_2S and other sulfur-containing compounds, cooled to 4.4 °C to remove water, passed through a siloxane/VOC removal system, and then passed through a CO_2 removal system. The resulting biomethane is used as fuel for approximately ten of the trucks operating at the facility. Upgraded biomethane was stored in transportable CNG storage tanks (61 liters) and collected for analysis in the laboratory. Biomethane was stored at a pressure of 248 bar (3600 psi) using a compressor designed for residential CNG vehicles (PHILL Compressor, BRC Fuel Maker Corporation; Cherasco, Italy). Raw biogas samples could not be collected at this location due to the facility's absolute commitment to zero emissions.

Zero Waste Energy Development

Zero Waste Energy Development in San Jose (ZWSJ) processes up to 90,000 tons per year of solid waste, food waste, and green waste collected from the adjacent cities of San Jose, Palo Alto, Mountain View, and Sunnyvale. Biogas is produced by anaerobic digestion in one of sixteen dry, sealed chambers at 52-55 $^{\circ}$C. Biogas is passed through an MV Technology Iron Sponge to remove H_2S and other sulfur compounds, cooled to approximately 5 $^{\circ}$C to remove water, passed through an activated carbon bed to remove siloxanes and VOCs, and then burned in a 2G generator powered by an MWM engine to produce electricity and heat. The total power generation at the facility is approximately 1600 kW. Raw biogas samples were collected immediately after the biogas collection chamber and clean biogas samples were collected immediately before use in the on-site engine.

Figure 4: Aerial View of Zero Waste Energy Development Facility in San Jose

Source:Imagery © 2019 Google, Map data

CR&R Incorporated

The CR&R anaerobic digestion facility in Perris, California, can process up to 335,000 tons per year of solid waste, food waste, and green waste obtained from multiple cities throughout southern California. Biogas is produced in wet anaerobic digesters. Raw biogas is washed with

water to remove CO_2 followed by vapor pressure swing adsorption (VPSA) to remove residual CO_2 and other impurities. The resulting biomethane has an energy content that meets the requirements for pipeline injection. A portion of the biomethane produced at CR&R is used to fuel the trucks servicing the facility. Raw biogas samples were collected immediately after the anaerobic digester. Clean biogas samples were collected after the VPSA system.

Orange County Waste Recycling – Olinda Landfill in Brea

Olinda landfill is a 565 acre (2.29 km^2) facility in Brea, California, that receives approximately 7000 tons per day of solid waste from neighboring cities. Landfill operations began in 1960 with current gas production estimated at 8300 cubic feet per minute. Landfill gas is cooled to remove water followed by siloxane removal (activated alumina, silica gel, molecular sieve) and carbon polishing to remove residual impurities. The clean biogas is burned in four T60 Solar turbines producing a combined 32 MW of power. Raw biogas samples were collected immediately before water removal, while clean gas samples were collected immediately before use by the turbines.

Figure 5: Aerial View of Olinda Landfill in Brea

Source:Imagery © 2019 Google, Map data

Yolo County Landfill

Yolo County landfill is a regional 720 acre (2.9 km^2) facility in Yolo County, California, that receives approximately 500 tons per day of solid waste from neighboring communities. Landfill operations began in 1975 with current gas production estimated at 1100 cubic feet per minute. Landfill gas is cooled to remove water and then burned in two Caterpillar Model G399 reciprocating engines and two Caterpillar Model G3516 reciprocating engines producing a combined 3000 kW of power. Raw biogas samples were collected immediately before water removal, while clean gas samples were collected immediately before use by the engines.

Figure 6: Aerial View of Yolo County Landfill Facility

Source:Imagery © 2019 Google, Map data

CHAPTER 3:
Results

The results shown in the following sections represent averages from multiple samples collected from the indicated source on different days to form a "sample stream." In virtually all cases, three individual samples collected at different times were analyzed and the results were averaged to describe a "sample stream." Reported uncertainty values are one standard deviation of the results obtained for the individual samples.

The natural gas sample stream was constructed by collecting and analyzing three samples of traditional natural gas from Pacific Gas and Electric at the UC Davis campus. CNG samples were stored and handled using the same methods as the biomethane samples obtained from the biogas production sites. Compressed CNG/biomethane was stored in transportable CNG storage tanks (61 liters) with pressures ranging from 200-3600 psi. Gas passed through a two-stage brass pressure-reducing regulator prior to collection on various sampling media and subsequent analysis.

Raw biogas samples were collected directly at the production sites without any intermediate steps involving compression into storage tanks or flow through a pressure-reducing regulator.

Limits of detection (LODs) for each measurement technique were defined to be the level at which a chromatographic peak could be detected but the quantification of the compound was not reliable because the signal was comparable to the baseline "noise" in the method. LODs were defined as 3x the baseline variability.

Limits of quantification (LOQs) for each measurement technique were defined to be the level at which quantification of the compound as possible. LOQs were defined as 10x the baseline variability. When all replicate measurements for a particular gas stream were below the respective LOQ, this is simply reported as <LOQ in the following data tables. In some cases, one or two of the three samples taken of a particular gas stream either had compound concentrations below the LOD or below the LOQ. Whenever at least one sample had a concentration that exceeded LOQ, an average was calculated by using 0.0 for values below the LOD, the estimated concentration for compounds with concentrations between LOD and LOQ, and the measured value for compounds at or above the LOQ. All values affected by any measurements below the LOQ are indicated with a footnote in the respective data tables.

All data in the report were reviewed to ensure that they met the project's quality control guidelines. If they did not, analyses were repeated (consistent with holding time limitations) or other necessary corrective actions were taken. In some cases, these steps still did not produce acceptable data; in these cases, the result is listed as "no measurement" (NM).

Major Components Analysis

The concentrations of major components measured in the current study are reported in Table 6 and Table 7. Methane concentrations in the raw biogas varied from 47.9 percent to 65.4 percent and were relatively consistent within a facility category. The average methane

concentrations varied in the order wastewater facilities (greatest concentrations), food waste, and landfills (lowest concentrations). Methane content did not increase greatly during the cleaning processes at EBMUD, Brea, Yolo, or ZWSJ, but methane content increased significantly at Point Loma and CR&R.

In addition to methane, the balance of the biogas composition was made up of CO_2 with smaller amounts of N_2 and O_2 (likely due to air intrusion) at all the biogas locations. Biomethane produced at Point Loma and CR&R exceeded the methane content of the commercial CNG collected in Northern California. Commercial CNG contained an additional ~5.4 percent ethane which yielded higher energy content than biomethane, which contained primarily N_2 and O_2 as major residual components. Biomethane produced at Point Loma met pipeline standards requiring oxygen < 0.2 percent, CO_2 < 3 percent, and total inerts <4 percent.

The concentrations of other potential major components listed in Table 6 and Table 7 were below the limits of quantification.

Ammonia Analysis

The results of ammonia measurements from the 14 sample streams are summarized in Table 8 and Table 9. Ammonia in the biogas was below the LOQ (100 ppbv) and/or not statistically significant for most samples except for raw biogas from EBMUD, ZWSJ, and CR&R, which showed overall >80 percent removal following cleaning procedures.

Extended Hydrocarbon Analysis

The concentrations of extended hydrocarbons measured in the current study are reported in Table 10 and Table 11. Concentrations of cyclic and straight-chain alkanes with 5-9 carbons in CNG samples exceeded 1 ppmv (1000 ppbv), with the highest concentrations (58-179 ppmv) for 6 carbon (hexanes and cyclohexanes) and 7 carbon (heptanes and methylcyclohexanes) species. Concentrations for 10-12 carbon alkanes were above the quantification limits but were much lower (0.6-150 ppbv). Extended hydrocarbons with more than 13 carbons were <LOQ for all CNG samples. Biogas samples exhibited very different patterns of extended hydrocarbon concentrations, with none of the biogas samples having a concentration of any compound with nine carbons or less that exceeded the corresponding CNG concentration. Longer chain alkanes, particularly those with 10-12, 18 and 20 carbon atoms, were frequently detected in the raw biogas samples and in some of the clean biogas samples. Concentrations for these compounds generally exceeded those found in CNG, most of which were below the limits of quantification. The highest concentrations of the higher molecular weight alkanes (C_{12}-C_{20}) were found in the landfill biogas samples.

Sulfur Analysis

The concentrations of sulfur species measured in the current study are reported in Table 12 and Table 13. As expected, the biogas and biomethane samples have substantially higher total concentrations of many sulfur species than the CNG, which contained thiophane and disulfide species commonly included in natural gas odorants but had levels of virtually all other volatile sulfur species at levels below the quantification limits. Concentrations of many volatile organic

sulfur species are significant in the biogas samples, with methyl and sec-butyl mercaptans exceeding 1 ppmv in some gas streams. Concentrations of several hundred ppbv were observed for a number of other sulfur containing compounds. The various cleaning steps applied to the biogas streams had differing levels of efficacy, with removal being nearly complete at Point Loma, significant for most constituents at CR&R, while less effective removals were observed at the other sites. It should be noted that the large standard deviations reported for some compounds in Table 9 (and in a number of subsequent tables) are not primarily the result of analytical uncertainty, but instead appear to be driven by fluctuations in biogas composition on time scales from days to months. Analytical uncertainty is much smaller than the measured variation in the three independent samples. Temperature variations, changes in feedstock composition, presence of compounds that inhibit certain microbial processes, and other changes in the bioreactor may be responsible for these variations.

Halocarbon and Volatile Organic Compound Analysis

The concentrations of halocarbons and other volatile organic compounds measured in the current study are reported in Table 14 and Table 15. All halocarbon concentrations are below the LOQ for the CNG samples.

A majority of the halocarbons monitored in this study are present in the two raw landfill biogas streams at levels above LOQ; these levels are generally not significantly reduced by the cleaning processes used at these facilities. Compounds present at relatively high concentrations in these streams include 1,2-dichloroethane (713-1480 ppbv), dichlorodifluoromethane (102-157 ppbv), and 1,1-dichloroethene (35-304 ppbv). These halocarbons likely originate from leaching of solvents or refrigerants from containers disposed at the landfills and/or from plastics in the feedstock to these facilities. Plastics in landfills can degrade over time and release halocarbons. None of the non-landfill biogas streams featured widespread halocarbon detections, and those that were detected were generally at much lower levels compared with the landfill gas streams. One exception was 1,2-dichloroethane at ZWSJ, which had individual sample concentrations of from 420 to 629 ppbv.

Benzene, toluene, ethylbenzene, and xylene (BTEX) compounds were present at concentrations above the limits of quantification for all CNG samples and most of the sources of biogas; concentrations in CNG were consistently above any of the biogas sources. Biogas sources contained more diverse aromatic compounds than CNG, including n-propylbenzene and isopropyl benzene, but total aromatic hydrocarbon concentrations in the CNG were higher than the biogas samples overall. Raw biogas likely contains aromatic hydrocarbons due to their presence in the original feedstock either through the direct incorporation of petroleum-based materials or through the use of fuels, solvents or pesticides in related processes that inadvertently become entrained into the feedstock to the digester.

Aldehyde and Ketone Analysis

The concentrations of aldehydes and ketones measured in the current study are reported in Table 16 and Table 17. The biogas streams that had been treated to achieve high methane contents (>87%, Point Loma clean, CR&R clean and Blue Line clean) had aldehyde and ketone

profiles that were generally similar to CNG except for acetone in Point Loma clean, which had 240 ppbv compared with <LOQ in CNG and for methylethylketone (MEK) and valeraldehyde, which were each 190-300 times higher in the clean biogas samples compared with CNG. Biogas sources that were not upgraded to achieve high methane contents had much higher concentrations of aldehydes and ketones, especially for MEK and valeraldehyde, compared with natural gas. The aldehyde and ketone concentrations measured in the biogas samples in this study are substantially higher than those reported in the Phase 1 report. Sampling times for aldehydes and ketones were significantly reduced during phase 2 because some of the compounds at some sites were saturated during Phase 1. These reduced sampling times are believed to improve the capture efficiency of the DNPH cartridges. Consequently, the Phase 2 results are viewed as being more broadly representative of the aldehyde and ketone concentrations in biogas sources.

VOC, SVOC, and PAH Component Analysis

The concentrations of additional VOCs, SVOCs, and PAHs measured in the current study are reported in Table 18 and Table 19. Some of the most commonly occurring compounds in biogas and biomethane include phenol and substituted phenol compounds. Another common family of compounds appears in the biogas and biomethane is naphthalene and substituted naphthalene compounds. Concentrations of all these compounds in CNG, biogas, and biomethane are generally below 1 ppbv.

Organic Silicon Analysis

The concentrations of organic silicon compounds measured in the current study are reported in Table 20 and Table 21. These compounds mainly originate from consumer products such as shampoo. They are of possible concern when combusted due to the formation of involatile silica. Other than a single detection of decamethylcyclo-pentasiloxane, siloxanes were absent from CNG. Siloxanes were detected in raw biogas samples from all source categories. Cleanup operations had varying degrees of success, with substantial reductions in siloxane concentrations at Point Loma, EBMUD, and CR&R, and minimal reductions at Yolo and ZWSJ.

Mercury Analysis

Mercury results are included in the next section.

Metals Analysis

The concentrations of metals measured in the current study are reported in Table 22 and Table 23. Metals were detected sporadically but at statistically significant levels above zero, often with groups of metals showing up all at once in a single sample – such as Cr, Mn, Ni, and Zn, which are often correlated. Presumably, these are aerosol particles of some mechanical origin, rather than actually from the biogas, in particular since these metals are just as likely to be detected in clean samples as in raw samples. Notably, two elements are known to produce volatile forms under reducing conditions (such as in biogas production), arsenic in several samples and antimony in a few samples, produced some detections. Overall, arsenic vapor was >90 percent removed by the clean-up processes employed at the sites where it was detected.

Biological Analysis

Table 24 summarizes cultivable biologicals measured in the raw biogas, cleaned biomethane, and CNG collected from eight different locations. The concentrations of biological entities detected in the sample volume were expressed per m^3 of the sample. The assay limit of detection of the single dilution MPN test was 5.1 MPN/sample. Since the gas sampling volume in the current project was 300 L for all samples, the sample limits of detection (SLODs) in the cultivation tests were considered to be 17.0 MPN/m^3. For calculation of the mean, the concentrations of non-detect samples were assumed to be half of the SLOD, which was 8.5 MPN/m^3. Triplicate biogas and biomethane samples were collected from six sampling locations except for Point Loma, where five biogas samples were obtained. In addition, three CNG samples from Northern California and three biomethane samples from Blue Line were analyzed.

Cultivable aerobic bacteria were found in biogas samples at Yolo (3 of 3), San Jose (1 of 3), Brea (2 of 3) and CR&R (2 of 3); however, their concentrations were not statistically different from samples in which no cultivable aerobic bacteria were found (p=0.083) based on the Kruskal-Wallis ANOVA on ranks test with a significance level set at p<0.05. Cultivable aerobic bacteria were also detected in biomethane samples at comparable or lower levels at those sites. Cultivable anaerobic bacteria were detected in the biogas and biomethane samples collected from Brea (1 of 3) and CR&R (3 of 3). Spore-forming bacteria results showed that aerobic spore-forming bacteria were found in biogas from Yolo (1 of 3), Point Loma (1 of 5), Brea (1 of 3) and CR&R (3 of 3). Anaerobic spore-forming bacteria were also enumerated from these sites except for Yolo. Biogas collected from CR&R showed relatively high spore-forming bacteria concentrations while their levels were close to SLODs at other sites. The Kruskal-Wallis analyses indicated that there was a statistically significant difference in spore-forming bacteria concentrations in biogas between sites (p <0.05). Aerobic and anaerobic spore-forming bacteria were detected from about 50 percent (10 of 21) and 25 percent (5 of 21) of biomethane samples collected from seven sites, respectively. Spore-forming bacteria were less than the SLOD in three CNG samples. The numbers of cultivable bacteria found in this project were comparable to those from previous studies reporting cultivable bacteria concentrations in biogas around 10 to 100 colony forming units per m^3 (Vinnerås, Schönning, and Nordin 2006; Saber 2009b).

Cultivation positive wells in the MPN tests were further analyzed for taxonomic identification of bacteria by DNA sequencing. The most common cultivable bacteria identified in biogas and biomethane from CR&R where cultivable (spore-forming) bacteria were found most frequently at relatively high concentrations were *Bacillus* species including *B. licheniformis, B. subtilis, B. foraminis, B. firmus,* and *B. oceanisedimini*. *Bacillus* spp. are ubiquitous endospore-forming aerobic or facultatively anaerobic bacteria in nature. The spores are resistant to adverse conditions such as heat, cold, desiccation, and radiation, thus it is not surprising that they were found most frequently in the current study. *B. anthracis* and *B. cereus* are *Bacillus* pathogens in warm-blooded animals including humans, but most *Bacillus* species are harmless. *Clostridium* species which may include *C. botulinum* were identified in one of the biogas samples from CR&R. *C. botulinum* is anaerobic spore-forming bacteria found in soils and aquatic sediments. *C. botulinum* is considered a pathogen and can be spread by food. The

spores usually do not cause people to become sick; however, in rare cases, serious illness can be caused by botulinum neurotoxin. *C. botulinum* was not found in biomethane samples from CR&R. *Lysinibacillus* species were found once in cultivation positive biogas samples from CR&R but the pathogenicity of this genus is not well established.

Table 25 summarizes the concentrations of target bacteria in the qPCR analysis. Data at levels below the SLOD were reported as "<SLOD". The SLODs of total bacteria, sulfate reducing bacteria, two iron oxidizing bacteria and acid producing bacteria were 12000, 43, 280 and 27, as well as 30 gene copies per m^3, respectively. The corrosion inducing bacteria tested in the current study were all below their detection limits.

PCB Analysis

The concentrations of PCBs measured in the current study are reported in Table 26 and Table 27. The 209 polychlorinated biphenyl congeners (structural isomers) comprise ten distinct molecular formulas containing from 1 to 10 chlorine atoms. In the results, the specific congeners have been grouped into the appropriate molecular formula "bin" as follows: dichloro- (PCB 4-PCB 15), trichloro- (PCB 16-PCB 39), tetrachloro- (PCB 40-PCB 81), pentachloro- (PCB 82-PCB 127), hexachloro- (PCB 128-PCB 169), heptachloro- (PCB 170-PCB 193), and octachloro- (PCB 194-PCB 205). Five of the tested sources (CNG, Point Loma, ZWSJ, CR&R, Blue Line) did not contain any PCB congener above the limit of quantification for our analyses. PCBs containing 2-3 chlorine atoms were above the quantification limit in all three raw biogas samples from both landfill sites (Brea and Yolo). Tetrachloro biphenyl congeners were detectable in 3 of 3 Brea samples, 2 of 3 Yolo samples and 1 of 3 EBMUD samples. Clean biogas samples did not contain PCBs above the quantification limits at either EBMUD or Brea, but detectable levels of di-chloro- (2 of 3 samples), tri-chloro- (1 of 3 samples) and tetra-chloro- (1 of 3 samples) congeners were observed in clean biogas from Yolo. None of the samples tested contained penta-, hexa-, hepta-, or octa-chlorinated PCB congeners at levels exceeding the quantification limits.

Pesticide Analysis

The concentrations of pesticides measured in the current study are reported in Table 28 and Table 29. The pesticides analyzed are all legacy compounds without current, approved uses in California. However, these compounds are considered bioaccumulative and persistent, and they are still detected in a wide variety of environmental samples. However, none of these compounds was above the quantification limit in either raw or clean biogas samples or in CNG.

Compositional Dependent and Other Physical Parameters

The values of parameters used to characterize raw and upgraded biomass samples determined in the current study are reported in Table 30 and Table 31.

Table 6: Results of Major Component Analysis
Point Loma, East Bay Municipal Utility District, Brea, and Yolo

Parameter	LOQ (%)	CNG	Point Loma Raw[a]	Point Loma Clean	EBMUD Raw	EBMUD Clean	Brea Raw[a]	Brea Clean[b]	Yolo Raw	Yolo Clean
Nitrogen/ Carbon Monoxide	0.23%	0.864± 0.191	0.782± 0.393	0.654± 0.408	1.3± 0.98	0.969± 0.916	7.83± 0.52	8.6	18.1± 3.8	17.5± 2.41
Oxygen/Argon	0.14%	<LOQ	0.364± 0.0834	<LOQ	1.11± 0.996	1.08± 1.03[c]	1.14± 0.11	1.3	3.18± 1.62	2.93± 1.22
Methane	0.76%	93.5± 0.105	59.2± 0.0409	98.2± 0.234	65.4± 3.31	66.3± 3.78	49.5± 0.758[c]	47.0	47.9± 3.7	48.3± 4.39
Carbon Dioxide	0.72%	0.889± 0.0613	39.6± 0.436	0.634± 0.598	32.2± 5.27	31.7± 5.71	41.6± 0.347	43.1	30.8± 8.2	31.3± 7.22
Hydrogen	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM
Ethane	1.29%	4.76± 0.0706	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Ethene	1.08%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Ethyne	1.07%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Propane	1.25%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Propene	1.07%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Propadiene	0.97%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Propyne	0.97%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
i-Butane	0.98%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
n-Butane	0.77%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1-Butene	0.86%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
i-Butene	0.85%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
trans-2-Butene	0.72%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
cis-2-Butene	0.72%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,3-Butadiene	0.71%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ

Parameter	LOQ (%)	CNG	Point Loma Raw[a]	Point Loma Clean	EBMUD Raw	EBMUD Clean	Brea Raw[a]	Brea Clean[b]	Yolo Raw	Yolo Clean
Isoprene	0.72%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
i-Pentane	0.54%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
n-Pentane	0.54%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
neo-Pentane	0.54%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Pentenes	0.54%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ

All results in percent, uncertainty is 1 standard deviation.

Average and standard deviation based on 2 samples because of problems with sample collection or storage.

[b]**Average based on 1 sample because of problems with sample collection, storage, or quality control check.**

[c]**One or two values were <LOQ.**

Source: University of California, Davis

Table 7: Results of Major Component Analysis
Zero Waste Energy Development, CR&R, and Blue Line

Parameter	LOQ (%)	CNG	ZWSJ Raw	ZWSJ Clean[a]	CR&R Raw	CR&R Clean	Blue Line Clean
Nitrogen/Carbon Monoxide	0.23%	0.864± 0.191	5.09± 2.77	5.8± 3.49	5.16± 3.57	1.85± 0.47	6.44± 0.04
Oxygen/Argon	0.14%	<LOQ	1.41± 1.55[b]	1.89± 2.14	2.93± 3.11	1.13± 1.06	0.61± 0.02
Methane	0.76%	93.5± 0.105	52.9± 4.39	55.9± 4.8	58.5± 10.3	97± 1.52	87.72±1.03
Carbon Dioxide	0.72%	0.889± 0.0613	40.6± 8.43	36.4± 10.4	33.4± 16.4	<LOQ	5.23± 1.07
Hydrogen	NM	NM	NM	NM	NM	NM	NM
Ethane	1.29%	4.76± 0.0706	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Ethene	1.08%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Ethyne	1.07%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Propane	1.25%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Propene	1.07%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Propadiene	0.97%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Propyne	0.97%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
i-Butane	0.98%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
n-Butane	0.77%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1-Butene	0.86%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
i-Butene	0.85%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
trans-2-Butene	0.72%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
cis-2-Butene	0.72%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,3-Butadiene	0.71%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Isoprene	0.72%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
i-Pentane	0.54%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
n-Pentane	0.54%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
neo-Pentane	0.54%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Pentenes	0.54%	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ

[a]**Average and standard deviation based on 2 samples because of problems with sample collection or storage.**

[b]**One or two values were <LOQ.**

Source: University of California, Davis

Table 8: Results of Ammonia Analysis
Point Loma, East Bay Municipal Utility District, Brea, and Yolo

Parameter	LOQ (ppbv)	CNG	Point Loma Raw	Point Loma Clean	EBMUD Raw	EBMUD Clean	Brea Raw	Brea Clean	Yolo Raw	Yolo Clean
Ammonia	100	<LOQ	<LOQ	<LOQ	13700± 2750	2450± 3000	<LOQ	<LOQ	732± 1270	<LOQ

All results in ppbv, uncertainty is 1 standard deviation.

Source: University of California, Davis

Table 9: Results of Ammonia Analysis
Zero Waste Energy Development, CR&R, and Blue Line

Parameter	LOQ (ppbv)	CNG	ZWSJ Raw	ZWSJ Clean	CR&R Raw	CR&R Clean	Blue Line Clean
Ammonia	100	<LOQ	90200± 99000	3390± 4780	28200± 16900	214± 371	<LOQ

All results in ppbv, uncertainty is 1 standard deviation.

Source: University of California, Davis

Table 10: Results of Extended Hydrocarbon Analysis
Point Loma, East Bay Municipal Utility District, Brea, and Yolo

Parameter	LOQ (ppbv)	CNG	Point Loma Raw[a]	Point Loma Clean	EBMUD Raw	EBMUD Clean	Brea Raw	Brea Clean[a]	Yolo Raw	Yolo Clean
Cyclopentane	1.87	41600± 358	<LOQ	<LOQ	<LOQ	19.7± 34.1[b]	3670± 354	381± 122	135± 37.2	134± 39.5
Methylcyclo-pentane	1.87	19300± 105	<LOQ	2.58± 0.262	<LOQ	<LOQ	51.1± 8.49	65.4± 8.42	59.2± 56.9	80.1± 88.7
Cyclohexane	1.87	58200± 408	<LOQ	<LOQ	2.56± 4.43[b]	<LOQ	190± 54.1	343± 59.1	201± 139	198± 140
Methylcyclo-hexane	1.87	179000± 1000	<LOQ	<LOQ	37.6± 57.2[b]	<LOQ	365± 61	538± 144	323± 253	315± 248
C2 Benzenes	5	11900± 32.4	50.6± 7.67	19.7± 6.05	111± 124[b]	<LOQ	1300± 128	164± 218[b]	983± 625	1260± 1140
C3 Benzenes	0.0080	5.02± 2.83[b]	3.45± 4.88	0.497± 0.195	36.9± 46.8	2.24± 3.88[b]	113± 4.69	2.2± 3.8[b]	201± 254	171± 206
C1 Naphthalenes	0.00656	<LOQ	1.44± 0.605	0.312± 0.101	<LOQ	<LOQ	12.9± 5.3	0.0208 ± 0.036[b]	8.21± 2.18	5.35± 4.58
C2 Naphthalenes	0.0119	<LOQ	0.115± 0.0618	<LOQ	0.0324± 0.0561[b]	<LOQ	1.06± 0.503	<LOQ	0.547± 0.23	0.245± 0.31[b]
Hexanes	1.87	63700± 330	23.2± 4.79	18.5± 1.39	111± 118	518± 865[b]	207± 39.2	245± 28.6	211± 152	220± 166
Heptanes	1.9	68800± 237	18.4± 0.51	4.05± 2.31	92.8± 71.6	<LOQ	387± 64	339± 294[b]	301± 159	293± 160
2,2,4-Trimethylpentane	1.87	1050± 27.8	37.9± 15.5	2.9± 0.236	10.3± 17.8[b]	<LOQ	162± 58.4	283± 210	136± 64.7	108± 28.7
Octanes	1.87	12800± 96.5	165± 106	1.3± 0.601[b]	133± 42.2	<LOQ	55.8± 5.68	144± 77.1	136± 66.1	114± 94.6
Nonanes	0.0291	2270± 6.61	26.7± 12.7	6.5± 1.58	93± 80.8[b]	<LOQ	492± 91.2	56± 73.1[b]	439± 441	404± 391
Decanes	0.00262	150± 2.58	23.1± 16.7	1.84± 0.136	117± 126[b]	<LOQ	300± 34.5	<LOQ	326± 361	323± 367
Undecanes	0.0119	45.5± 0.925	6.27± 8.86[b]	3.04± 1.3	168± 242[b]	<LOQ	83.3± 11.2	<LOQ	165± 228	149± 207

Parameter	LOQ (ppbv)	CNG	Point Loma Raw[a]	Point Loma Clean	EBMUD Raw	EBMUD Clean	Brea Raw	Brea Clean[a]	Yolo Raw	Yolo Clean
Dodecanes	0.00219	0.625± 0.184	<LOQ	1.73± 0.511	<LOQ	<LOQ	11.7± 3.4	<LOQ	19.4± 33.7[b]	19.4± 33.6[b]
Tridecanes	0.00219	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Tetradecanes	0.0094	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Pentadecanes	0.0094	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Hexadecanes	0.00165	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Heptadecanes	0.00165	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Octadecanes	0.00367	<LOQ	0.567± 0.0111	<LOQ	0.206± 0.19[b]	<LOQ	1.01± 1.02	0.0441 ± 0.0383[b]	1.07± 0.876	0.243± 0.371[b]
Nonadecanes	0.00367	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Eicosanes	0.0033	<LOQ	0.0451± 0.0327	<LOQ	0.0183± 0.0169[b]	<LOQ	0.0497± 0.0461[b]	0.0189 ± 0.0328[b]	0.0778± 0.0777[b]	0.0101 ± 0.0175[b]

All results in ppbv, uncertainty is 1 standard deviation.

[a]Average and standard deviation based on 2 samples because of problems with sample collection or storage.

[b]One or two values were <LOQ.

Source: University of California, Davis

Table 11: Results of Extended Hydrocarbon Analysis
Zero Waste Energy Development, CR&R, and Blue Line

Parameter	LOQ (ppbv)	CNG	ZWSJ Raw	ZWSJ Clean[a]	CR&R Raw	CR&R Clean	Blue Line Clean
Cyclopentane	1.87	41600± 358	110± 50.3	62.8± 11.5	<LOQ	<LOQ	9.64± 2.31
Methylcyclo-pentane	1.87	19300± 105	261± 418[b]	<LOQ	<LOQ	<LOQ	3.78± 0.823
Cyclohexane	1.87	58200± 408	80.8± 51.4	25.2± 1.65	<LOQ	<LOQ	6.8± 1.93
Methylcyclo-hexane	1.87	179000± 1000	29.2± 27.4	12.8± 0.0258	<LOQ	<LOQ	20.1± 7.04
C2 Benzenes	5	11900± 32.4	442± 508	92± 10	16± 13.9[b]	<LOQ	7.97± 1
C3 Benzenes	0.0080	5.02± 2.83[b]	48.7± 50.9	2.77± 3.91[b]	14.8± 12.9[b]	<LOQ	84.9± 44.4
C1 Naphthalenes	0.00656	<LOQ	10.8± 4.52	5.74± 3.38	3.63± 1.47	0.0612± 0.0537[b]	0.433± 0.162
C2 Naphthalenes	0.0119	<LOQ	0.79± 0.503	0.389± 0.156	0.24± 0.0382	<LOQ	<LOQ
Hexanes	1.87	63700± 330	763± 1320[b]	1860± 82.6	<LOQ	<LOQ	580± 119
Heptanes	1.9	68800± 237	56± 32	31.9± 3.92	215± 186	<LOQ	13.3± 3.54
2,2,4-Trimethylpentane	1.87	1050± 27.8	749± 1250	23.5± 2.24	135± 119[b]	<LOQ	1.46± 0.906[b]
Octanes	1.87	12800± 96.5	51.8± 43.5	47± 15.4	8.53± 2.93	<LOQ	1.8± 0.751[b]
Nonanes	0.0291	2270± 6.61	233± 196	59.1± 7.15	33± 29.6[b]	<LOQ	4± 0.997
Decanes	0.00262	150± 2.58	89.8± 104	10.8± 1.8	<LOQ	<LOQ	1.53± 0.493
Undecanes	0.0119	45.5± 0.925	32.8± 49.3	<LOQ	39.2± 42.8	<LOQ	7.36± 3.94
Dodecanes	0.00219	0.625± 0.184	20.1± 22.5	7.5± 0.408	<LOQ	<LOQ	8.8± 2.3
Tridecanes	0.00219	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Tetradecanes	0.0094	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ

Parameter	LOQ (ppbv)	CNG	ZWSJ Raw	ZWSJ Clean[a]	CR&R Raw	CR&R Clean	Blue Line Clean
Pentadecanes	0.0094	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Hexadecanes	0.00165	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Heptadecanes	0.00165	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Octadecanes	0.00367	<LOQ	0.364± 0.236	0.162± 0.0917	0.17± 0.0326	0.0464± 0.0435[b]	<LOQ
Nonadecanes	0.00367	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Eicosanes	0.0033	<LOQ	0.0491± 0.0503[b]	<LOQ	0.0641± 0.0267	0.00763± 0.0132[b]	<LOQ

All results in ppbv, uncertainty is 1 standard deviation.

[a]Average and standard deviation based on 2 samples because of problems with sample collection or storage.

[b]One or two values were <LOQ.

Source: University of California, Davis

Table 12: Results of Sulfur Analysis
Point Loma, East Bay Municipal Utility District, Brea, and Yolo

Parameter	LOQ (ppbv)	CNG	Point Loma Raw	Point Loma Clean	EBMUD Raw	EBMUD Clean	Brea Raw	Brea Clean	Yolo Raw	Yolo Clean
Hydrogen Sulfide (in ppmv)	5.0	<LOQ	40.6± 17.2	<LOQ	393± 219	177± 154	53.2± 23.2	44.6± 42.2	48.6± 35.2	46.2± 33
Sulfur Dioxide	26.2	<LOQ	1110± 851	<LOQ	2360± 2600	2820± 3750	1900± 985	1550± 284	1180± 497	1040± 563
Carbonyl sulfide	15.2	<LOQ	18.9± 6.7	<LOQ	45.6± 63.5[a]	57.9± 70.6	71.7± 14.5	66.4± 17.4	27.5± 12.1	27.9± 13.5
Carbon disulfide	2.9	<LOQ	10.4± 14.7[a]	<LOQ	77.2± 90.6	86.8± 83.7	107± 38.3	115± 40.9	44.7± 27.5	37.1± 12.5
Methyl mercaptan	52.5	<LOQ	134± 189[a]	<LOQ	472± 397	396± 352[a]	8100± 1010	6440± 785	5310± 1550	4800± 1320
Ethyl mercaptan	7.8	<LOQ	56.4± 34.1	<LOQ	103± 58.7	53.5± 92.7[a]	<LOQ	42.1± 41.1[a]	46.2± 12.7	35± 1.82
Isopropyl mercaptan	4.9	<LOQ	17.1± 24.2	<LOQ	51± 72.1[a]	<LOQ	622± 219	21.2± 36.8[a]	401± 298	334± 198
n-Propyl mercaptan	4.3	<LOQ	<LOQ	<LOQ	328± 514[a]	<LOQ	98.7± 21.8	4.69± 8.12[a]	17.9± 22.7[a]	8.71± 8.08[a]
t-Butyl mercaptan	4.4	<LOQ	<LOQ	<LOQ	38.7± 37.6[a]	15.8± 27.4[a]	<LOQ	<LOQ	33.9± 58.8[a]	21.1± 36.5[a]
sec-Butyl mercaptan	4.9	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	29± 36.8[a]	21.2± 25.8[a]
Dimethyl sulfide	4.3	<LOQ	<LOQ	9.6± 0.853	13.3± 16.6[a]	93.5± 162[a]	1790± 173	2100± 1050	242± 141	232± 133
Methyl Ethyl sulfide	3.5	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Diethyl sulfide	5.7	<LOQ	<LOQ	<LOQ	5.97± 10.3[a]	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Di-tert-butyl sulfide	3.0	<LOQ	<LOQ	<LOQ	4.16± 7.2[a]	<LOQ	40.3± 35[a]	<LOQ	46.2± 20.4	45.8± 22.6
Dimethyl Disulfide	0.8	<LOQ	<LOQ	<LOQ	2.34± 4.06[a]	5.52± 9.56[a]	91.3± 39	119± 61.2	16± 20.4[a]	13.8± 19.2[a]

Parameter	LOQ (ppbv)	CNG	Point Loma Raw	Point Loma Clean	EBMUD Raw	EBMUD Clean	Brea Raw	Brea Clean	Yolo Raw	Yolo Clean
Diethyl Disulfide	1.1	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Thiofuran	3.0	<LOQ	<LOQ	<LOQ	8.57± 14.8[a]	<LOQ	<LOQ	<LOQ	5.3± 9.18[a]	4.81± 8.33[a]
Methyl ethyl disulfide	10.0	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Methyl i-propyl disulfide	10.0	<LOQ	<LOQ	39.8± 12.8	<LOQ	<LOQ	<LOQ	6.16± 10.7[a]	<LOQ	<LOQ
Methyl n-propyl disulfide	10.0	<LOQ	<LOQ	174± 32.2	10.9± 18.9[a]	<LOQ	12.6± 2.94	<LOQ	7.48± 12.9[a]	6.38± 11[a]
Methyl t-butyl disulfide	10.0	169± 4.06	<LOQ	<LOQ	49± 65[a]	<LOQ	194± 38	10.6± 13[a]	130± 124	120± 113
Ethyl i-propyl disulfide	10.0	<LOQ	<LOQ	41.7± 5.16	19.7± 34.1[a]	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Ethyl n-propyl disulfide	10.0	<LOQ	<LOQ	26.8± 2.38	21.8± 37.8[a]	<LOQ	62.8± 3.41	<LOQ	16.3± 7.9	13.8± 5.03[a]
Ethyl t-butyl disulfide	10.0	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	6.8± 11.8[a]	5.28± 9.14[a]
Di-i-propyl disulfide	10.0	<LOQ	<LOQ	14.2± 0.972	<LOQ	<LOQ	<LOQ	<LOQ	6.77± 11.7[a]	5.19± 9[a]
i-Propyl n-propyl disulfide	10.0	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	19.7± 34[a]	<LOQ
Di-n-propyl disulfide	10.0	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
i-Propyl t-butyl disulfide	10.0	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
n-Propyl t-butyl disulfide	10.0	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Di-t-butyl disulfide	10.0	77.9± 0.575	<LOQ	<LOQ	3.95± 6.84[a]	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Dimethyl trisulfide	0.007	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	3.33± 5.76[a]	<LOQ
Diethyl trisulfide	0.007	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ

Parameter	LOQ (ppbv)	CNG	Point Loma Raw	Point Loma Clean	EBMUD Raw	EBMUD Clean	Brea Raw	Brea Clean	Yolo Raw	Yolo Clean
Di-t-butyl trisulfide	0.007	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Thiophene	10	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	20.9± 4.01	31.6± 8.6	17.2± 14.7[a]	14.4± 11.9[a]
C1-Thiophenes	10	<LOQ	29± 12	<LOQ	12.7± 3.51[a]	<LOQ	57± 76.6	72.1± 60.5[a]	7.97± 6.22[a]	<LOQ
C2-Thiophenes A	0.017	<LOQ	5.32± 0.841	<LOQ	4.49± 0.5	<LOQ	3.39± 1.54	0.767± 0.643	1.54± 0.344	1.73± 0.269
C2-Thiophenes B	0.017	0.284± 0.169	0.679± 0.115	<LOQ	0.352± 0.161	<LOQ	1.1± 0.397	0.315± 0.201	0.781± 0.438	0.82± 0.414
C3-Thiophenes	0.007	<LOQ	1.08± 0.162	<LOQ	3.15± 1.51	<LOQ	0.345± 0.387[a]	0.0183± 0.0317[a]	0.455± 0.171	0.505± 0.134
Benzothiophene	0.007	<LOQ	0.0604± 0.035[a]	<LOQ	0.0221± 0.0382[a]	<LOQ	2.13± 1.89	0.0327± 0.0567[a]	2.19± 0.858	2.25± 0.346
C1-Benzothiophenes	0.063	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.426± 0.264	<LOQ	0.238± 0.0919	0.222± 0.05
C2-Benzothiophenes	0.006	<LOQ	0.00671 ± 0.015[a]	<LOQ	<LOQ	<LOQ	0.371± 0.256	0.0231± 0.0177	0.164± 0.0529	0.0773± 0.0819[a]
Thiophane	10	5560± 50.3	<LOQ	12.2± 0.977	<LOQ	<LOQ	601± 114	<LOQ	123± 122	115± 107
Thiophenol	10	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ

All results in ppbv unless otherwise noted, uncertainty is 1 standard deviation.[a]one or two values were <LOQ.

Source: University of California, Davis

Table 13: Results of Sulfur Analysis
Zero Waste Energy Development, CR&R, and Blue Line

Parameter	LOQ (ppbv)	CNG	ZWSJ Raw	ZWSJ Clean	CR&R Raw	CR&R Clean	Blue Line Clean
Hydrogen Sulfide (in ppmv)	5.0	<LOQ	196± 71.8	29.3± 41.5	29.9± 22.3	<LOQ	NM
Sulfur Dioxide	26.2	<LOQ	2770± 1060	182± 26.9	3610± 3790	158± 139	499± 241
Carbonyl sulfide	15.2	<LOQ	666± 278	267± 47.1	72.6± 55.2[a]	<LOQ	<LOQ
Carbon disulfide	2.9	<LOQ	838± 750[a]	607± 3.99	117± 135[a]	<LOQ	24.7± 1
Methyl mercaptan	52.5	<LOQ	18200± 3020	2270± 228	785± 591	<LOQ	409± 38.3
Ethyl mercaptan	7.8	<LOQ	365± 179	58.3± 18.5	12.3± 21.3[a]	<LOQ	<LOQ
Isopropyl mercaptan	4.9	<LOQ	621± 982	55.4± 6.93	<LOQ	<LOQ	<LOQ
n-Propyl mercaptan	4.3	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
t-Butyl mercaptan	4.4	<LOQ	15.1± 26.2[a]	<LOQ	<LOQ	<LOQ	1350± 191
sec-Butyl mercaptan	4.9	<LOQ	1760± 333	303± 119	<LOQ	<LOQ	<LOQ
Dimethyl sulfide	4.3	<LOQ	676± 229	504± 40.1	156± 175[a]	<LOQ	70.1± 9.44
Methyl Ethyl sulfide	3.5	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	1220± 149
Diethyl sulfide	5.7	<LOQ	83.7± 87.7	32.7± 5.53	<LOQ	<LOQ	<LOQ
Di-tert-butyl sulfide	3.0	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Dimethyl Disulfide	0.8	<LOQ	348± 161	615± 484	3.52± 6.1[a]	<LOQ	<LOQ
Diethyl Disulfide	1.1	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ

Parameter	LOQ (ppbv)	CNG	ZWSJ Raw	ZWSJ Clean	CR&R Raw	CR&R Clean	Blue Line Clean
Thiofuran	3.0	<LOQ	7.6± 13.2[a]	<LOQ	<LOQ	<LOQ	<LOQ
Methyl ethyl disulfide	10.0	<LOQ	10.7± 9.28[a]	22.5± 22.4[a]	<LOQ	<LOQ	<LOQ
Methyl i-propyl disulfide	10.0	<LOQ	43.3± 12	80.9± 27.1	<LOQ	<LOQ	85.8± 22.4
Methyl n-propyl disulfide	10.0	<LOQ	47.9± 62.1[a]	26± 36.8[a]	20.1± 15.7[a]	<LOQ	99.2± 17.2
Methyl t-butyl disulfide	10.0	169± 4.06	184± 153	70.2± 7.1	189± 169[a]	<LOQ	15.5± 5.56
Ethyl i-propyl disulfide	10.0	<LOQ	99.5± 123	13± 1.65	14± 13.3[a]	<LOQ	25.2± 5.29
Ethyl n-propyl disulfide	10.0	<LOQ	53.8± 61.8	<LOQ	92.9± 89.8[a]	<LOQ	19.6± 5.11
Ethyl t-butyl disulfide	10.0	<LOQ	6.94± 12[a]	<LOQ	<LOQ	<LOQ	<LOQ
Di-i-propyl disulfide	10.0	<LOQ	6.94± 12[a]	<LOQ	<LOQ	<LOQ	20.9± 7.34
i-Propyl n-propyl disulfide	10.0	<LOQ	7.81± 13.5[a]	<LOQ	<LOQ	<LOQ	<LOQ
Di-n-propyl disulfide	10.0	<LOQ	9.45± 16.4[a]	<LOQ	<LOQ	<LOQ	<LOQ
i-Propyl t-butyl disulfide	10.0	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
n-Propyl t-butyl disulfide	10.0	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Di-t-butyl disulfide	10.0	77.9± 0.575	<LOQ	<LOQ	<LOQ	<LOQ	51.8± 17.3
Dimethyl trisulfide	0.007	<LOQ	<LOQ	7.45± 10.5[a]	<CRQ	<LOQ	<LOQ
Diethyl trisulfide	0.007	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Di-t-butyl trisulfide	0.007	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ

Parameter	LOQ (ppbv)	CNG	ZWSJ Raw	ZWSJ Clean	CR&R Raw	CR&R Clean	Blue Line Clean
Thiophene	10	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
C1-Thiophenes	10	<LOQ	32.3± 32.3[a]	14.1± 3.35	74.3± 52.3	<LOQ	60.5± 21.2
C2-Thiophenes A	0.017	<LOQ	3.25± 1.37	3.53± 1.05	8.72± 1.87	<LOQ	4.18± 0.877
C2-Thiophenes B	0.017	0.284± 0.169	0.777± 0.239	0.775± 0.452	1.34± 0.493	<LOQ	0.688± 0.304
C3-Thiophenes	0.007	<LOQ	0.64± 0.196	0.624± 0.352	2.51± 0.354	<LOQ	0.593± 0.168
Benzothiophene	0.007	<LOQ	0.181± 0.0572	0.107± 0.0716	1.86± 0.134	<LOQ	<LOQ
C1-Benzothiophenes	0.063	<LOQ	0.061± 0.018[a]	<LOQ	0.0721± 0.125[a]	<LOQ	<LOQ
C2-Benzothiophenes	0.006	<LOQ	0.309± 0.12	<LOQ	<LOQ	<LOQ	<LOQ
Thiophane	10	5560± 50.3	14.9± 25.8[a]	<LOQ	<LOQ	<LOQ	14.5± 4.09
Thiophenol	10	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ

All results in ppbv unless otherwise noted, uncertainty is 1 standard deviation.[a]one or two values were <LOQ.

Source: University of California, Davis

Table 14: Results of Halocarbon and VOC Analysis
Point Loma, East Bay Municipal Utility District, Brea, and Yolo

Parameter	LOQ (ppbv)	CNG	Point Loma Raw[a]	Point Loma Clean	EBMUD Raw	EBMUD Clean	Brea Raw	Brea Clean	Yolo Raw	Yolo Clean
Dichlorodifluoromethane	6.0	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	117± 49	102± 47.1	157± 88.5	152± 89.5
1,2-dichloro-1,1,2,2-tetrafluoroethane	0.9	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	10.7± 4.87	10.4± 5.46	23.5± 16.3	28.4± 24.9
1,1,2-trichloro-1,2,2-trifluoroethane	2.2	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Trichlorofluoromethane	1.4	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	18.2± 12.5	18.6± 14.8	8.07± 4.5	8.17± 4.85
Methylene chloride	1.7	<LOQ	<LOQ	<LOQ	2.8± 4.85	2.11± 3.66[b]	76.3± 5.66	87.4± 11.1	18.2± 8.82	17.6± 8.25
Chloroform	2.2	<LOQ	<LOQ	<LOQ	<LOQ	4.51± 7.82[b]	<LOQ	<LOQ	<LOQ	<LOQ
Carbon Tetrachloride	2.3	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	24.7± 8.29	<LOQ	<LOQ	<LOQ
Chloroethane	11.7	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	65.2± 22.3	57.6± 21.4
1,1-dichloroethane	2.1	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	10.1± 2.01	16± 5.38	4.2± 3.02[b]	4.09± 2.97[b]
1,2-Dichloroethane	0.04	<LOQ	<LOQ	<LOQ	22.8± 25.8[b]	<LOQ	1330± 51.9	1480± 510	718± 133	713± 126
1,1,1-trichloroethane	2.8	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,1,2-trichloroethane	3.7	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,1,1,2-tetrachloroethane	3.9	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	15.1± 3.43	2.24± 3.88[b]	11.7± 9.84	10.8± 8.59
1,1,2,2-tetrachloroethane	2.4	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Chloroethene	2.4	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	29.2± 13.4	28.4± 4.46	129± 29	125± 32.2
1,1-dichloroethene	1.5	<LOQ	<LOQ	<LOQ	1.89± 3.28[b]	13.6± 23.5[b]	259± 26.1	304± 156	36.3± 20.8	34.9± 19.2
cis-1,2-Dichloroethene	2.6	<LOQ	<LOQ	<LOQ	10± 12.4[b]	18.5± 32[b]	35± 11.8	73.8± 17.9	56.9± 41.2	55.1± 39.7

Parameter	LOQ (ppbv)	CNG	Point Loma Raw[a]	Point Loma Clean	EBMUD Raw	EBMUD Clean	Brea Raw	Brea Clean	Yolo Raw	Yolo Clean
Trans-1,2-dichloroethene	1.7	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	11.6± 1.52	19.6± 10.5	17.9± 8.81
Trichloroethene	4.7	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	25.2± 3.44	34.9± 6.37	22.5± 20.7	21.7± 19.7
Tetrachloroethene	3.8	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	33.3± 5.04	43.1± 24.3	27± 27.6	24.9± 24.5
1,2-dichloropropane	2.8	<LOQ	<LOQ	<LOQ	2.33± 2.69[b]	<LOQ	14± 3.11	10.1± 9.24[b]	2.37± 4.11[b]	2.31± 4[b]
2,2-dichloropropane	2.3	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	16.9± 5.14	<LOQ	<LOQ	<LOQ
1,2,3-trichloropropane	199.1	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
3-chloropropene	10.3	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,1-Dichloropropene	65.8	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
cis-1,3-dichloropropene	1.9	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
trans-1,3-dichloropropene	1.4	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,1,2,3,4,4-hexachloro-1,3-Butadiene	2.9	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Chlorobenzene	3.0	<LOQ	<LOQ	<LOQ	12.5± 11.6	<LOQ	16.4± 0.885	6.05± 5.75[b]	21.7± 19.5	19.9± 17.3
1,2-dichlorobenzene	3.3	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	3.92± 0.062	<LOQ	5.67± 3.29	5.21± 2.55
1,3-dichlorobenzene	1.3	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,4-Dichlorobenzene	1.5	<LOQ	<LOQ	<LOQ	2.86± 4.95[b]	<LOQ	14.9± 1.08	<LOQ	42.1± 56.4	34.6± 43.8
1,2,3-Trichlorobenzene	3.4	<LOQ	<LOQ	<LOQ	5.42± 9.39[b]	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,2,4-trichlorobenzene	1.8	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
2-Chlorotoluene	2.7	<LOQ	<LOQ	<LOQ	5.49± 5.85[b]	<LOQ	12.7± 3.1	<LOQ	24.1± 27.1	20.3± 20.7
4-Chlorotoluene	1.8	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	2.19± 3.8[b]	<LOQ	4.93± 8.53[b]	3.74± 6.48[b]
Bromomethane	4.6	<LOQ	<LOQ	<LOQ	<LOQ	2.22± 3.84[b]	3.2± 5.55[b]	2.11± 3.45[b]	<LOQ	<LOQ

Parameter	LOQ (ppbv)	CNG	Point Loma Raw[a]	Point Loma Clean	EBMUD Raw	EBMUD Clean	Brea Raw	Brea Clean	Yolo Raw	Yolo Clean
dibromomethane	4.4	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Bromoform	2.1	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
bromochloromethane	4.0	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
bromodichloromethane	2.4	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
dibromochloromethane	2.7	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,2-dibromoethane	2.3	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Bromochloroethane	2.3	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,2-dibromo-3-chloropropane	3.0	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
bromobenzene	2.1	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,3-Butadiene	1.0	5730± 64.8	<LOQ	<LOQ	<LOQ	2.36± 4.09[b]	36.5± 33.8[b]	33.1± 30.6[b]	<LOQ	<LOQ
Benzene	8.5	13800± 16.9	<LOQ	<LOQ	18.4± 20.5[b]	<LOQ	289± 68.5	429± 247	164± 110	161± 108
Toluene	4.1	42200± 115	49.2± 8.23	6.15 ± 2.47	251± 288	<LOQ	<LOQ	279± 421[b]	288± 260[b]	279± 250[b]
Ethylbenzene	3.4	1670± 10.7	42.3± 6.93	<LOQ	44.4± 39.1	<LOQ	419± 41.4	62.6± 84.6[b]	158± 138[b]	488± 453
m,p-Xylene	3.1	8840± 20.5	8.29± 0.744	<LOQ	58.1± 52.8	<LOQ	688± 80.5	81± 106[b]	568± 470	533± 433
o-Xylene	3.0	1440± 16.7	<LOQ	<LOQ	20.3± 17.7	<LOQ	193± 20.9	20.4± 27.2[b]	258± 290	234± 254
Styrene	2.8	<LOQ	15.6± 13	<LOQ	2.34± 4.06[b]	<LOQ	36.3± 8.4	15± 19.8[b]	52.2± 60.8	45.3± 49.4
Isopropylbenzene	2.8	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	34.3± 2.76	2.2± 3.8[b]	54.6± 62.2	48± 52.1
4-Ethyltoluene	1.9	<LOQ	<LOQ	<LOQ	7.04± 6.81[b]	<LOQ	21.1± 1.53	<LOQ	29± 34	25.5± 28.6
n-Propylbenzene	2.5	<LOQ	<LOQ	<LOQ	19.7± 11.6	<LOQ	59.2± 7.47	8.62± 14.9[b]	64.6± 74.2	57.3± 63.3
1,3,5-trimethylbenzene	2.5	240± 18	<LOQ	<LOQ	9.81± 11.3[b]	<LOQ	28.4± 1.37	<LOQ	46.5± 56.5	39.3± 44.9
tert-butylbenzene	2.6	<LOQ	<LOQ	<LOQ	5.64± 9.78[b]	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ

Parameter	LOQ (ppbv)	CNG	Point Loma Raw[a]	Point Loma Clean	EBMUD Raw	EBMUD Clean	Brea Raw	Brea Clean	Yolo Raw	Yolo Clean
1,2,4-trimethylbenzene	6.1	446± 71.8	3.45± 4.88[b]	<LOQ	19.4± 22.1[b]	2.24± 3.88[b]	57.3± 0.507	<LOQ	102± 132	85.8± 105
s-Butylbenzene	1.5	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	14.3± 0.568	<LOQ	11± 19.1[b]	9.44± 16.3[b]
p-Isopropyltoluene	472.8	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	295± 384[b]	242± 305[b]
n-butylbenzene	10.8	<LOQ	<LOQ	<LOQ	4.53± 7.85[b]	<LOQ	<LOQ	<LOQ	6.31± 10.9[b]	5.33± 9.23[b]
Naphthalene	6.1	<LOQ	<LOQ	<LOQ	4.16± 7.21[b]	<LOQ	<LOQ	<LOQ	11.2± 19.3[b]	9.47± 16.4[b]
Pyridine	5.0	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Nitrobenzene	0.076	<LOQ	4.79± 2.69	<LOQ	5.68± 3.89	0.131± 0.125[b]	1.83± 3.17[b]	1.31± 2.27[b]	4.71± 4.16[b]	4.26± 3.73[b]

All results in ppbv, uncertainty is 1 standard deviation.

[a]Average and standard deviation based on two samples because of problems with sample collection or storage.

[b]One or two values were <LOQ.

Source: University of California, Davis

Table 15: Results of Halocarbon and VOC Analysis
Zero Waste Energy Development, CR&R, and Blue Line

Parameter	LOQ (ppbv)	CNG	ZWSJ Raw	ZWSJ Clean[a]	CR&R Raw	CR&R Clean	Blue Line Clean
Dichlorodifluoromethane	6.0	<LOQ	7.69± 9.35[b]	<LOQ	<LOQ	<LOQ	<LOQ
1,2-dichloro-1,1,2,2-tetrafluoroethane	0.9	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,1,2-trichloro-1,2,2-trifluoroethane	2.2	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Trichlorofluoromethane	1.4	<LOQ	51.8± 71.6	8.63± 0.998	<LOQ	<LOQ	<LOQ
Methylene chloride	1.7	<LOQ	17.2± 12.3	10.5± 1.23	<LOQ	<LOQ	<LOQ
Chloroform	2.2	<LOQ	1.71± 2.96[b]	<LOQ	<LOQ	<LOQ	<LOQ
Carbon Tetrachloride	2.3	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Chloroethane	11.7	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,1-dichloroethane	2.1	<LOQ	2.7± 4.68[b]	<LOQ	<LOQ	<LOQ	<LOQ
1,2-Dichloroethane	0.04	<LOQ	535± 91.2	460± 57.6	159± 153[b]	<LOQ	<LOQ
1,1,1-trichloroethane	2.8	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,1,2-trichloroethane	3.7	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,1,1,2-tetrachloroethane	3.9	<LOQ	14.3± 11.9	3.1± 4.38[b]	<LOQ	<LOQ	<LOQ
1,1,2,2-tetrachloroethane	2.4	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Chloroethene	2.4	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,1-dichloroethene	1.5	<LOQ	93.9± 30.7	70.3± 5.27	22.4± 25.2[b]	<LOQ	<LOQ
cis-1,2-Dichloroethene	2.6	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Trans-1,2-dichloroethene	1.7	<LOQ	13.4± 23.3[b]	3.59± 5.07[b]	<LOQ	<LOQ	<LOQ
Trichloroethene	4.7	<LOQ	3.82± 6.61[b]	<LOQ	<LOQ	<LOQ	<LOQ
Tetrachloroethene	3.8	<LOQ	22.2± 33.8[b]	<LOQ	<LOQ	<LOQ	<LOQ
1,2-dichloropropane	2.8	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
2,2-dichloropropane	2.3	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,2,3-trichloropropane	199.1	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
3-chloropropene	10.3	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,1-Dichloropropene	65.8	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ

Parameter	LOQ (ppbv)	CNG	ZWSJ Raw	ZWSJ Clean[a]	CR&R Raw	CR&R Clean	Blue Line Clean
cis-1,3-dichloropropene	1.9	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
trans-1,3-dichloropropene	1.4	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,1,2,3,4,4-hexachloro-1,3-Butadiene	2.9	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Chlorobenzene	3.0	<LOQ	2.04± 3.53[b]	<LOQ	<LOQ	<LOQ	<LOQ
1,2-dichlorobenzene	3.3	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,3-dichlorobenzene	1.3	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,4-Dichlorobenzene	1.5	<LOQ	36.4± 48.2	3.44± 4.87[b]	<LOQ	<LOQ	<LOQ
1,2,3-Trichlorobenzene	3.4	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,2,4-trichlorobenzene	1.8	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
2-Chlorotoluene	2.7	<LOQ	3.22± 5.58[b]	<LOQ	<LOQ	<LOQ	<LOQ
4-Chlorotoluene	1.8	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Bromomethane	4.6	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
dibromomethane	4.4	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Bromoform	2.1	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
bromochloromethane	4.0	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
bromodichloromethane	2.4	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
dibromochloromethane	2.7	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,2-dibromoethane	2.3	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Bromochloroethane	2.3	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,2-dibromo-3-chloropropane	3.0	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
bromobenzene	2.1	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,3-Butadiene	1.0	5730± 64.8	<LOQ	<LOQ	<LOQ	<LOQ	47.09 ± 5.63
Benzene	8.5	13800± 16.9	17.8± 8.65	13.3± 0.87	7.9± 6.98[b]	<LOQ	<LOQ
Toluene	4.1	42200± 115	249± 259	80.1± 21.1	46.5± 44[b]	<LOQ	12.93 ± 3.92
Ethylbenzene	3.4	1670± 10.7	189± 195	49.1± 8.51	10.1± 8.76[b]	<LOQ	<LOQ
m,p-Xylene	3.1	8840± 20.5	208± 270	31.6± 0.997	5.88± 5.35[b]	<LOQ	7.97 ± 1.0
o-Xylene	3.0	1440± 16.7	44.3± 43.1	11.3± 0.532	<LOQ	<LOQ	<LOQ

Parameter	LOQ (ppbv)	CNG	ZWSJ Raw	ZWSJ Clean[a]	CR&R Raw	CR&R Clean	Blue Line Clean
Styrene	2.8	<LOQ	49.5± 54.4	12.2± 3.31	5.39± 9.34[b]	10.3± 17.8[b]	<LOQ
Isopropylbenzene	2.8	<LOQ	5.94± 10.3[b]	<LOQ	<LOQ	<LOQ	<LOQ
4-Ethyltoluene	1.9	<LOQ	5.74± 9.95[b]	<LOQ	<LOQ	<LOQ	<LOQ
n-Propylbenzene	2.5	<LOQ	45.8± 43.3	9.15± 0.576	54.3± 54.5[b]	<LOQ	9.24 ± 0.85
1,3,5-trimethylbenzene	2.5	240± 18	8.39± 9.78[b]	<LOQ	<LOQ	<LOQ	<LOQ
tert-butylbenzene	2.6	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,2,4-Trimethylbenzene	6.1	446± 71.8	21.9± 20.4	<LOQ	8.91± 7.86[b]	<LOQ	5.49 ± 0.21
s-Butylbenzene	1.5	<LOQ	2.42± 4.19b	<LOQ	15.2± 14.3[b]	<LOQ	<LOQ
p-Isopropyltoluene	472.8	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	154.76 ± 24.14
n-butylbenzene	10.8	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Naphthalene	6.1	<LOQ	3.39± 5.87[b]	<LOQ	<LOQ	<LOQ	<LOQ
Pyridine	5.0	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	3.96± 5.43[b]
Nitrobenzene	0.076	<LOQ	4.95± 6.57[b]	4.61± 6.51[b]	0.692± 0.933[b]	2.77± 4.8[b]	<LOQ

All results in ppbv, uncertainty is 1 standard deviation.

[a]Average and standard deviation based on two samples because of problems with sample collection or storage.

[b]One or two values were <LOQ.

Source: University of California, Davis

Table 16: Results of Aldehyde and Ketone Analysis
Point Loma, East Bay Municipal Utility District, Brea, and Yolo

Parameter	LOQ (ppbv)	CNG	Point Loma Raw	Point Loma Clean	EBMUD Raw[a]	EBMUD Clean	Brea Raw	Brea Clean	Yolo Raw	Yolo Clean
Formaldehyde	0.00621	3.42± 0.841	4.34± 0.252	4.79± 2.08	3.52± 0.368	5.15± 3.54	3.93± 1.94	1.61± 1.4	7.58± 0.766	9.98± 5.19
Acetaldehyde	0.000847	7.03± 1.53	14.8± 1.82	7.54± 1.97	14.9± 0.636	8.76± 2.96	201± 51.4	130± 97.1	120± 94.7	107± 77.4
Acetone	0.00321	<LOQ	2.49± 4.31[b]	240± 22	24.3± 13.2	64.4± 112[b]	1150± 236	134± 170[b]	450± 270	401± 211
Acrolein (2-propenal)	0.00333	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Propionaldehyde	0.00321	0.0298± 0.0516[b]	<LOQ	0.0157± 0.0272[b]	<LOQ	<LOQ	63.1± 19.2	18.2± 31.5[b]	38.4± 32	31.9± 25.5
Crotonaldehyde	0.0532	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
2-Butanone (MEK)	0.0259	2.01± 0.118	3.79± 2.74	9.52± 1.17	493± 57.5	1010± 1740	3490± 646	225± 245	1470± 428	1410± 243
Methacrolein (Isobutenal)	0.0532	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Butyraldehyde (Butanal)	0.00259	0.675± 0.19	<LOQ	2.31± 0.381	<LOQ	<LOQ	168± 59.8	20.1± 27.7[b]	43.8± 31	40.8± 28.1
Benzaldehyde	0.00176	0.16± 0.0116	1.07± 0.191	0.456± 0.252	0.711± 0.0531	0.467± 0.0362	2.22± 0.878	0.655± 0.184	2.42± 2.05	2.37± 1.7
Valeraldehyde (Pentanal)	0.00217	0.772± 0.263	<LOQ	3.08± 2.29	82.6± 15.7	<LOQ	478± 166	2.54± 2.75[b]	153± 116	135± 71.5
m,p-Tolualdehyde	0.00155	0.0208± 0.0361[b]	<LOQ	0.0663± 0.115[b]	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.0921± 0.16[b]
Hexanaldehyde (Hexanal)	0.000373	0.465± 0.34	0.887± 0.14	0.814± 0.408	1.56± 0.219	0.527± 0.292	5.81± 0.732	1.27± 0.755	4.24± 1.64	3.87± 2.31
2,5-Dimethyl-benzaldehyde	0.00278	<LOQ	<LOQ	0.177± 0.174[b]	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ

Parameter	LOQ (ppbv)	CNG	Point Loma Raw	Point Loma Clean	EBMUD Raw[a]	EBMUD Clean	Brea Raw	Brea Clean	Yolo Raw	Yolo Clean
Iso-valeraldehyde	0.000433	0.304± 0.0955	0.845± 0.283	0.67± 0.43	<LOQ	<LOQ	5.29± 1.98	0.337± 0.293[b]	3.75± 2.37	3.72± 3.41[b]
o-Tolualdehyde	0.00155	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ

All results in ppbv, uncertainty is 1 standard deviation. [a]Average and standard deviation based on 2 samples because of problems with sample collection or storage. [b]one or two values were <LOQ.

Source: University of California, Davis

Table 17: Results of Aldehyde and Ketone Analysis
Zero Waste Energy Development, CR&R, and Blue Line

Parameter	LOQ (ppbv)	CNG	ZWSJ Raw	ZWSJ Clean[a]	CR&R Raw	CR&R Clean	Blue Line Clean
Formaldehyde	0.00621	3.42± 0.841	6.86± 4.08	3.34± 4.72[b]	5.67± 0.585	7.2± 2.3	1.72± 0.459
Acetaldehyde	0.000847	7.03± 1.53	28.3± 11.8	46.5± 34.1	25.9± 18.4	12.8± 3.99	5.47± 0.298
Acetone	0.00321	<LOQ	2970± 890	1980± 352	58.7± 53.2[b]	<LOQ	<LOQ
Acrolein (2-propenal)	0.00333	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Propionaldehyde	0.00321	0.0298± 0.0516[b]	3.75± 6.49[b]	14.1± 20[b]	<LOQ	<LOQ	<LOQ
Crotonaldehyde	0.0532	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.333± 0.288[b]
2-Butanone (MEK)	0.0259	2.01± 0.118	6630± 568	5930± 720	697± 659	642± 1110	425± 28.2
Methacrolein (Isobutenal)	0.0532	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.333± 0.288[b]
Butyraldehyde (Butanal)	0.00259	0.675± 0.19	<LOQ	<LOQ	<LOQ	<LOQ	0.759± 0.389
Benzaldehyde	0.00176	0.16± 0.0116	4.72± 4.98	0.8± 0.0915	0.611± 0.0982	0.527± 0.0624	0.671± 0.13
Valeraldehyde (Pentanal)	0.00217	0.772± 0.263	322± 24.5	302± 2.03	151± 131[b]	63.5± 109[b]	171± 12.4
m,p-Tolualdehyde	0.00155	0.0208± 0.0361[b]	<LOQ	<LOQ	<LOQ	<LOQ	0.126± 0.0211
Hexanaldehyde (Hexanal)	0.000373	0.465± 0.34	0.203± 0.23[b]	1.61± 1.97	1.74± 1.36	2± 1.65	0.558± 0.254
2,5-Dimethyl-benzaldehyde	0.00278	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.0661± 0.058[b]
Iso-valeraldehyde	0.000433	0.304± 0.0955	<LOQ	<LOQ	<LOQ	0.661± 0.74[b]	<LOQ
o-Tolualdehyde	0.00155	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ

All results in ppbv, uncertainty is 1 standard deviation. [a]Average and standard deviation based on 2 samples because of problems with sample collection or storage. [b]one or two values were <LOQ.

Source: University of California, Davis

Table 18: Results of VOC, SVOC, and PAH Component Analysis
Point Loma, East Bay Municipal Utility District, Brea, and Yolo

Parameter	LOQ (ppbv)	CNG	Point Loma Raw	Point Loma Clean	EBMUD Raw	EBMUD Clean	Brea Raw	Brea Clean	Yolo Raw	Yolo Clean
N-nitroso-dimethylamine	1.260	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Phenol	5.0	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	2.66± 3.8[a]	<LOQ
Aniline	0.40	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Bis(2-Chloroethyl) ether	5.0	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
2-Chlorophenol	0.007	<LOQ	<LOQ	<LOQ	0.2± 0.182[a]	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Benzyl Alcohol	5.0	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
2-methylphenol	0.017	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.102± 0.177[a]	0.303± 0.525[a]	<LOQ
bis(2-chloro-isopropyl)ether	0.055	<LOQ	<LOQ	<LOQ	0.213± 0.37	<LOQ	0.137± 0.237[a]	0.0713± 0.124[a]	0.298± 0.26[a]	0.34± 0.197
N-Nitroso-di-n-propylamine	0.029	<LOQ	<LOQ	<LOQ	0.575± 0.996[a]	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
3-methylphenol	0.017	<LOQ	0.11± 0.108[a]	<LOQ	1.63± 1.94[a]	<LOQ	0.927± 0.697	0.384± 0.336	2.42± 1.92	0.865± 0.78
4-methylphenol	0.003	<LOQ	0.0625± 0.0355[a]	<LOQ	0.231± 0.0766[a]	<LOQ	0.18± 0.157[a]	<LOQ	0.332± 0.00579	0.203± 0.176[a]
Isophorone	0.027	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.112± 0.162[a]	<LOQ	0.0981± 0.111[a]	0.0205± 0.0198[a]
2-nitrophenol	0.013	<LOQ	<LOQ	<LOQ	0.203± 0.352[a]	<LOQ	0.151± 0.161[a]	<LOQ	0.24± 0.208[a]	0.225± 0.195[a]
2,4-dimethyl-phenol	0.031	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.2± 0.346[a]	<LOQ

Parameter	LOQ (ppbv)	CNG	Point Loma Raw	Point Loma Clean	EBMUD Raw	EBMUD Clean	Brea Raw	Brea Clean	Yolo Raw	Yolo Clean
Bis(2-chloro-ethoxy)methane	0.011	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
2,4-dichlorophenol	0.057	<LOQ	0.0861± 0.193[a]	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
4-Chloroaniline	0.029	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
4-chloro-3-methylphenol	0.003	<LOQ	0.0368± 0.0822[a]	<LOQ	<LOQ	<LOQ	0.522± 0.167[a]	<LOQ	0.363± 0.0346	0.223± 0.2[a]
2-methyl-naphthalene	0.013	<LOQ	1.65± 0.81	0.394± 0.14	0.316± 0.464[a]	<LOQ	9.66± 3.57	0.0536± 0.0365	9.13± 2.08	6.12± 5.09
1-methyl-naphthalene	0.003	<LOQ	0.946± 0.561	<LOQ	<LOQ	<LOQ	10.5± 2.71[a]	<LOQ	6.5± 1.13	4.07± 3.46
Hexachloro-cyclopentadiene	0.014	<LOQ	0.0487± 0.0273[a]	0.148± 0.128[a]	0.0196± 0.0339[a]	<LOQ	0.00121± 0.00209	<LOQ	0.0385± 0.0333[a]	0.0389± 0.0337[a]
2,4,6-trichloro-phenol	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM
2,4,5-trichloro-phenol	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM
2-chloro-naphthalene	0.006	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.0133± 0.023[a]	<LOQ	0.0401± 0.0484[a]	<LOQ
2-Nitroaniline	0.068	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,4-dinitro-benzene	0.222	<LOQ	0.13± 0.29[a]	<LOQ	0.23± 0.398[a]	<LOQ	<LOQ	<LOQ	0.223± 0.387[a]	<LOQ
Dimethyl phthalate	0.048	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,3-dinitro-benzene	0.222	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ

Parameter	LOQ (ppbv)	CNG	Point Loma Raw	Point Loma Clean	EBMUD Raw	EBMUD Clean	Brea Raw	Brea Clean	Yolo Raw	Yolo Clean
2,6-dinitro-toluene	0.102	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Acenaphthylene	0.002	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.0157 ± 0.0272	<LOQ	0.0101± 0.0175[a]	<LOQ
1,2-dinitro-benzene	0.555	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
3-Nitroaniline	0.068	<LOQ	0.0718± 0.161[a]	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Acenaphthene	0.006	<LOQ	0.0888± 0.107[a]	<LOQ	0.0963± 0.131[a]	<LOQ	4.48± 2.01[a]	<LOQ	1.35± 0.55	0.652± 0.749
2,4-dinitro-phenol	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM
4-nitrophenol	0.671	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Dibenzofuran	0.011	<LOQ	0.0472± 0.0718[a]	<LOQ	0.0918± 0.0799[a]	<LOQ	1.88± 1.12[a]	<LOQ	0.537± 0.274	0.273± 0.311
2,4-dinitro-toluene	0.102	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
2,3,4,6-Tetrachloro-phenol	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM
2,3,5,6-Tetrachloro-phenol	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM
Diethyl Phthalate	0.084	<LOQ	0.0759± 0.17[a]	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Fluorene	0.022	<LOQ	0.0493± 0.0765[a]	<LOQ	0.0956± 0.0828[a]	<LOQ	1.72± 1.16[a]	<LOQ	0.442± 0.24	0.228± 0.245
4-chlorophenyl phenyl ether	0.009	<LOQ	0.0293± 0.0402[a]	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
4-Nitroaniline	0.135	<LOQ	0.523± 0.0592	<LOQ	0.543± 0.134[a]	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ

Parameter	LOQ (ppbv)	CNG	Point Loma Raw	Point Loma Clean	EBMUD Raw	EBMUD Clean	Brea Raw	Brea Clean	Yolo Raw	Yolo Clean
4,6-dinitro-2-methylphenol	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM
Diphenylamine	0.011	<LOQ	<LOQ	<LOQ	0.0145± 0.0251[a]	<LOQ	0.186± 0.166[a]	<LOQ	0.122± 0.112	<LOQ
n-Nitroso-diphenylamine	N/A	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Azobenzene	0.021	<LOQ	<LOQ	<LOQ	0.168± 0.291	<LOQ	<LOQ	<LOQ	0.0983± 0.17[a]	0.0687± 0.119[a]
4-Bromophenyl phenyl ether	0.007	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.000305 ± 0.000529	<LOQ
Hexachloro-benzene	0.007	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.000892± 0.00155	<LOQ	0.000823 ± 0.00143	0.000643 ± 0.00111
Pentachloro-phenol	1.400	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Phenanthrene	0.021	<LOQ	0.0363± 0.0539[a]	<LOQ	<LOQ	<LOQ	0.982± 0.783[a]	<LOQ	0.221± 0.204[a]	0.0881± 0.147[a]
Anthracene	0.052	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.168± 0.146[a]	<LOQ	<LOQ	<LOQ
Carbazole	0.056	<LOQ	0.0204± 0.0456[a]	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Di-n-butyl phthalate	0.013	<LOQ	0.0096± 0.00754[a]	<LOQ	<LOQ	0.000362 ± 0.000627	0.0488 ± 0.0511[a]	0.0105± 0.00941[a]	0.0115± 0.00838[a]	0.0057± 0.00987[a]
Fluoranthene	0.005	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.00815± 0.0141	<LOQ	<LOQ	<LOQ
Pyrene	0.002	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.0054 ±	<LOQ	<LOQ	<LOQ

Parameter	LOQ (ppbv)	CNG	Point Loma Raw	Point Loma Clean	EBMUD Raw	EBMUD Clean	Brea Raw	Brea Clean	Yolo Raw	Yolo Clean
							0.00935			
Benzyl butyl phthalate	0.060	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Bis(2-ethyl-hexyl)adipate	0.025	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Benzo(a) anthracene	0.008	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Chrysene	0.008	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Bis(2-ethyl-hexyl)phthalate	0.048	0.116± 0.1	<LOQ	<LOQ	<LOQ	<LOQ	0.0048 ± 0.00831	<LOQ	<LOQ	<LOQ
Di-n-octyl phthalate	0.048	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Benzo(b) fluoranthene	0.037	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Benzo(k) fluoranthene	0.037	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Benzo(a)pyrene	0.037	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Indeno(1,2,3-cd)pyrene	0.135	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Dibenzo(a,h) anthracene	0.134	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Benzo[g,h,i) perylene	0.068	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ

All results in ppbv, uncertainty is 1 standard deviation).[a]Average and standard deviation based on 2 samples because of problems with sample collection or storage.

[b]One or two values were <LOQ.

Source: University of California, Davis

Table 19: Results of VOC, SVOC, and PAH Component Analysis
Zero Waste Energy Development, CR&R, and Blue Line

Parameter	LOQ (ppbv)	CNG	ZWSJ Raw	ZWSJ Clean[a]	CR&R Raw	CR&R Clean	Blue Line Clean
N-nitroso-dimethylamine	1.260	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Phenol	5.0	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Aniline	0.40	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Bis(2-Chloroethyl) ether	NM	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.77± 0.123
2-Chlorophenol	0.007	<LOQ	0.0603± 0.0624	0.0481± 0.068[b]	<LOQ	<LOQ	<LOQ
Benzyl Alcohol	5.0	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
2-methylphenol	0.017	<LOQ	<LOQ	<LOQ	<LOQ	0.0442± 0.0766[b]	<LOQ
bis(2-chloro-isopropyl)ether	0.055	<LOQ	<LOQ	0.0948± 0.134[b]	0.0673± 0.117[b]	<LOQ	<LOQ
N-Nitroso-di-n-propylamine	0.029	<LOQ	<LOQ	<LOQ	0.0889± 0.154[b]	0.0145± 0.0252[b]	<LOQ
3-methylphenol	0.017	<LOQ	1.38± 0.372	2.42± 3.42[b]	2.54± 0.502	<LOQ	<LOQ
4-methylphenol	0.003	<LOQ	0.382± 0.0731	0.444± 0.263	0.33± 0.0821	0.0357± 0.0618	<LOQ
Isophorone	0.027	<LOQ	0.144± 0.0342	0.0781± 0.00694	0.104± 0.0483	<LOQ	<LOQ
2-nitrophenol	0.013	<LOQ	0.104± 0.18[b]	<LOQ	<LOQ	<LOQ	<LOQ
2,4-dimethyl-phenol	0.031	<LOQ	<LOQ	0.189± 0.267[b]	<LOQ	<LOQ	<LOQ
Bis(2-chloro-ethoxy)methane	0.011	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
2,4-dichlorophenol	0.057	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
4-Chloroaniline	0.029	<LOQ	0.064± 0.111[b]	<LOQ	<LOQ	<LOQ	<LOQ
4-chloro-3-methylphenol	0.003	<LOQ	0.446± 0.143	0.304± 0.048	0.267± 0.022	<LOQ	<LOQ
2-methyl-naphthalene	0.013	<LOQ	9.68± 3.09	7.02± 3.33	5.05± 1.68	0.0727± 0.0686[b]	0.547± 0.183

Parameter	LOQ (ppbv)	CNG	ZWSJ Raw	ZWSJ Clean[a]	CR&R Raw	CR&R Clean	Blue Line Clean
1-methyl-naphthalene	0.003	<LOQ	8.56± 3.32	4.59± 2.1	3.15± 0.918	0.0629± 0.0613[b]	0.225± 0.234[b]
Hexachloro-cyclopentadiene	0.014	<LOQ	0.0403± 0.035[b]	0.0305± 0.0431[b]	<LOQ	<LOQ	0.236± 0.102
2,4,6-trichloro-phenol	NM	NM	NM	NM	NM	NM	NM
2,4,5-trichloro-phenol	NM	NM	NM	NM	NM	NM	NM
2-chloro-naphthalene	0.006	<LOQ	0.0316± 0.0548[b]	0.0128± 0.0181[b]	<LOQ	<LOQ	<LOQ
2-Nitroaniline	0.068	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,4-dinitro-benzene	0.222	<LOQ	<LOQ	<LOQ	0.719± 0.624[b]	<LOQ	<LOQ
Dimethyl phthalate	0.048	<LOQ	0.00126± 0.00219	<LOQ	<LOQ	<LOQ	<LOQ
1,3-dinitro-benzene	0.222	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
2,6-dinitro-toluene	0.102	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Acenaphthylene	0.002	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
1,2-dinitro-benzene	0.555	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
3-Nitroaniline	0.068	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Acenaphthene	0.006	<LOQ	0.111± 0.102[b]	0.0981± 0.0751	1.01± 0.339	<LOQ	<LOQ
2,4-dinitro-phenol	NM	NM	NM	NM	NM	NM	NM
4-nitrophenol	0.671	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.293± 0.508[b]
Dibenzofuran	0.011	<LOQ	0.0662± 0.0685[b]	0.0237± 0.016[b]	0.467± 0.182	0.0000785± 0.000136	<LOQ
2,4-dinitro-toluene	0.102	<LOQ	<LOQ	<LOQ	0.183± 0.159[b]	<LOQ	<LOQ
2,3,4,6-Tetrachloro-phenol	NM	NM	NM	NM	NM	NM	NM
2,3,5,6-Tetrachloro-phenol	NM	NM	NM	NM	NM	NM	NM
Diethyl Phthalate	0.084	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Fluorene	0.022	<LOQ	0.0805± 0.0778[b]	0.0187± 0.0265[b]	0.514± 0.179	<LOQ	<LOQ

Parameter	LOQ (ppbv)	CNG	ZWSJ Raw	ZWSJ Clean[a]	CR&R Raw	CR&R Clean	Blue Line Clean
4-chlorophenyl phenyl ether	0.009	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
4-Nitroaniline	0.135	<LOQ	<LOQ	0.265± 0.375[b]	<LOQ	<LOQ	<LOQ
4,6-dinitro-2-methylphenol	NM	NM	NM	NM	NM	NM	NM
Diphenylamine	0.011	<LOQ	0.0262± 0.0232[b]	<LOQ	0.00992± 0.0172	<LOQ	<LOQ
n-Nitroso-diphenylamine	N/A	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Azobenzene	0.021	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
4-Bromophenyl phenyl ether	0.007	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Hexachloro-benzene	0.007	<LOQ	<LOQ	<LOQ	0.000621± 0.00108	<LOQ	<LOQ
Pentachloro-phenol	1.400	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Phenanthrene	0.021	<LOQ	0.0203± 0.0259[b]	<LOQ	0.274± 0.146	<LOQ	<LOQ
Anthracene	0.052	<LOQ	<LOQ	<LOQ	0.0251± 0.0434[b]	<LOQ	<LOQ
Carbazole	0.056	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Di-n-butyl phthalate	0.013	<LOQ	0.0175± 0.0124[b]	<LOQ	0.102± 0.0266	0.0129± 0.0147[b]	<LOQ
Fluoranthene	0.005	<LOQ	<LOQ	<LOQ	0.00759± 0.0132[b]	<LOQ	<LOQ
Pyrene	0.002	<LOQ	<LOQ	<LOQ	0.00582± 0.0101[b]	<LOQ	<LOQ
Benzyl butyl phthalate	0.060	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Bis(2-ethyl-hexyl)adipate	0.025	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Benzo(a) anthracene	0.008	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Chrysene	0.008	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ

Parameter	LOQ (ppbv)	CNG	ZWSJ Raw	ZWSJ Clean[a]	CR&R Raw	CR&R Clean	Blue Line Clean
Bis(2-ethyl-hexyl)phthalate	0.048	0.116± 0.1	<LOQ	<LOQ	<LOQ	0.00208± 0.00359	<LOQ
Di-n-octyl phthalate	0.048	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Benzo(b) fluoranthene	0.037	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Benzo(k) fluoranthene	0.037	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Benzo(a)pyrene	0.037	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Indeno(1,2,3-cd)pyrene	0.135	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Dibenzo(a,h) anthracene	0.134	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Benzo[g,h,i] perylene	0.068	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ

All results in ppbv, uncertainty is 1 standard deviation).[a]Average and standard deviation based on 2 samples because of problems with sample collection or storage.

[b]One or two values were <LOQ.

Source: University of California, Davis

Table 20: Results of Organic Silicon Analysis
Point Loma, East Bay Municipal Utility District, Brea, and Yolo

Parameter	LOQ (ppbv)	CNG	Point Loma Raw	Point Loma Clean	EBMUD Raw	EBMUD Clean	Brea Raw	Brea Clean	Yolo Raw	Yolo Clean
1,1,3,3-Tetramethyldisiloxane	5	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Pentamethyldisiloxane	5	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Hexamethyldisilane	5	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Hexamethyldisiloxane (L2,MM)	5	<LOQ	22.9± 6.6	<LOQ	<LOQ	<LOQ	3240± 646	261± 400[b]	624± 456	583± 391
Octamethyltrisiloxane (L3, MOM)	0.04	<LOQ	5.44± 0.717	<LOQ	2.74± 1.12	<LOQ	16.4± 1.38	0.0328± 0.00904[b]	4.31± 1.08	3.09± 2.43
Octamethylcyclo-tetrasiloxane (04)	0.03	<LOQ	4.37± 4.41	<LOQ	6.52± 2.54	0.00327± 0.00566	20.4± 11.8	1.85± 2.5[b]	8.85± 4.05	6.33± 0.436
Decamethyltetrasiloxane (L4,MD2M)	0.03	<LOQ	2.7± 0.368	<LOQ	2.41± 0.804	0.0815± 0.0523	1.69± 0.8	<LOQ	1± 0.401	0.833± 0.67
Decamethylcyclo-pentasiloxane (OS)	0.03	0.111± 0.121[b]	11.2± 11.9	0.157± 0.128[b]	6.64± 3.55	<LOQ	10.7± 4.03	0.822± 0.669	8.65± 4.37	6.31± 0.168
Dodecamethylpenta-siloxane (LS,MD3M)	0.02	<LOQ	3.55± 0.693	<LOQ	2.7± 0.384	0.0352± 0.0349[b]	0.616± 0.284	<LOQ	0.311± 0.0572	0.235± 0.191
Dodecamethylcyclo-hexasiloxane (06)	0.04	<LOQ	6.31± 2.74	<LOQ	7.74± 1.22	<LOQ	5.18± 2.06	0.562± 0.494[b]	4.27± 0.835	3.72± 2.29

All results in ppbv, uncertainty is 1 standard deviation).[a]Average and standard deviation based on two samples because of problems with sample collection or storage.

[b]One or two values were <LOQ.

Source: University of California, Davis

Table 21: Results of Organic Silicon Analysis
Zero Waste Energy Development, CR&R, and Blue Line

Parameter	LOQ (ppbv)	CNG	ZWSJ Raw	ZWSJ Clean[a]	CR&R Raw	CR&R Clean	Blue Line Clean
1,1,3,3-Tetramethyldisiloxane	5	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Pentamethyldisiloxane	5	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Hexamethyldisilane	5	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Hexamethyldisiloxane (L2,MM)	5	<LOQ	171± 120	104± 12.8	5.67± 9.81[b]	<LOQ	<LOQ
Octamethyltrisiloxane (L3, MOM)	0.04	<LOQ	6.19± 1.31	4.7± 1.28	0.0332± 0.0102[b]	0.00635± 0.011	0.231± 0.0803
Octamethylcyclo-tetrasiloxane (04)	0.03	<LOQ	16.1± 17.9	6.58± 0.861	1.32± 0.26	0.057± 0.0863[b]	3.75± 0.552
Decamethyltetrasiloxane (L4,MD2M)	0.03	<LOQ	3.25± 0.498	2.86± 1.2	0.125± 0.0518	0.0263± 0.0455[b]	<LOQ
Decamethylcyclo-pentasiloxane (OS)	0.03	0.111± 0.121[b]	9.38± 12	13.8± 7.94	5.16± 1.03	0.563± 0.864[b]	<LOQ
Dodecamethylpenta-siloxane (LS,MD3M)	0.02	<LOQ	2.58± 0.611	2.17± 0.0906	0.158± 0.0876	0.00986± 0.0171[b]	<LOQ
Dodecamethylcyclo-hexasiloxane (06)	0.04	<LOQ	7.22± 1.29	6.91± 1.65	1.47± 0.208	0.36± 0.624[b]	<LOQ

All results in ppbv, uncertainty is 1 standard deviation).[a]Average and standard deviation based on two samples because of problems with sample collection or storage.

[b]One or two values were <LOQ.

Source: University of California, Davis

Table 22: Results of Metals Analysis
Point Loma, East Bay Municipal Utility District, Brea, and Yolo

Element	QL (μg m^{-3})	CNG	Point Loma Raw	Point Loma Clean	EBMUD Raw	EBMUD Clean	Brea Raw	Brea Clean	Yolo Raw	Yolo Clean
Be	0.005	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Cr	0.005	0.984± 1.52	0.0178± 0.0308	1.93± 3.35	2.4± 4.16	0.209± 0.362	0.933± 1.62	3.82± 6.62	6± 10.4	0.00889± 0.0154
Mn	0.005	0.207± 0.254	0.129± 0.184	0.189± 0.246	0.6± 1.04	0.207± 0.358	0.0156± 0.0269	1.41± 1.51	6± 10.4	0.0311± 0.0539
Co	0.005	0.00467± 0.00371	0.00533± 0.00924	0.016± 0.0266	0.0351± 0.0562	0.0133± 0.0231	0.000889± 0.00154	0.0791± 0.117	0.322± 0.558	0.00156± 0.00269
Ni	0.02	0.236± 0.222	0.0867± 0.15	7.88± 13.4	6.73± 11.5	1.29± 2.23	0.0333± 0.0577	8.36± 13.8	60.2± 104	0.289± 0.272
Cu	0.005	0.4± 0.693	0.578± 1	11.9± 19.2	0.189± 0.327	9.33± 16.2	<LOQ	9.11± 15.8	2.31± 4	0.667± 0.611
Zn	0.2	14.9± 25.8	3.51± 3.6	12.7± 21.9	28.4± 47.6	17.6± 30.3	11.1± 15.4	5.33± 9.24	113± 196	1.78± 2.96
As	0.005	<LOQ	0.292± 0.434	0.00556± 0.00962	0.851± 0.362	0.00889± 0.0154	8.36± 4.43	0.924± 0.538	1.44± 2.39	0.0511± 0.05
Se	0.2	<LOQ	0.0267± 0.0462	0.0444± 0.077	0.0133± 0.0231	<LOQ	0.0844± 0.0834	0.0178± 0.0308	0.0222± 0.0385	<LOQ
Sr	0.01	0.384± 0.649	0.0756± 0.0734	<LOQ	0.109± 0.0948	0.0689± 0.102	0.0222± 0.0385	<LOQ	0.511± 0.885	0.0356± 0.0616
Mo	0.02	0.0178± 0.0308	0.00444± 0.00407	0.467± 0.808	0.196± 0.333	0.0422± 0.0731	0.0316± 0.0317	0.747± 1.26	0.0778± 0.135	<LOQ
Cd	0.005	0.00222± 0.00385	0.0662± 0.099	0.6± 1.04	0.0964± 0.165	0.0704± 0.118	0.0289± 0.05	0.0449± 0.0553	0.0104± 0.0181	0.00511± 0.00719
Sb	0.005	0.00311± 0.00539	0.84± 0.795	0.11± 0.16	1.01± 0.25	0.0222± 0.0385	2.02± 3.5	0.527± 0.464	1.06± 1.63	0.362± 0.155
Ba	0.02	10.8± 17.8	1.02± 1	0.296± 0.279	<LOQ	0.164± 0.285	0.178± 0.308	0.204± 0.354	7.22± 12.2	0.167± 0.289
Hg	0.005	0.0000222± 0.0000385	<LOQ	0.000756± 0.00131	0.00627± 0.00734	<LOQ	0.000889± 0.00154	0.00136± 0.00235	0.00102± 0.00177	<LOQ

Element	QL (μg m^{-3})	CNG	Point Loma Raw	Point Loma Clean	EBMUD Raw	EBMUD Clean	Brea Raw	Brea Clean	Yolo Raw	Yolo Clean
Tl	0.005	<LOQ	<LOQ	0.000222 ± 0.000385	0.0000444± 0.000077	<LOQ	<LOQ	0.000222 ± 0.000385	<LOQ	<LOQ
Pb	0.1	1.31± 2.27	0.753± 1.14	<LOQ	3.56± 6.16	3.9± 6.73	0.0889± 0.154	2.44± 4.23	0.193± 0.335	0.04± 0.0693

All results in μg m^{-3}, uncertainty is 1 standard deviation.

Source: University of California, Davis

Table 23: Results of Metals Analysis
Zero Waste Energy Development, CR&R, and Blue Line

Element	QL (µg m^{-3})	CNG	ZWSJ Raw	ZWSJ Clean	CR&R Raw	CR&R Clean	Blue Line Clean
Be	0.005	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Cr	0.005	0.984± 1.52	<LOQ	<LOQ	0.131± 0.21	1.1± 1.88	0.0798± 0.121
Mn	0.005	0.207± 0.254	<LOQ	0.00667± 0.00943	0.0933± 0.162	1.03± 1.71	0.113± 0.158
Co	0.005	0.00467± 0.00371	0.000889± 0.00154	<LOQ	0.00644± 0.00948	0.0264± 0.0441	0.008± 0.0106
Ni	0.02	0.236± 0.222	<LOQ	<LOQ	0.213± 0.37	1.82± 3.16	0.664± 1.1
Cu	0.005	0.4± 0.693	0.667± 1.15	<LOQ	0.822± 1.42	10.4± 17.5	0.262± 0.408
Zn	0.2	14.9± 25.8	<LOQ	<LOQ	1.8± 3.12	17.5± 28.7	11.2± 11.3
As	0.005	<LOQ	0.49± 0.846	0.0833± 0.118	1.88± 3.22	0.32± 0.543	0.00133± 0.00231
Se	0.2	<LOQ	<LOQ	0.015± 0.0212	<LOQ	<LOQ	0.0333± 0.0577
Sr	0.01	0.384± 0.649	<LOQ	<LOQ	0.0444± 0.077	0.118± 0.152	0.0689± 0.0668
Mo	0.02	0.0178± 0.0308	0.00356± 0.00407	<LOQ	0.00689± 0.0108	0.145± 0.249	0.00756± 0.00983
Cd	0.005	0.00222± 0.00385	<LOQ	0.00367± 0.00519	0.0118± 0.0111	0.38± 0.652	0.0111± 0.0192
Sb	0.005	0.00311± 0.00539	0.0711± 0.123	0.107± 0.151	<LOQ	0.733± 1.27	0.00533± 0.00706
Ba	0.02	10.8± 17.8	0.756± 1.31	0.712± 0.973	0.0444± 0.0555	0.533± 0.611	0.131± 0.178
Hg	0.005	0.0000222± 0.0000385	<LOQ	<LOQ	0.0016± 0.00277	0.000978± 0.00169	<LOQ
Tl	0.005	<LOQ	<LOQ	<LOQ	<LOQ	0.000111± 0.000192	0.000378± 0.000654
Pb	0.1	1.31± 2.27	<LOQ	<LOQ	0.222± 0.385	3.3± 5.69	0.305± 0.509

All results in µg m^{-3}, uncertainty is 1 standard deviation.

Source: University of California, Davis

Table 24: Microbiota Found in t Biogas and Biomethane Samples Measured by Cultivation Analysis

Source Cultivation analysis (MPN/m^3)[a]	Yolo	EBMUD	San Jose	Point Loma	Brea	CR&R	Blue Line	CNG
Biogas								
Cultivable aerobic bacteria	17 ± 0[b] (3/3)[c]	<SLOD (0/3)	23 ± 25 (1/3)	<SLOD (0/5)	14 ± 5 (2/3)	157 ± 139 (2/3)	n/a[e]	n/a
Cultivable anaerobic bacteria	<SLOD[d] (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/5)	11 ± 5 (1/3)	47 ± 28 (3/3)	n/a	n/a
Cultivable aerobic spore bacteria	11 ± 5 (1/3)	<SLOD (0/3)	<SLOD (0/3)	10 ± 4 (1/5)	17 ± 15 (1/3)	119 ± 106 (3/3)	n/a	n/a
Cultivable anaerobic spore bacteria	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	10 ± 4 (1/5)	14 ± 5 (2/3)	93 ± 52 (3/3)	n/a	n/a
Biomethane/Natural gas								
Cultivable aerobic bacteria	<SLOD (0/3)	<SLOD (0/3)	20 ± 13 (2/3)	<SLOD (0/3)	26 ± 15 (2/3)	75 ± 69 (3/3)	23 ± 25 (1/3)	11±5 (1/3)
Cultivable anaerobic bacteria	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	11 ± 5 (1/3)	23 ± 10 (3/3)	<SLOD (0/3)	<SLOD (0/3)
Cultivable aerobic spore bacteria	11 ± 5 (1/3)	<SLOD (0/3)	11 ± 5 (1/3)	14 ± 5 (2/3)	46 ± 57 (2/3)	65 ± 63 (2/3)	14 ± 5 (2/3)	<SLOD (0/3)
Cultivable anaerobic spore bacteria	<SLOD (0/3)	<SLOD (0/3)	11 ± 5 (1/3)	<SLOD (0/3)	30 ± 36 (1/3)	29 ± 10 (3/3)	<SLOD (0/3)	<SLOD (0/3)

[a] MPN, most probable number

[b] Results shown are means ± standard deviations. Data below SLODs of the MPN tests (17 MPN/m^3) were assumed to be half of the SLODs for the mean calculation.

[c] Number of detected samples out of total replicates tested is shown in the parenthesis.

[d] When all replicates tested were below the detection limit, results are presented as "<SLOD" to simplify the table.

[e] n/a, not applicable. Samples were not collected.

Source: University of California, Davis

Table 25: Microbiota Found in Biogas Measured by qPCR

Source Molecular analysis (gene copies/m^3)	Yolo	EBMUD	San Jose	Point Loma	Brea	CR&R	Blue Line	CNG
Biogas								
Total bacteria	<SLOD[a] (0/3)[b]	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/5)	<SLOD (0/3)	<SLOD (0/3)	n/a[c]	n/a
Sulfate reducing bacteria	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/5)	<SLOD (0/3)	<SLOD (0/3)	n/a	n/a
Iron oxidizing bacteria 1	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/5)	<SLOD (0/3)	<SLOD (0/3)	n/a	n/a
Iron oxidizing bacteria 2	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/5)	<SLOD (0/3)	<SLOD (0/3)	n/a	n/a
Acid producing bacteria	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/5)	<SLOD (0/3)	<SLOD (0/3)	n/a	n/a
Biomethane/natural gas								
Total bacteria	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)
Sulfate reducing bacteria	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)
Iron oxidizing bacteria 1	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)
Iron oxidizing bacteria 2	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)
Acid producing bacteria	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)	<SLOD (0/3)

Data below SLODsare indicated as "<SLOD". The SLODs of molecular assays are as follows: total bacteria 12,000; sulfate reducing bacteria 43; iron oxidizing bacteria 1 280; iron oxidizing bacteria 2 27; acid producing bacteria 30 gene copies/m^3.

[b] Number of detected samples out of total replicates tested is shown in the parenthesis.

[c] n/a, not applicable. Samples were not collected

Source: University of California, Davis

Table 26: Results of PCB Analysis
Point Loma, East Bay Municipal Utility District, Brea, and Yolo

Parameter	LOQ (ppbv)	CNG	Point Loma Raw	Point Loma Clean	EBMUD Raw	EBMUD Clean	Brea Raw	Brea Clean	Yolo Raw	Yolo Clean
Biphenyl, Dichloro	0.00167	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.196± 0.174	<LOQ	0.0876± 0.0725	0.0367± 0.0552[a]
Biphenyl, Trichloro	0.00724	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	0.161± 0.146	<LOQ	0.0549± 0.026	0.0176± 0.0305[a]
Biphenyl, Tetrachloro	0.00319	<LOQ	<LOQ	<LOQ	0.00627± 0.0109	<LOQ	0.0297± 0.021	<LOQ	0.0126± 0.0112[a]	0.00633± 0.011[a]
Biphenyl, Pentachloro	0.00288	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Biphenyl, Hexachloro	0.00103	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Biphenyl, Heptachloro	0.00236	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Biphenyl, Octachloro	0.00217	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ

[a]One or two values were <LOQ.

Source: University of California, Davis

Table 27: Results of PCB Analysis
Zero Waste Energy Development, CR&R, and Blue Line

Parameter	LOQ (ppbv)	CNG	ZWSJ Raw	ZWSJ Clean[a]	CR&R Raw	CR&R Clean	Blue Line Clean
Biphenyl, Dichloro	0.00167	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Biphenyl, Trichloro	0.00724	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Biphenyl, Tetrachloro	0.00319	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Biphenyl, Pentachloro	0.00288	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Biphenyl, Hexachloro	0.00103	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Biphenyl, Heptachloro	0.00236	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Biphenyl, Octachloro	0.00217	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ

All results in ppbv, uncertainty is 1 standard deviation.[a]Average and standard deviation based on 2 samples because of problems with sample collection or storage.

Source: University of California, Davis

Table 28: Results of Pesticide Analysis
Point Loma, East Bay Municipal Utility District, Brea, and Yolo

Parameter	LOQ (ppbv)	CNG	Point Loma Raw	Point Loma Clean	EBMUD Raw	EBMUD Clean	Brea Raw	Brea Clean	Yolo Raw	Yolo Clean
a-BHC	0.006	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
b-BHC	0.013	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
g-BHC	0.013	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
d-BHC	0.006	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Heptachlor	0.005	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Aldrin	0.001	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Heptachlor epoxide	0.002	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
g-Chlordane	0.001	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Endosulfan I	0.005	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
a-Chlordane	0.002	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Dieldrin	0.010	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
4,4'-DDE	0.006	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Endrin	0.010	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Endosulfan II	0.009	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
4,4'-DDD	0.006	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Endrin aldehyde	0.025	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Endosulfan sulfate	0.002	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
4,4'-DDT	0.005	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Endrin ketone	0.010	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Methoxychlor	0.011	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Toxaphene	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM
Technical Chlordane	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM

All results in ppbv, uncertainty is 1 standard deviation.[a]Average and standard deviation based on 2 samples because of problems with sample collection or storage.

Source: University of California, Davis

Table 29: Results of Pesticide Analysis
Zero Waste Energy Development, CR&R, and Blue Line

Parameter	LOQ (ppbv)	CNG	ZWSJ Raw	ZWSJ Clean[a]	CR&R Raw	CR&R Clean	Blue Line Clean
a-BHC	0.006	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
b-BHC	0.013	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
g-BHC	0.013	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
d-BHC	0.006	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Heptachlor	0.005	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Aldrin	0.001	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Heptachlor epoxide	0.002	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
g-Chlordane	0.001	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Endosulfan I	0.005	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
a-Chlordane	0.002	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Dieldrin	0.010	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
4,4'-DDE	0.006	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Endrin	0.010	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Endosulfan II	0.009	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
4,4'-DDD	0.006	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Endrin aldehyde	0.025	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Endosulfan sulfate	0.002	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
4,4'-DDT	0.005	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Endrin ketone	0.010	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Methoxychlor	0.011	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ
Toxaphene	NM	NM	NM	NM	NM	NM	NM
Technical Chlordane	NM	NM	NM	NM	NM	NM	NM

All results in ppbv, uncertainty is 1 standard deviation.[a]Average and standard deviation based on 2 samples because of problems with sample collection or storage.

Source: University of California, Davis

**Table 30: Parameters Used to Characterize Raw and Upgraded Biogas
Point Loma, East Bay Municipal Utility District, Brea, and Yolo**

Parameter	CNG	Point Loma Raw	Point Loma Clean	EBMUD Raw	EBMUD Clean	Brea Raw	Brea Clean	Yolo Raw	Yolo Clean
Compressibility Factor [z] (Dry)	0.29± 0.0000521	0.284± 0.0000459	0.29± 0.0000385	0.286± 0.00061	0.286± 0.00066	0.286± 0.00302	0.287± 0.00259	0.286± 0.000965	0.286± 0.000841
Compressibility Factor [z] (Sat.)	0.289± 0.0000522	0.268± 0.0000433	0.289± 0.000897	0.269± 0.000575	0.285± 0.000659	0.27± 0.00285	0.287± 0.00259	0.27± 0.00091	0.286± 0.00084
Relative Density (Dry)	0.593± 0.000582	0.944± 0.00152	0.567± 0.000985	0.879± 0.034	0.872± 0.0376	0.999± 0.0039	1.01± 0.00561	0.946± 0.047	0.946± 0.0459
HHV (Dry) (Btu/ft3)	1030±1.47	600±0.293	995±1.01	662±27.3	671±31.2	334±236	229±185	485±30.6	489±36.3
HHV (Sat.) (Btu/ft3)*	1030±1.47	566±0.276	991±4.22	624±25.8	670±31.2	315±223	229±185	457±28.8	489±36.2
Wobbe Number (dry)	1340±2.26	617±0.195	1320± 0.197	707±43.2	719±49.3	334±236	228±184	500±44	504±50.1
LHV (Dry) (Btu/ft3)	928±1.33	539±0.263	895± 0.91	595±24.6	603±28.1	300±212	206±167	436±27.5	440±32.6
LHV (Sat.) (Btu/ft3)*	927±1.33	509±0.248	891± 3.79	562±23.2	603±28.1	283±200	206±167	411±25.9	439±32.6
Real Gas Density (lbs/ft3)	0.0445± 0.0000436	0.0708± 0.000114	0.0425± 0.0000739	0.0659± 0.00255	0.0654± 0.00282	0.0749± 0.000293	0.0757± 0.00042	0.0709± 0.00353	0.071± 0.00345
Motor Octane Number	125±0.236	140	140	140	140	140	140	140	140
Methane Number[1]	84.2± 0.383	108	108	108	108	108	108	108	108
Methane Number[2]	87.4± 0.852	140±0.35	94.9±0.75	130±6.29	130±6.68	147±0.85	151	138±13.1	139±12.4

Uncertainty is 1 standard deviation. [1] Using Methane Number=1.624*(motor octane number) -119.1 (www.arb.ca.gov/regact/cng-lpg/appd.pdf). [2] Using Methane Number from the online calculator (www.cumminswestport.com/fuel-quality-calculator).

Source: University of California, Davis

Table 31: Parameters Used to Characterize Raw and Upgraded Biogas Zero Waste Energy Development, CR&R, and Blue Line

Parameter	CNG	ZWSJ Raw	ZWSJ Clean[a]	CR&R Raw	CR&R Clean	Blue Line Clean
Compressibility Factor [z] (Dry)	0.29±0.0000521	0.284±0.000985	0.285±0.00106	0.285±0.00191	0.29±0.00000384	0.289±0.000222
Compressibility Factor [z] (Sat.)	0.289±0.0000522	0.268±0.000929	0.285±0.00106	0.269±0.0018	0.29±0.00000383	0.289±0.000222
Relative Density (Dry)	0.593±0.000582	0.978±0.0512	0.942±0.0531	0.916±0.106	0.569±0.0063	0.635±0.00816
HHV (Dry) (Btu/ft3)	1030±1.47	535±36.3	566±34.3	592±85.1	982±12.6	888±8.59
HHV (Sat.) (Btu/ft3)*	1030±1.47	505±34.2	565±34.3	559±80.3	981±12.6	887±8.58
Wobbe Number (dry)	1340±2.26	543±51.7	584±51.8	628±131	1300±23.8	1110±18
LHV (Dry) (Btu/ft3)	928±1.33	481±32.6	509±30.9	533±76.5	883±11.3	798±7.72
LHV (Sat.) (Btu/ft3)*	927±1.33	454±30.8	508±30.8	503±72.2	882±11.3	798±7.72
Real Gas Density (lbs/ft3)	0.0445±0.0000436	0.0733±0.00384	0.0707±0.00398	0.0687±0.00794	0.0426±0.000473	0.0476±0.000612
Motor Octane Number	125±0.236	140	140	140	140	140
Methane Number[1]	84.2±0.383	108	108	108	108	108
Methane Number[2]	87.4±0.852	142±9.37	136±10.7	130±21.4	90.4±1.85	94.4±1.18

Uncertainty is 1 standard deviation.

[1] Using Methane Number=1.624*(motor octane number) -119.1 (www.arb.ca.gov/regact/cng-lpg/appd.pdf).

[2] Using Methane Number from the online calculator (www.cumminswestport.com/fuel-quality-calculator).

Source: University of California, Davis

CHAPTER 4:
Conclusions

Summary of Results

A comprehensive set of measurements was conducted for 13 different biogas and biomethane sample streams (each consisting of three different individual samples) and a single natural gas stream (consisting of three individual samples). Biogas and biomethane sample streams were derived from seven different production sources: two wastewater treatment plants, three green waste and solid waste facilities, and two landfills. Each facility used a unique combination of feedstock, digester configuration, and upgrading technology.

The composition of raw biogas was predominantly methane and CO_2 with minor amounts of air intrusion depending on the process type. Methane concentrations in the raw biogas varied from 47.9 percent to 65.4 percent and were relatively consistent within a facility category. The average methane concentrations varied in the following order: wastewater facilities (highest concentrations), food waste, landfills (lowest concentration). Upgraded biomethane had methane contents between ~87.7 percent to 98.3 percent depending on the technology employed, which compared favorably with the ~93.5 percent methane content of CNG obtained from Pacific Gas and Electric in northern California. Commercial natural gas contained an additional ~4.8 percent ethane, which yielded higher energy content than biomethane.

Ammonia in the biogas was below the LOQ (100 ppbv) for most samples except for raw biogas from EBMUD, ZWSJ, and CR&R, which showed overall >80 percent removal from cleaning operations.

Concentrations of cyclic and straight-chain alkanes with 5-9 carbons in CNG samples exceeded 1 ppmv (1000 ppbv), with the highest concentrations (58-179 ppmv) for 6 carbon (hexanes and cyclohexanes) and 7 carbon (heptanes and methylcyclohexanes) species. Biogas samples exhibited very different patterns of extended hydrocarbon concentrations, with none of the biogas samples having a concentration of any compound with nine carbons or less that exceeded the corresponding CNG concentration. Longer chain alkanes, particularly those with 10-12, 18 and 20 carbon atoms, were frequently detected in the raw biogas samples and in some of the clean biogas samples.

Biogas and biomethane samples have substantially higher total concentrations of many organic sulfur species than the CNG, which contained only odorants. Concentrations of many volatile sulfur species are significant in the biogas samples, with methyl and sec-butyl mercaptans exceeding 1 ppmv in some gas streams. Concentrations of several hundred ppbv were observed for a number of other sulfur containing organic compounds. The various cleaning steps applied to the biogas streams had differing levels of efficacy, with removal being nearly complete at Point Loma, significant for most constituents at CR&R, with less effective removals observed at the other sites.

A majority of the halocarbons monitored in this study are present in the two raw landfill biogas streams at levels above LOQ; these levels are generally not significantly reduced by the cleaning processes used at these facilities. Species present at relatively high concentrations in these streams include 1,2-dichloroethane (713-1480 ppbv), dichlorodifluoromethane (102-157

ppbv), and 1,1-dichloroethene (35-304 ppbv). These halocarbons likely originate from leaching of solvents or refrigerants from containers disposed at the landfills and/or from plastics in the feedstock to these facilities.

The biogas streams that had been treated to achieve high methane contents (>87%, Point Loma clean, CR&R clean, and Blue Line clean) had aldehyde and ketone profiles that were generally similar to CNG except for acetone in Point Loma Clean, which had 240 ppbv compared with <LOQ in CNG and for MEK and valeraldehyde, which were each 190-300 times higher in the upgraded biogas samples compared with CNG.

VOCs commonly observed in biogas and upgraded biomethane include phenols and substituted phenols as well as naphthalene and substituted naphthalene compounds.

Siloxanes were detected in raw biogas samples from all source categories. Cleanup operations had varying degrees of success, with substantial reductions in siloxane concentrations at Point Loma, EBMUD, and CR&R, and minimal reductions at Yolo and ZWSJ.

Metals were detected sporadically but at statistically significant levels above zero, often with groups of metals showing up all at once in a single sample – such as Cr, Mn, Ni, and Zn, which are often correlated. Presumably, these are aerosol particles of some mechanical origin, rather than actually from the biogas – in particular since these metals are just as likely to be detected in clean samples as in raw samples.

Cultivable aerobic bacteria were found at all sites except the wastewater treatment facilities. Cultivable anaerobic bacteria were consistently detected at two sites. The numbers of cultivable bacteria found in this project were comparable to those from previous studies reporting cultivable bacteria concentrations in biogas around 10 to 100 colony forming units per m^3. Upgrading biogas to biomethane did not completely remove the bacteria from the gas streams. DNA sequencing revealed that the most common cultivable (spore-forming) bacteria detected were *Bacillus.* These natural bacteria are ubiquitous and their spores are resistant to adverse conditions such as heat, cold, desiccation, and radiation. Most *Bacillus* species are harmless.

Polychlorinated biphenyls were detected in landfill gas in the present study.

Pesticides were not detected at concentrations that could be reliably quantified in any of the biogas/biomethane sample streams collected in the present study.

Future Research

The summarized findings confirm that California has several issues related to biogas production and adoption as a new energy source because of the presence of compounds in biogas/biomethane that are not present in natural gas. These compounds do not rule out the future use of biogas but require consideration to minimize potential negative effects. Additional research is needed to characterize the variability of biogas/biomethane composition in California. Consistent measurements are needed across all of these sources to fully characterize the range of potential biogas/biomethane production in California.

LIST OF ACROYNMS

Term	Definition
AB	Assembly bill
BLAST	Basic Logical Assignment Search Tool
CARB	California Air Resources Board
CEC	California Energy Commission
CNG	Compressed natural gas
CPUC	California Public Utilities Commission
CSTR	Continuous stirred tank reactor
DNA	Deoxyribonucleic acid
FPD	Flame photometric detector
GC	Gas chromatography
FTI	Gas Technology Institute
H/C	Hydrogen to carbon ratio
ICPMS	Inductively coupled plasma mass spectrometry
LC	Liquid chromatography
LOD	Limit of detection
LOQ	Limit of quantification
MPN	Most probable number
MS	Mass spectrometry
NM	No measurement
NQ	Not quantifiable
OEHHA	Office of environmental health hazard assessment
PAC	Project advisor committee
PAH	Polycyclic aromatic hydrocarbon
PBS	Phosphate buffered saline
PCB	Polychlorinated biphenyl
PCR	Polymerase chain reaction
POTWs	Publicly owned treatment works water systems
Ppbv	Parts per billion by volume

Term	Definition
qPCR	Quantitative polymerase chain reaction
qTOF	Quadrupole time-of-flight
READ	Renewable Energy Anaerobic Digester
RNG	Renewable natural gas
SATS	South Area Transfer Station
SVOC	Semi-volatile organic compound
TCD	Thermal conductivity detector
TG	Thioglycolate
TSB	Tryptic soy broth
VOC	Volatile organic compound

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