Energy Research and Development Division
FINAL PROJECT REPORT

AIR QUALITY ISSUES RELATED TO USING BIOGAS FROM ANAEROBIC DIGESTION OF FOOD WASTE

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PREFACE

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

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This report is the final report for the project, titled *Air Quality Issues Related to Using Biogas From Anaerobic Digestion of Food Waste* (Contract Number 500-11-030) conducted by California State University, Fullerton. The information from this project contributes to Energy Research and Development Division's Energy-Related Environmental Research Program.

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ABSTRACT

Biopower can diversify energy supply and improve energy resilience in California. Increases in biopower production from sustainable biomass can provide many economic and environmental benefits. For example, increasing biogas production through anaerobic digestion of food waste would increase the use of renewable fuels throughout the State and add to California's renewables portfolio. Although a biopower project will produce renewable energy, the process of producing bioenergy should harmonize with the goal of protecting public health. Meeting air emission requirements is paramount to the successful implementation of any biopower project.

A literature review on anaerobic digestion of food waste, biogas generation, and beneficial uses of biogas was conducted. Field data were collected from a wastewater treatment plant that employs anaerobic codigestion of fats, oils, and grease, food waste, and wastewater sludge and uses an internal combustion engine to generate biopower using the biogas. This project generated scientific information on the quality and quantity of biogas from anaerobic codigestion of food waste and municipal wastewater sludge, levels of contaminants in raw biogas that may affect beneficial uses of the biogas, removal of the contaminants by the biogas conditioning systems, emissions of oxides of nitrogen (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO), carbon dioxide (CO_2), and methane (CH_4), and types and levels of air toxics present in the exhausts of the internal combustion engine fueled by the biogas. The information is valuable to those who consider similar operations (that is, codigestion of food waste with municipal sludge and power generation using the produced biogas) and to support rulemaking decisions with regards to air quality issues for such applications.

Keywords: Food waste, anaerobic digestion, bioenergy, biogas, biopower, air quality, greenhouse gases, internal combustion engine, California Energy Commission

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Introduction

Using biopower can diversify energy supply and improve energy resiliency in California. Increases in biopower production from sustainable biomass can provide many economic and environmental benefits. Increased biopower also addresses Governor Brown's *Clean Energy Jobs Plan*, which calls for the state to increase renewable energy capacity by 20,000 megawatts (MW) by 2020.

One of the main energy sources for biopower generation is the biogas produced from anaerobic digestion of biomass. Recently, anaerobic digestion of food waste for biogas generation has received considerable attention, mainly due to the high energy content and biodegradability of food waste. Increasing biogas production through anaerobic digestion of food waste would increase the use of renewable fuels throughout the state and add to California's renewables portfolio.

Although a biopower project will produce renewable energy, the process of producing bioenergy should harmonize with the goal of protecting public health. Meeting air emission requirements is paramount to the successful implementation of any biopower project.

Project Purpose

Anaerobic codigestion of food waste is a viable process; however, full-scale operation of this process is still new. There is a lack of readily available scientific information on the quality of raw biogas, as well as on potential emissions from power generation systems using this biogas. This information is needed for determining conditioning requirements for beneficial uses of raw biogas, for selecting power-generating equipment, and for air quality permitting. The overall objectives of this research are (1) to develop scientific information with regards to quality and quantity of biogas from anaerobic codigestion of food waste and municipal wastewater sludge, (2) to assess the need and performance of conditioning/pretreatment systems for biopower generation, and (3) to develop scientific information regarding impacts on air quality from biopower generation using this biogas.

Project Findings

The findings from the experiments of this study include the following:

- With fats, oils, and grease and food waste as 25 percent of total solids loading to the anaerobic digesters, the digesters are being operated under stable conditions.
- With 33 percent percent more volatile solids loading from fats, oils, and greaseG and food waste, the daily biogas production is 60 percent greater.
- Hydrogen sulfide is the dominant reduced sulfur compound in the raw biogas.

- With regard to siloxanes, only hexamethylcyclotrisiloxane, octamethylcyclotetrasiloxane, and decamethylcyclopentasiloxane were detected in the raw biogas.
- The internal combustion engine at the site uses both natural gas and biogas daily. The official source test data showed that NO_x concentrations (at 15 percent oxygen [O_2]) in the exhausts using natural gas and biogas were essentially the same. Regarding emissions of organic compounds, natural gas-fueled operations emitted less methane but higher nonmethane organic carbon. The average carbon dioxide (CO_2) emission from using biogas was higher (12.8 percent vs. 7.5 percent), probably due to the higher CO_2 concentration in the biogas. The average carbon monoxide (CO) concentration from biogas-fueled combustion was higher. The average sulfur dioxide (SO_2) concentration from biogas-fueled combustion was also higher, probably due to the presence of reduced sulfur compounds in the biogas.

Project Benefits

This project generated scientific information on (1) quality and quantity of biogas from anaerobic codigestion of food waste and municipal wastewater sludge, (2) levels of contaminants in raw biogas that may affect beneficial uses, (3) removal capability of biogas conditioning systems, (4) emissions of NO_x, SO_2, CO, CO_2, and methane from internal combustionengines using biogas, and (5) types and levels of air toxics present in exhausts of IC engines using biogas.

Several conclusions can be drawn from this study:

- With a contribution of 25 percent from food waste to the total volatile solid applied to the anaerobic digesters, the codigestion of food waste and municipal wastewater sludge is a viable and stable process. The daily biogas production increased by 60 percent.
- The IC engine fueled by biogas can meet stringent emission limits for CO at 15 percent O_2 (250 ppmv) and volatile organic compounds. However, additional emission control may be needed to meet the low NO_x limit of 11 ppmv.
- Codigestion of food waste with municipal wastewater sludge would help divert organic wastes from landfills and increase the use of renewable fuels throughout the state and help diversify California's renewables portfolio.

The emissions data from this study are valuable to those considering implementing similar operations (such as codigestion of food waste with municipal sludge and power generation using the produced biogas) and provide a basis to support rulemaking decisions with regard to air quality issues for such applications.

CHAPTER 1:
Introduction

1.1 Introduction

Bioenergy is energy produced from biomass. It can be in the form of electricity (biopower), renewable gas (biomethane), or liquid transportation fuels (biofuels). Biopower can diversify energy supply and improve energy resiliency in California. Increases in biopower production from sustainable biomass can provide many economic and environmental benefits including creation of green jobs, promotion of local economic stability, and reduction of water and air pollution including greenhouse gas (GHG) emissions (O'Neill and Nuffer, 2011; CEC, 2012).

Increased biopower also addresses Governor Brown's Clean Energy Jobs Plan, which calls for the state to increase renewable energy capacity by 20,000 megawatts (MW) by 2020. Biopower has the potential to provide between 2,000 and 5,000 MW of the localized renewable energy capacity needed to achieve the Governor's goals (O'Neill and Nuffer, 2011). In the electricity sector, biopower contributes to California's renewable energy goals. California's Renewable Portfolio Standards (RPS) requires that utilities increase the ratio of renewable electricity purchased to a minimum of 20% per year from the start of 2011 to the end of 2013; 25% by the end of 2016; and 33% by the end of 2020. Digester gas, along with municipal solid waste (MSW), biomass, and landfill gas are the four types identified as eligible for the RPS (O'Neill, 2012; CEC, 2012).

The Legislature and Governor Brown set a goal of 75% recycling, composting or source reduction of solid waste by 2020. The California Department of Resources Recycling and Recovery (CalRecycle) Strategic Directive 6.1 establishes a goal to divert 50% of organic waste from landfills by 2020. Most of the diverted organic materials (e.g., food waste) contain high enthalpies and are readily biodegradable. The diversion of organic materials from landfills can provide a significant reduction in GHG emissions through landfill methane avoidance, alternative energy production, and water conservation (O'Neill, 2012). Anaerobic digestion of these diverted organic wastes (to generate biogas for biopower generation) may be a good alternative to the common practice of composting (Franco, 2012). CalRecycle has developed the Anaerobic Digestion Initiative to encourage the development of anaerobic digestion facilities in California and is taking actions to implement the policy (CalRecycle, 2011).

Recently, anaerobic digestion of food waste for biogas generation has received considerable attention, mainly due to the high energy content and biodegradability of food waste (Arsova, 2010; USEPA, 2014a). Food waste is typically co-digested with sludge from wastewater treatment at municipal wastewater treatment plants (WWTPs). Increasing biogas production through anaerobic digestion of food waste would increase the use of renewable fuels throughout the state and diversity California's renewables portfolio.

Although a biopower project will produce renewable energy, the process of producing bioenergy should harmonize with the goal of protecting public health. Many air districts in California are designated as

non-attainment areas in regard to air quality standards of ozone and particulate matter (PM). Emissions of nitrogen oxides (NO_x), precursors for ozone generation, and other compounds from stationary engines that utilize biogas are of concern. The NO_x emission limits can be as low as 9 parts per million by volume (ppmv) in some air pollution control districts (Drake, 2010). Meeting air emission requirements is paramount to the successful implementation of any biopower project.

1.2 Food Wastes

1.2.1 Quantities of food wastes

Total MSW generation in the United States in 2012 was 251 million tons. Food waste is the second largest component of MSW at 36.4 million tons which represents 15.5% of total MSW generated. Due to difficulties in recovery/reuse of food waste, only 4.8% of the generated food waste was diverted from landfills and incinerators for recovery, mainly by composting. Consequently, food waste became the largest category of MSW discards, accounting for 21.1% of the total after recycling and composting (USEPA, 2014b). Over 30 million tons of food waste is sent to landfills each year. According to the California 2008 Statewide Waste Characterization Study, food waste is the most prevalent material in the California's overall disposed waste system (15.5%) amounting to 6,158,120 tons in 2008 (CIWMB, 2009).

1.2.2 Benefits of diverting food waste from landfills

Diverting food waste from landfills has many benefits. For example, since food waste is often left out of recycling programs, diverting food waste from landfills will help to meet the diversion goals mandated by many local and state governments. Additionally, the emission of methane gas from landfills will be reduced. Food waste can be readily digested under anaerobic conditions for capture of energy content. The volume of food waste will be greatly reduced and the residuals may be beneficially reused as fertilizer or soil amendments (USEPA, 2014a).

1.2.3 Energy recovery from food waste

Food waste can be categorized into pre-consumer and post-consumer food waste. A recent assessment study was conducted on California food processing industry to compile a county-level inventory of food processing residues and to estimate the amount of energy that these residues could generate. The assessed food processing sectors included cannery, dehydrated, fresh/frozen fruits and vegetables, winery, creamery, poultry, red meat, and almond hulls and shells. Energy potential was estimated at 557 MW of electricity. Energy, from fruits and vegetables, creamery, winery, and meat processing liquid and solid residues, was estimated at 96 MW of electricity and 3.4 million MMBTU of recoverable heat through conversion of biogas produced by anaerobic digestion, while solid residues from these facilities amounts to about 760,000 dry tons solid per year (Amon *et al.*, 2012).

Food waste has three times the methane production potential of biosolids (376 vs. 120 m^3 gas/ton) and both are much higher than that of cattle manure at 25 m^3 gas/ton. If 50% of the food waste generated each year in the United States was anaerobically digested, enough electricity would be generated to power 2.5 million homes for a year (USEPA, 2014a). Conversion of biogas to electricity using engine-generator

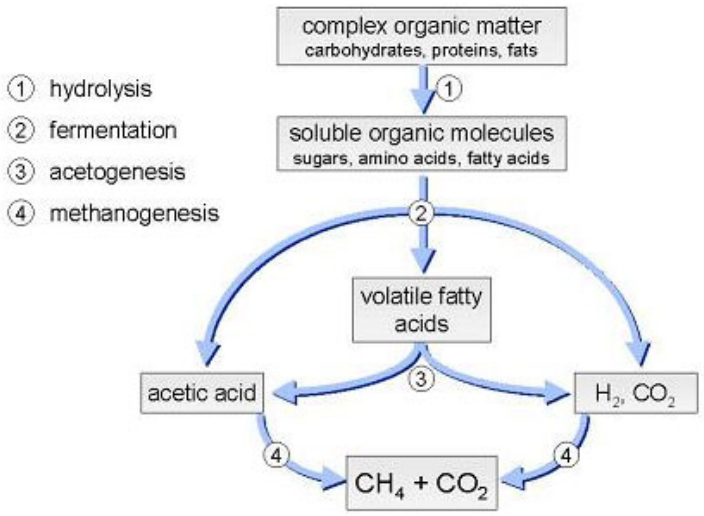
sets is about 35% efficient. Yields from anaerobic digestion can be as high as 3,200 standard cubic feet (scf) methane per ton of raw food waste. Assuming an electricity cost of $0.10/kWh, energy in food waste would be about $33/ton (Kraemer, 2012).

1.3 Anaerobic Digestion

1.3.1 Basics of anaerobic digestion

Anaerobic digestion is a series of processes in which different species of bacteria break down organic matter, such as food scraps, manure, and sewage sludge in the absence of oxygen. The process goes through four phases: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The digestion process begins with microbial hydrolysis that breaks down insoluble organics. They are then converted into simple carboxylic acids, along with additional ammonia, hydrogen (H_2), and carbon dioxide (CO_2), by acidogenes and acetogens. Finally, methanogens convert the acids to methane (CH_4) and CO_2 (Figure 1.1).

Figure 1.1: Phases in Anaerobic Digestion



Source: http://www.epa.gov/region9/organics/ad/science.html

Anaerobic digesters can be designed and engineered to operate using a number of different process configurations: batch or continuous; mesophilic or thermophilic; high solids or low solids; and single-stage or two-stage (CIWMB, 2008; Franco, 2012; Kraemer, 2012; Moriarty, 2013).

Biogas is the main desirable product from anaerobic digestion of organic carbon. Quality and quantity of biogas will be affected by many parameters including pH, temperature, feed composition, loading rate, mixing condition, reactor design, and residence time. The most important initial issue when considering the application of anaerobic digestion is the feed to the digesters. Physical and chemical characteristics of

the organic waste are important for designing and operating anaerobic digesters, because they affect biogas production and process stability during anaerobic digestion. Although almost any organic material can be processed with anaerobic digestion; the level of digestibility is the key factor in its successful application, if biogas production is the goal. The more digestible the feed is, the higher the gas yield potential. The biogas or methane yield is measured by the amount of biogas or methane that can be produced per unit of volatile solids (VS) contained in the feedstock after a given amount of time under a given temperature. The nutrient contents and particle size are also parameters of concern for anaerobic digestion (Banks *et al.*, 2011; Zhang *et al.*, 2007).

1.3.2 Anaerobic digestion in wastewater treatment plants (WWTPs)

Many WWTPs in California use anaerobic digestion to reduce the volume of biosolids before disposal and/or reuse. Due to the cost and feasibility of siting power generation equipment at many of these facilities, much of the biogas produced is flared. The amount of biogas produced by existing facilities could fuel 125 MW of generation capacity. A recent CEC study estimated that, using existing infrastructure, codigesting fats, oil, and grease (FOG), food processing waste, and dairy waste at existing WWTPs could increase the biogas yield potential to 450 MW of capacity, representing 2,500 gigawatt hour (GWh) per year (Kulkarni, 2009). Codigestion is the treatment of a mixture of at least two different substrates with an aim of improving efficiency of anaerobic digestion.

WWTPs are ideal for accepting food waste diverted from landfills because the facilities are often located in urban areas and have a short haul distance (i.e., smaller carbon footprint), have experiences in operating anaerobic digesters, and have existing infrastructure in place to capture biogas. In addition, large treatment facilities could use the produced electricity and heat onsite (USEPA, 2014a).

Additional biopower generation can also be derived from diverting food processing industry wastewater, currently discharged on agricultural land, to municipal WWTPs. For example, although the land discharge practice is the least-cost option in the Central Valley region of California, environmental impacts on groundwater quality have indicated the need to find alternatives to land disposal. The increased revenue from biopower generation could potentially cover the cost of trucking wastewater and solid residues from food processing factories to nearby municipal WWTPs (Rubin *et al.*, 2007).

1.3.3 Anaerobic digestion of food waste in WWTPs

Food waste can either be digested at facilities specifically designed for the organic portion of MSW, or codigested at WWTPs. Codigestion of wastewater sludge with additional, energy-rich organic materials (e.g., food scraps or FOG) is ideal for wastewater digesters with excess capacity. Some haulers charge less if the food waste is separated from the trash and sent for anaerobic digestion rather than landfilling.

It should be noted that pre-processing of food waste is often required because WWTP digesters can be damaged by highly fibrous material, metal, and plastic. Codigesion should not exceed the design capacity of WWTP digesters with regards to flow, solid loading and biogas handling (Kraemer, 2012).

The two main types of anaerobic digesters for food waste based on the percent solids of the material being digested are low-solids and high-solids (dry fermentation) digesters. Low-solids digesters generally process materials with less than 15% solids and are common at WWTPs. High-solids digesters are common in Europe and are becoming more common in the United States. East Bay Municipal Utility

District (EBMUD) in Oakland, CA was the first large-scale wastewater treatment plant in the nation to convert post-consumer food scraps to energy through anaerobic codigestion (EBMUD, 2008). There are many facilities now that are in different stages of anaerobic digestion of food waste (ILSR, 2012; Kraemer, 2012; Moriarty, 2013).

Food waste collected at the City of San Francisco, California, was characterized for its potential for use as a feedstock for anaerobic digestion. With regards to digestibility, food waste is often characterized by its moisture content (MC) and the ratio of volatile solids to total solids (VS/TS). The MC and VS/TS ratios on the average were 74% and 87%, respectively. The nutrient content analysis showed that the food waste contained well balanced nutrients for anaerobic microorganisms. The digestibility and methane yields of the food waste were evaluated using batch digestion tests. The methane yields were 348 and 435 mL/g VS applied, respectively, after 10 and 28 days of digestion at 50 °C. The average methane content of biogas was 73% and the average VS destruction was 81% after 28 days of digestion (CEC, 2005; Zhang *et al.*, 2007).

Table 1.1 compares anaerobic digestion of food waste and municipal wastewater sludge digestion under mesophilic conditions and mean cell residence time (MCRT) of 15 days. The data were extracted from EBMUD (2008). As shown, the food waste tested had a higher VS content than municipal wastewater sludge (86.3 vs. 77%). Food waste is more digestible as indicated by the larger VS destruction (73.8 vs. 38-57%) after 15 days of anaerobic digestion and has larger methane formation potential (6-8.5 vs. 5 ft^3/lb TS applied). The methane concentrations in the biogas produced from these two types of feed are essentially the same (64 vs. 63%). However, it should be noted that the methane concentration was lower (59%) at a shorter MCRT of 10 days (EBMUD, 2008).

Table 1.1: Comparison of Anaerobic Digestion of Food Waste and Wastewater Sludge

Parameter	Units	Food Waste	Wastewater Sludge
VS in Feed (as % of TS)	**%**	86.3	77
VS destruction	**%**	73.8	38 - 57
CH_4 content	**%**	64	63
Methane Production	**ft^3/lb TS applied**	6-8.5	5

Source: EBMUD, 2008.

1.4 Biogas from Anaerobic Digestion

1.4.1 Characteristics of biogas generated from anaerobic digestion

CH_4 and CO_2 are the main components of biogas generated from anaerobic digestion. Biogas also contains other trace gases, moisture, PM and contaminants such as volatile organic compounds (VOCs), sulfur compounds, siloxanes, and ammonia. Table 1.2 shows the typical compositions of biogas (values of landfill gas are listed for comparison). It should be noted that the ranges of concentrations reported in the literature are wider than those shown in this table. This composition can vary between different plants and within in a specific plant due to the differences in feed composition and operating conditions of its anaerobic digesters.

Table 1.2: Biogas Composition and Quality

Parameter	Units	Sewage Gas	Landfill Gas
CH_4	%	65-75	45-55
CO_2	%	20-35	20-30
CO	%	<0.2	<0.2
N_2	%	3.4	10-25
O_2	%	0.5	1-5
H_2	%	trace	0.0
H_2S	mg/Nm^3	<8,000	<8,000
NH_3	mg/Nm^3	trace	trace
Siloxanes	mg/Nm^3	<0.1-5.0	<0.1-5.0
Net Calorific Value	kWh/Nm^3	6.0-7.5	4.5-5.5
Normal Density	kg/Nm^3	1.16	1.27
Wobbe Index	kWh/Nm^3	7.3	
Methane Number	-	134	136

Source: Razbani et al., 2011.

1.4.2 Beneficial uses of biogas

Using biogas in power generation (when compared to fossil fuels) avoids additional GHG emissions because it emits the same amount of CO_2 into the atmosphere as was originally absorbed during photosynthesis in the natural CO_2 cycle (Razbani *et al.*, 2011). With regards to beneficial uses of biogas generated from anaerobic digestion, internal combustion (IC) engines are the most prevalent technology used in WWTPs and it is often in a combined heat and power (CHP) arrangement where the electricity and waste heat generated are used to warm the digesters or to heat buildings (O'Neill, 2012). Two basic designs of IC engines are compression-ignition (diesel engines) and spark-ignition (Otto-cycle), the latter of which being almost exclusively used for cogeneration applications fueled solely by biogas (CH2M HILL, 2014; Razbani *et al.*, 2011).

IC engines are available in sizes from 300 kW to >5 MW. IC engines have proven to be reliable power generators, provided proper maintenance is given. However, emissions from IC engines are typically higher than those of other prime movers. The most significant pollutants in the exhausts are carbon monoxide (CO), NO_x, VOCs, and sulfur oxides (SO_x) when biogas is used as the fuel. The emission profile can be improved through better design and control of the combustion process (e.g., lean-burn combustion). With lean-burn and CHP operation, the overall energy recovery efficiency of 70 to 85% have been reported (CH2M HILL, 2014; Razbani *et al.*, 2011). For engine emission controls, other alternatives include using 3-way catalysts on rich- or lean-burn engines, and using selective catalytic reduction (SCR) on lean-burn engines (Warner, 2009).

A flaring system and a boiler are often needed to manage excess biogas during outage or maintenance of the cogeneration system. Fueling boilers is the most common approach for biogas utilization for small installations (CH2M HILL, 2014).

Although significant developments have been made on IC engines to operate primarily on biogas over the past decade, the smallest IC engines are approximately 300 kW, which require 12,000 scf biogas/day. Small WWTPs may need to supplement their biogas with natural gas to fulfill the minimum fuel requirement. Microturbines, small high-speed combustion gas turbines, are suitable for small to mid-size WWTPs. The electrical efficiency of microturbines is approximately 27% at 30 kW operations. With a CHP arrangement, the overall efficiency is between 70% and 90%. Due to their lower NO_x emissions, microturbines are gaining popularity in areas with stringent air quality regulations (CH2M HILL, 2014).

Biogas can be converted to biomethane (95 to 98% methane by volume) by removing CO_2 and other impurities. Biomethane can replace fossil fuels such as natural gas in homes and factories. It can be injected into a natural gas pipeline, and converted to compressed natural gas (CNG) or liquefied natural gas (LNG) for vehicle uses. Biomethane can also be used to produce renewable hydrogen in fuel cells (O'Neill, 2012). Biomethane suitable for injection into a natural gas pipeline is typically >95% CH_4, <3% CO_2, <0.4% O_2, and <10 ppm H_2S (CH2M HILL, 2014; Liang, 2009). Compressed biomethane, in compliance with CARB's Alternative Fuel Specifications for CNG, can also be used as vehicle fuel. The requirements include <88% CH_4, <6% ethane (C_2H_6), >3% propane (C_3H_8), <1% O_2, 1.5-4.5% "CO_2 + N_2", and <16 ppm total sulfur (CH2M HILL, 2014).

1.5 Air Quality Issues Related to Beneficial Uses of Biogas

1.5.1 Compounds of concern in biogas

Presence of several trace compounds in raw biogas produced from anaerobic digestion may have adverse effects on beneficial uses. Removal of these trace compounds is often done through pretreatment (or conditioning). The most significant components targeted in biogas conditioning/pretreatment are hydrogen sulfide (H_2S), siloxanes, moisture, PM, ammonia, and CO_2.

Hydrogen sulfide is a toxic product formed from sulfates and organic sulfur compounds in the feedstock under anaerobic conditions. During combustion, H_2S will react to form SO_2, then sulfurous acid (H_2SO_3) and sulfuric acid (H_2SO_4). These acids are corrosive to downstream equipment such as IC engines (Razbani *et al.*, 2011). Stringent H_2S limits are usually imposed by regulatory agencies. Formation of H_2S can be prevented through liquid phase treatment by adding iron salts such as ferrous chloride ($FeCl_2$), ferric chloride ($FeCl_3$), and ferrous sulfate ($FeSO_4$) into the digester or to the digester feed. Gas treatments for H_2S removal include adsorption, chemical scrubbing, and biological scrubbing using bio-trickling filters (Huertas *et al.*, 2011). Iron sponge adsorption is the most commonly-used H_2S removal system. In this process, biogas flows through process vessels containing wood chips or granular activated carbon (GAC) impregnated with hydrated ferric oxide. Hydrogen sulfide in the biogas reacts with ferric oxide to form iron sulfide. Historically, the spent iron sponge was disposed of at municipal landfills; however, it is now characterized as hazardous by OSHA Hazard Communication Standard (29 CFR 1910.1200) and is listed among the California Hazardous Substances. Alternative iron oxide adsorbents such as SulfaTreat®, Sulfur-Rite®, and Sulfa-Bind®, that overcome these disadvantages of safety and disposal, are increasingly popular (CH2M HILL, 2014).

Siloxanes are often used in cosmetics, detergents and building materials and frequently found in household waste and wastewater. If siloxanes are present in the feedstock to the anaerobic digesters, the low-molecular-weight siloxanes will volatilize into biogas. When this biogas is subsequently combusted in an IC engine, turbine, or boiler, siloxanes will be converted into silicon dioxide and deposited internally in the machine, exhaust manifolds, and turbochargers, increasing wear and tear. Although food waste slurry should contain few or no siloxanes, they are often contained in biogas from codigestion with wastewater sludge. Activated carbon adsorption is currently the best available technology for removing siloxanes from biogas. Upstream removal of H_2S and moisture are important for optimal performance of the GAC absorbers. Silica gels are an alternative to GAC that are gaining acceptance as an option for siloxanes removal for their faster removal rates (CH2M HILL, 2014).

Nitrogen in the food waste typically enters the digesters as organic nitrogen and a significant fraction of it hydrolyzed in the process, leaving the digesters as ammonia in the digestate. The level of ammonia concentration in the digestate of municipal WWTPs can be as high as 1,300 mg/L. Consequently, biogas also contains ammonia at a concentration in equilibrium with that in the digestate. Ammonia in the ambient air poses health risks and it can be a precursor to airborne particles. Ammonia in the biogas can react with water to form ammonium hydroxide (NH_4OH), which will corrode certain metals, such as aluminum and copper, making bearings more susceptible to corrosion from ammonia (Razbani *et al.*, 2011).

Presence of high amount of diluents (e.g., moisture and CO_2) in biogas causes lower heating value and smaller Wobbe index compared to natural gas. The heat of combustion is shared with diluent, which causes a lower flame temperature and a slower flame propagation speed (BACWA, 2014; Razbani *et al.*, 2011). High moisture content may also cause starting problems. Often used for moisture removal are mechanical gas dryers, heat exchangers coupled with water chillers, desiccant dryers coupled with coalescing filters. Common CO_2 removal methods include water scrubbing, chemical scrubbing, pressure swing adsorption, condensation and membrane separation (CH2M HILL, 2014; Huertas *et al.*, 2011). Particulates should also be removed to improve the performance of downstream power generation equipment for which particulate filters are commonly used (CH2M HILL, 2014).

It should be noted that odorous compounds are often generated under anaerobic conditions. Proper odor control in areas of food waste processing and biogas generation and utilization may be needed.

1.5.2 Air regulations related to beneficial uses of biogas

There are many federal, state, and local regulations governing biogas production and uses in various aspects (air, water/wastewater and waste). As an example, the *Permit Guidance for Anaerobic Digesters and Co-digesters* provides the basic permitting framework and requirements for anaerobic digestion projects in California (California EPA, 2011). Since the main objective of this project is to evaluate air quality issues related to biogas from anaerobic digestion of food waste, the focus here is on air-related concerns.

Federal air permitting requirements include (AgSTAR, 2014):

- IC engines must meet federal emission standards (40 CFR Part 89) for non-road engines. These standards include thresholds for NO_x, hydrocarbons, CO, and PM.

- Newer models of spark ignition IC engines must also meet federal regulations (40 CFR Part 60, Subpart JJJJ). These standards include thresholds for NO_x, CO and VOCs. Engines greater than 500 horsepower require initial and periodic performance testing, while smaller engines require initial testing.
- Steam generating units constructed after June 19, 1984 with a heat capacity of 10 MMBTU/hr must meet federal requirements on PM, sulfur dioxide (SO_2), and NO_x (40 CFR Part 60, Subpart Db or 40 CFR Part 60, Subpart Dc).
- Boilers with a heat capacity over 10 MMBTU/hr are subject to National Emission Standards for Hazardous Air Pollutants (40 CFR 63 Subpart DDDDD). Regulated pollutants include PM, arsenic, cadmium, chromium, lead, magnesium, mercury, and nickel. Emissions from combustion device must not exceed EPA's National Ambient Air Quality Standards for criteria air pollutants (i.e., ozone, PM, CO, NO_x, SO_2 and lead).
- Reciprocating IC engines or generators are required to meet the revised national emission standards (40 CFR Part 63, Subpart ZZZZ). Under this regulation, generators over 300 horsepower must meet a CO emission limit and perform specified maintenance and control procedures.

CARB oversees 35 air districts. Each air district has different requirements depending on its attainment status. Combustion devices may require permits if they are over federal thresholds. If organic waste is added, the type of organic waste may cause additional permit requirements (AgSTAR, 2014).

As an example, stringent regulations are being imposed in the jurisdictional area of the South Coast Air Quality Management District (SCAQMD) in southern California (Liang, 2009). In its most recent amendment of Rule 1110.2, SCAQMD requires biogas-fueled engines to meet stringent emission limits for NO_x (11 ppmvd), CO (250 ppmvd) and VOCs (30 ppmvd) by January 1, 2016, provided that the monthly-average biogas usage by the engines is 90% or more (Note: ppmvd = parts per million by volume, corrected to 15% oxygen on a dry basis and averaged over 15 minutes) (SCAQMD, 2012). To generate information to support rulemaking decisions, SCAQMD provided partial funding to the Orange County Sanitation District to conduct a full-scale demonstration project. The project included an activated carbon system for removal of siloxanes and other contaminants from the digester gas, an oxidative catalyst for post-combustion control of CO and VOCs emissions, and an SCR system with urea injection for post-combustion control of NO_x emissions. The data collected from this demonstration project showed that the system can meet average emissions limits for NO_x, CO and VOCs of 11, 250 and 30 ppmvd @15% O_2, respectively. Further evaluations were being performed to determine if the control system could meet the emission limits under all operating scenarios such as start up, shut down, changing loads and fuel blends (Liang *et al.*, 2011).

1.5.3 Environmentally-friendly beneficial uses of biogas

Biogas is being recognized as a renewable fuel and it can reduce GHG emissions when used in place of fossil fuel, depending on how the biogas is created, transported, and ultimately utilized. CARB supports the environmentally-friendly beneficial use of biogas as a low carbon fuel to reduce anthropogenic GHG emissions. Further, the most environmentally-friendly beneficial uses of biogas are in processes that do not exacerbate existing air quality issues in areas such as the South Coast Air Basin and the San Joaquin Valley. Residents of these regions are especially vulnerable to the health effects of air pollution, and

some of the highest incidences of asthma in California can be found in communities located in these areas. It is therefore critical to understand the emission profile of biogas from its creation to end use to ensure that the affected communities are not further harmed. Whether the captured biogas is used as a replacement for transportation fuel or to generate electricity, the reuse projects should ensure that regulatory requirements, such as meeting Best Available Control Technology (BACT), are met (Le, 2015).

Ensuring that biogas creation, transportation, and use is as environmentally beneficial as possible aligns well with existing federal, state, and local regulations governing the use of renewable fuels. Regardless of project type, the reuse projects should ensure the employment of the most up-to-date technologies that have already been proven and are cost-effective, to ensure public health continues to improve (Le, 2015).

CHAPTER 2:
Project Objectives and Approaches

2.1 Objectives of This Project

Although anaerobic codigestion of food waste is a viable process, full-scale operation of this process is still new. There is a lack of readily available scientific information on the quality of raw biogas as well as on potential emissions from power generation using this biogas. This information is needed for determining conditioning requirements for beneficial use of raw biogas, for selecting power-generating equipment, and for air quality permitting.

The overall objectives of this research were (1) to develop scientific information with regards to quality and quantity of biogas from anaerobic codigestion of food waste and municipal wastewater sludge, (2) to assess the need for and performance of conditioning/pretreatment systems for biopower generation, and (3) to develop scientific information with regards to impacts on air quality from biopower generation using this biogas.

2.2 Approaches of This Project

In addition to conducting a literature review on anaerobic digestion of food waste, biogas generation, and beneficial uses of biogas, field data were collected from the wastewater treatment plant of the Central Marin Sanitation Agency (San Rafael, CA) which employs two anaerobic digesters for codigestion of FOG, food waste, primary sludge, and thickened waste activated sludge and which uses an internal combustion engine to generate biopower using biogas from the anaerobic digesters. The experimental approaches of this study were (1) to assess the production rate and composition of biogas from anaerobic codigestion of food waste, (2) to evaluate the removal of reduced sulfur compounds and siloxanes from raw biogas by the gas conditioning systems, and (3) to determine the characteristics of air emissions from biopower generation.

CHAPTER 3:
Experimental Plan and Sampling Protocol

3.1 Experimental Plan

3.1.1 The project site

All field data for this project were collected from the Central Marin Sanitation Agency (CMSA) WWTP, which is located at 11301 Andersen Drive, San Rafael, California. This plant is the largest wastewater treatment facility in Marin County. It treats wastewater collected from households, businesses, and institutions in central Marin County and discharges the treated wastewater into the central San Francisco Bay through a 2-mile long outfall. In full compliance with State and Federal water pollution control laws, regulations, and policies, the CMSA processes and disposes of approximately ten million gallons per day (MGD) of wastewater and has treated in excess of 116 MGD during peak rainfall periods. A total of approximately 3,988 million gallons of wastewater was treated in 2013 (CMSA, 2013).

The incoming raw wastewater goes through bar screens, aerated grit chambers, primary clarifiers, biological treatment units (i.e., biotowers + fine-bubble aeration tanks for activated sludge process), secondary clarifiers, chlorine contact tanks, and then dechlorination before discharge.

The primary sludge and the thickened waste activated sludge (TWAS) which is thickened by dissolved air flotation are fed to two mesophilic anaerobic digesters. The biogas produced in the digesters is used to generate electricity (which supplies about one-half of the Agency's power needs) and to heat plant process water. When digester biogas is not available, the internal combustion (IC) engine generator switches to natural gas. The digested biosolids are pumped to centrifuges where excess water is removed. The dewatered biosolids are hauled to a sanitary landfill for use as alternative daily cover, or utilized in a reuse process such as compost or land applied for agricultural use (CMSA, 2013). Figure 3.1 is the site plan of the CMSA and Figure 3.2 is an aerial photo of the CMSA.

3.1.2 Food waste management at the project site

The Central Marin Commercial Food-to-Energy Program is a public-private partnership between CMSA and Marin Sanitary Service (MSS). There are over 500 food waste generators (restaurants, delis, grocery stores) in the MSS service area. The estimated amount of food waste that could be collected if all the generators in the area participated in the program, is estimated to be up to 20 tons per day. The pre-consumer commercial food waste is collected and then transferred to the MSS Transfer Station for processing by hoppers, belts and magnet, and then transported to CMSA for further treatment (Dow and Garbarino, 2013). The facility has received approximately 10,000 gallons/day of FOG, mostly from restaurants in the area, since November of 2013 and approximately four tons/day of food waste up to six days a week since February of 2014.

Figure 3.1: Site Plan of the Central Marin Sanitation Agency

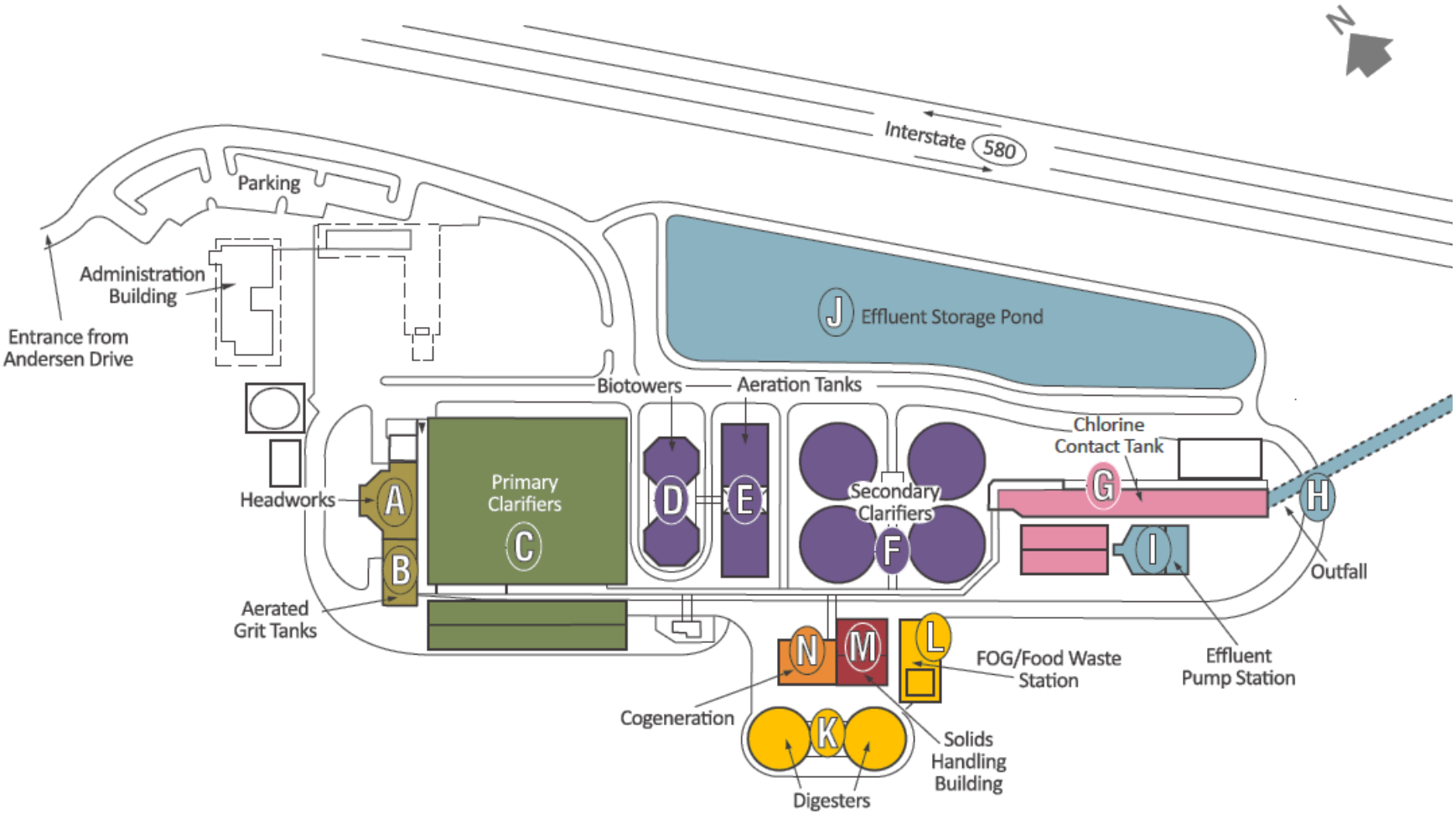


Figure 3.2: Aerial Photo of the Central Marin Sanitation Agency

The FOG and food waste are typically received in the mornings. They are then mixed, grinded, and recirculated in a storage tank for a couple of hours. Pictured in Figure 3.3 is a truck unloading FOG at the FOG and food waste processing area. The area in the center of the photo is for unloading of food waste and the storage/slurry tank is underneath that area. The slurry is then screened, by using a drum screen paddle mixer, to remove materials that are not readily digestible before being fed into the digesters (typically in late afternoons).

Figure 3.3: Photo of the Processing Area for the FOG and Food Waste

Figure 3.4 shows the pipes for slurry recirculation and for digester feeding. Figure 3.5 is a photo of fibrous material or screenings removed from the food waste slurry. The food waste slurry is fed to each digester on alternate days to be co-digested with primary sludge and TWAS.

Figure 3.4 – Photo of Piping for Slurry Recirculation and for Digester Feeding

Figure 3.5: Photo of Fibrous Material or Screenings Removed from the Food Waste Slurry

3.1.3 Anaerobic digestion at the project site

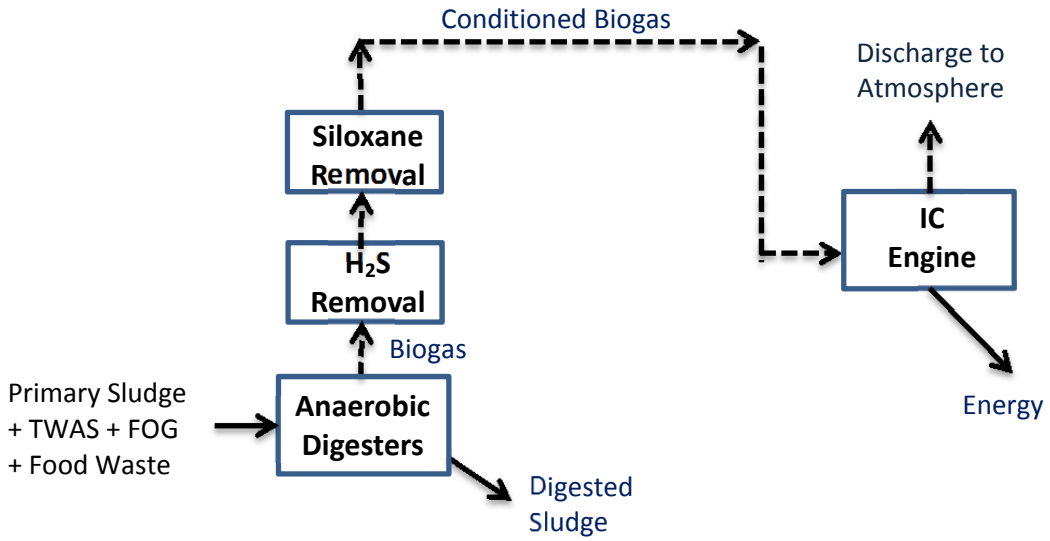
To upgrade for codigestion of FOG and food waste, CMSA overhauled its 1985 anaerobic digestion system by installing new covers, mixers, biogas purification equipment and support systems (Creer, 2012). The gas mixing system was replaced with a pump mixing system. The floating cover of each digester was replaced with a two-layer plastic membrane roof top with air in between to regulate the pressure inside the digesters. The covers were replaced to increase available digester volume and to avoid potential difficulties that could arise from using floating covers (Kennedy/Jenks Consultants, 2008). The two digesters at the project site are currently running in a mesophilic, single-stage, and continuous mode. The hydraulic residence time of the digesters is typically 36 days at the current solids loading rates (Dow and Garbarino, 2013). Figure 3.6 is a photo of the anaerobic digesters at CMSA.

Figure 3.6: Photo of the Anaerobic Digesters at CMSA

3.1.4 Biogas pretreatment at the site

The biogas from the two anaerobic digesters goes through a H_2S removal system and a siloxanes removal system before being fed to an IC engine for power generation. Figure 3.7 is the process flow diagram of biogas generation, conditioning, and utilization.

Figure 3.7: Process Flow Diagram of Biogas Generation, Conditioning, and Utilization



The biogas generated from anaerobic digestion is first fed to a recently-installed system (Mi SWACO, Chesterfield, MO) for removal of H_2S from the raw biogas. The system consists of two vessels filled with a synthetic blend of iron oxide media (SulfaTreat® 410 CHP) and operates in series and in a down-flow mode. Figure 3.8 is a photo of the hydrogen sulfide removal system. Some of the system parameters are listed below:

- Vessel diameter: 10 ft
- Media height per vessel: 4.5 ft
- Type of media: SulfaTreat® 410 CHP
- Media volume per vessel: 353 ft^3
- Media weight per vessel: 22,000 lbs
- Size of the media: 4 to 16 mesh
- Expected H_2S removal capacity: 25%-weight
- Expected influent biogas temperature: 95 ^oF
- Expected influent gas pressure: 10-in water column
- Design biogas flow rate: 260 cubic feet per minute (cfm)
- Design gas velocity: 3.35 ft/min

- Design influent H_2S concentration (max): 400 ppmv
- Design effluent H_2S concentration: 15 ppmv

Figure 3.8: Photo of the Treatment System for H_2S Removal

The effluent from the H_2S removal system goes through a condenser to reduce moisture content before fed to two activated carbon adsorbers (Model SAG 48V, Applied Filter Technologies, Snohomish, WA) for siloxanes removal. The system consists of two vessels filled with GAC and operates in parallel and in an up-flow mode. Figure 3.9 is a photo of the siloxanes removal system. Some of the system parameters are listed below:

- Vessel size: 48-inch diameter × 72-in straight side, 45^o bottom cone
- Media height per vessel: 6 ft
- Type of media: GAC
- Media capacity per vessel: 2,500 lbs
- Expected influent gas relative humidity: 25 to 50%
- Expected influent gas temperature: 50 to 80 ^{o}F
- Expected influent gas pressure: 2 psig
- Design biogas flow rate: 260 cfm
- Design influent siloxanes concentration: 2 to 6 ppm
- Design effluent siloxanes concentration: < 100 ppb total siloxanes

Figure 3.9: Photo of the Siloxane Adsorbers

CMSA currently budgets for one SulfaTreat® media and two siloxanes media bed disposals per year (CMSA, 2014).

The effluent from the siloxane removal system is fed to the IC engine (Waukesha P48GLD, GE Power & Water, Waukesha, WI) for cogeneration. Figure 3.10 is a photo of the IC engine. Some of the system parameters are listed below:

- Cylinders: V16
- Piston displacement: 2,924 in^3 (48L)
- Bore & stroke: 5.98-in × 6.5-in (152 mm × 165 mm)
- Compression ratio: 11:1
- Power: 710 to 1175 bhp
- Fuel pressure system: 8” water column to 5 psig
- Starting system: 150 psi max. air/gas 24V DC electric

The historic average of congenerator runtime on biogas is around 8 hours/day. With codigestion of food waste and FOG, the runtime on biogas could increase to 15 hours or longer (Dow and Garbarino, 2013).

Figure 3.10: Photo of the IC Engine

3.1.5 Experimental approaches

The following experimental approaches were used in this study:

(1) to assess production rate and composition of raw biogas from anaerobic codigestion of food waste and municipal wastewater sludge;

(2) to evaluate removals of reduced sulfur compounds and siloxanes from raw biogas by the gas conditioning systems and to evaluate the energy content of the biogas as well as the performance and robustness of the conditioning systems; and

(3) to determine characteristics of emissions from the IC engine and the reliabilities and efficiencies of the system.

3.2 Sampling Plan and Analytical Methods

3.2.1 Purposes of sampling

It should be noted that all of the biogas and IC engine emission samples collected in this study were for the purpose of research only, and are not intended to be used for regulatory compliance. Although samples were collected with care, the sampling approach might not meet all requirements for compliance data. Historical data from this facility prior to beginning codigestion were also included in the analysis when appropriate so that comparisons could be made. Samples were collected for a consecutive twelve-week period (mid-August to early November of 2014).

3.2.2 Biogas production and characteristics

Table 3.1 tabulates the sampling locations, types of analysis, and frequencies of sampling. TS and VS of various components of the feed stock (i.e., primary sludge (PS), TWAS, FOG, and food waste) were sampled and analyzed on a daily basis. Selected samples were also analyzed for chemical oxygen

demand (COD). The loading rates for PS, TWAS, FOG, and food waste were recorded and used to calculate the mass loading rates to the digesters. Operational temperature and pH of the digesters were also recorded. TS and VS of the digestate were analyzed on a daily basis to facilitate the determination of VS destruction. Concentrations of ammonia and volatile acids (VA) and alkalinity of the digestate were also determined daily.

Table 3.1: Location and Frequency of Sampling and Types of Analysis (Anaerobic Digesters)

	Feed to Digesters	Digestate	Biogas	Frequency of Sampling
Total Solids (%)	√	√		Daily
Volatile Solids (%)	√	√		Daily
COD (mg/kg)	√			Selected samples
pH		√		Daily
Temperature (^oF)		√		Daily
Methane (%)			√	Daily
CO_2 (%)			√	Daily
H_2S (ppmv)			√	Daily
VOCs			√	Twice
Ammonia (mg/L)		√		Daily
Siloxanes (ppmv)			√	Once
Loading Rate (gallon/d)	√			Daily
Biogas Production (ft^3/d)			√	Daily

3.2.3 Biogas conditioning

A portable biogas analyzer, Gas Data GFM416 (Gas Data Limited, Whitley, Coventry, United Kingdom) was acquired for this project. The measurement ranges of the analyzer are: CH_4 (0 to 100%), CO_2 (0 to 100%), O_2 (0 to 25%) and H_2S (0 to 5,000 ppmv). Biogas samples were collected from the effluent from the digesters, the H_2S removal system, and the siloxane adsorbers and were analyzed for CH_4, CO_2, O_2, and H_2S twice daily with the portable biogas analyzer. The analyzer was routinely calibrated according to manufacturer's specifications.

Selected samples were also analyzed for siloxanes and VOCs as well as for EPA Method 3C testing by an outside certified laboratory (Atmospheric Analysis and Consulting, Ventura, CA) as a QA/QC check. The sampling apparatus consisted of a stainless probe connected by a Teflon line to a Tedlar sample bag contained in an airtight canister. Upon evacuation of the air in the canister, sample gas was drawn into the bag. On completion of each run, the bag sample was sealed and transported to the laboratory.

Table 3.2: Location and Frequency of Sampling and Types of Analysis (Biogas Conditioning Systems)

	Influent	Effluent	Frequency of Sampling
Methane, CO_2, H_2S, O_2	√	√	Twice Daily
Siloxanes and VOCs	√	√	Selected Samples
Biogas Flow Rate (ft^3/d)	√		Daily

3.2.4 Emissions from the IC engine

Table 3.3 tabulates the sampling locations, types of analysis, and frequencies of sampling to assess the emissions from the IC engine. A portable emission analyzer, EMCON J2KN Pro Industrial OCNX-IR (ECOM America, Ltd., Gainesville, GA), was acquired for this project. The unit is equipped with sensors for CH_4, CO_2, CO, NO_2, NO, SO_2, and O_2. The emissions were surveyed by the portable emission analyzer twice daily (once when the engine was fueled by biogas and the other when the engine was fueled by natural gas). The analyzer was routinely calibrated according to manufacturer's specifications.

Tests on the IC engine emissions were also conducted by a Bay Area Air Quality Management District (BAAQMD)-certified source tester (Total Air Analysis, Carson, CA) on two separate days during the study period. For each test run, samples were also taken and analyzed for air toxics (i.e., formaldehyde, polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzodioxins/furans (PCDD/F) and VOCs) by a certified laboratory, Quantum Analytical Services (Carson, CA). These IC engine emissions tests were conducted when the engine was fueled by the biogas.

Table 3.3: Location and Frequency of Sampling and Types of Analysis (IC Engine)

	Influent	Effluent	Frequency of Sampling
Methane	√	√	Daily
H_2S	√		Daily
CO_2	√	√	Daily
CO		√	Daily
NO_2		√	Daily
NO		√	Daily
SO_2		√	Daily
O_2	√	√	Daily
VOCs	√	√	Twice
Formaldehyde		√	Twice
PAHs		√	Twice
PCDD/F		√	Twice
H_2S		√	Twice
Biogas Flow Rate (ft^3/d)	√		Daily

3.2.5 Distribution of samples for in-house versus outside laboratories

The collected field samples were analyzed by in-house and/or outside laboratories for NO, NO_2, CO, CO_2, O_2, SO_2, formaldehyde, VOCs, PAHs, and PCDD/F of the gaseous samples and TS, VS, COD, pH, temperature, ammonia, VA, and alkalinity of the food waste and/or digestate samples. Table 3.4 summarizes the distribution of samples for in-house and outside laboratory analyses.

Table 3.4: Samples Analyzed In-house vs. Outside Laboratories

	Type	In-house	Outside Lab
TS	Liquid	√	
VS	Liquid	√	
COD	Liquid	√	
Alkalinity	Liquid	√	
Ammonia	Liquid	√	
Siloxanes	Gas		√
CH_4	Gas	√	√
CO_2	Gas	√	√
CO	Gas	√	√
H_2S	Gas	√	√
NO_2	Gas	√	√
NO	Gas	√	√
SO_2	Gas	√	√
O_2	Gas	√	√
VOCs	Gas		√
Formaldehyde	Gas		√
PAH	Gas		√
PCDD/F	Gas		√

3.2.6 Analytical methods

Table 3.5 tabulates the analytical methods that were used to analyze the collected samples.

Table 3.5: Analytical Methods for Collected Samples

	Type	Analytical Methods
TS	Liquid	SM 2540G
VS	Liquid	SM 2540G
COD	Liquid	SM 5220 C,D
Ammonia	Liquid	SM 4500-NH_3 H
pH	Liquid	SM 4500-H^+ B
Temperature	Liquid	EPA 170.1
Siloxanes	Gas	GC/FID
Methane	Gas	Portable Biogas and Emission Analyzers
CO_2	Gas	Portable Biogas and Emission Analyzers
H_2S	Gas	Portable Biogas Analyzer
NO_2	Gas	Portable Emission Analyzer
NO	Gas	Portable Emission Analyzer
SO_2	Gas	Portable Emission Analyzer
CO	Gas	Portable Emission Analyzer
O_2	Gas	Portable Biogas and Emission Analyzers
VOCs	Gas	TO-14/TO-15
Formaldehyde	Gas	EPA Method 323
PAHs	Gas	CARB Method 429
PCDD/F	Gas	CARB Method 428

CHAPTER 4:
Results and Discussion

4.1 Characteristics of Feed and Digestate of Anaerobic Digestion

4.1.1 Characteristics of feed to the anaerobic digesters

The two digesters at CMSA were designed to treat PS and TWAS, which is thickened by dissolved air flotation, from its wastewater treatment operation. The digesters started to receive FOG up to six days per week in November, 2013 and food waste in February, 2014.

A consecutive 12-week period of field data collection was conducted from 08/18/14 to 11/07/14, at CMSA. Since there are considerable daily fluctuations in the quantity and quality of FOG and food waste, and the typical hydraulic residence time of anaerobic digestion was 36 days during the study period, determination of characteristics of feed and digestate on a daily basis would not be meaningful. Instead, average values were used for the following analyses in order to identify trends.

Samples of PS, TWAS, FOG, and food waste were collected daily and analyzed for TS and percentage of VS in the TS. The loading rates of these four streams were measured and recorded. Table 4.1 provides statistics on the characteristics and flow rates of the feed streams to the anaerobic digesters (the raw data can be found in Appendix A). As shown, the average TS values are 4.4 ±0.6%, 4.5±0.7%, 3.1±2.1%, and 20.6±3.3% for PS, TWAS, FOG, and food waste, respectively. The data indicate that the TS concentrations for PS, TWAS, and food waste are relatively consistent, while those for FOG vary considerably. The average percentages of VS in the TS are 84±2%, 83±1%, 91±4%, and 90±3% for PS, TWAS, FOG, and food waste, respectively. As expected, the organic contents of FOG and food waste (91% and 90%) are higher than those of PS and TWAS (84% and 83%). Samples were also taken from the combined feed stream of FOG and food waste, and the TS, percentage of VS, and COD were 5.5±5.7%, 88.6±7.2%, and 39,900±28,600 mg/L (see Appendix A). They are grab samples and the results show significant variation among individual samples. However, the average TS and VS values of the combined stream are comparable to the corresponding flow-rate weighted average values of the FOG and food waste.

Table 4.1: Characteristics and Flow Rates of Feed Streams to the Anaerobic Digesters

	Primary Sludge			TWAS			FOG			Food Waste		
	TS (%)	VS (%)	Loading Rate (gallons)	TS (%)	VS (%)	Loading Rate (gallons)	TS (%)	VS (%)	Loading Rate (gallons)	TS (%)	VS (%)	Loading Rate (tons)
Count	59	59	65	59	59	65	60	60	58	70	70	71
Maximum	7.8	88	42,072	5.3	92	26,685	11.0	98	20,500	29.3	94	8.6
Minimum	3.5	80	17,630	3.8	80	8,930	0.4	77	4,000	12.9	72	1.7
Median	4.3	84	28,069	4.6	83	16,016	2.4	92	10,500	20.4	91	3.6
Mean	4.4	84	28,588	4.6	83	16,098	3.1	91	11,543	20.6	90	4.1
Std. Dev.	0.6	2	4,769	0.7	11	2,967	2.1	4	4,316	3.3	3	1.9

By using the average values of TS, VS and loading rate of each stream (i.e., PS, TWAS, FOG, and food waste), the corresponding values were calculated for the total feed stream to the anaerobic digesters (Table 4.2). As shown, the average total flow rate to the digesters is 57,300 gallons per day which contains 4.5% TS and the VS percentage is 85.1% during the days when FOG and food waste were added as part of the feed to the digesters. The average mass loadings of TS and VS are 21,500 and 18,300 lb/day, respectively. The contributions to the total or volatile solids in the total feed are 49, 28, 15, and 9% for PS, TWAS, FOG, and food waste, respectively. FOG and food waste combined represents approximately 25% of TS or VS fed to the digesters. In other words, the addition of FOG and food waste increases the VS loading to the digester by one-third (25%:75%), which implies that biogas formation should increase by at least 33% with codigestion, since the volatile solids of FOG and food waste are more readily digestible than those in the municipal wastewater sludge.

It should be noted that the facility currently only receives FOG and food waste up to six days per week. By taking that into consideration, the weighted daily average flow rate would be 55,500 gallons, the TS and VS percentage would be 4.5% and 84.5%, and the mass loadings of TS and VS would be 20,800 and 17,700 lb/day. These values are slightly smaller than the corresponding ones in Table 4.2, which do not consider the off-days for FOG and food waste addition.

Table 4.2: Characteristics and Loading Rates of Total Feed to the Anaerobic Digesters

	PS	TWAS	FOG	Food Waste	Total Daily Feed
Loading Rate (gallons)	28,588	16,098	11,543	1,077	57,305
TS (%)	4.4	4.6	3.1	20.6	4.5
VS (%)	83.7	82.7	91.5	90.4	85.1
TS (lb/d)	10,543	6,155	2,943	1,854	21,495
VS (lb/d)	8,828	5,089	2,692	1,676	18,285
% in TS of Total Feed	49.0	27.8	14.7	9.2	100.0
% in VS of Total Feed	48.3	27.8	14.7	9.2	100.0

4.1.2 Characteristics of the digestate

The digestate samples were also taken and analyzed for TS, VS, pH, temperature, VA, alkalinity, and ammonium. Table 4.3 provides some statistics on characteristics of the digestate (the raw data can be found in Appendix A). Using the TS and VS values of the combined feed and the digestate and assuming that the flow rates of the feed and the digester effluent are the same, the calculated VS destruction is 11,460 lb VS/day and VS destruction efficiency is 64.9% (lb VS destructed/lb VS applied). The destruction efficiency is in line with the data in literature, as shown in Table 1.1 (EBMUD, 2008).

The average values are 7.2±0.0, 99.7±0.3 ^{o}F, 4,853±179 mg/L, and 1,137±83 mg/L for pH, temperature, alkalinity, and NH_4^+-N, respectively. As shown, all of these operational parameters are in narrow ranges. This implies the anaerobic digesters are being operated under stable conditions. The ammonium concentrations are around 1,150 mg/L, which does not seem to inhibit to biological activities.

Table 4.3: Characteristics of the Digestate

	TS (%)	VS (%)	pH	Temp (^oF)	Volatile Acids (mg/L)	Alkalinity (mg/L)	NH_4^+-N (mg/L)
Count	59	59	59	60	60	60	58
Maximum	2.2	70	7.3	100.7	162	5,300	1,322
Minimum	1.9	63	7.2	99.3	90	4,600	1,008
Median	2.0	68	7.2	99.7	122	4,850	1,119
Average	2.0	67	7.2	99.7	124	4,853	1,137
Std. Dev.	0.1	2	0.0	0.3	18	179	83

4.2 Biogas Production and Conditioning

4.2.1 Production and characteristics of biogas generated

Raw biogas generated from the anaerobic digesters was sampled and analyzed by the portable biogas analyzer for CH_4, CO_2, O_2, and H_2S twice daily. Table 4.4 provides statistics on the characteristics of the biogas from the digesters (the raw data can be found in Appendix B). The concentrations in the raw biogas are 62.6±0.7%, 36.1±0.7%, 0.0±0.0%, and 127±75 ppmv for CH_4, CO_2, O_2, and H_2S, respectively. With the average methane concentration of 62.6%, the heating value of the raw biogas is slightly greater than 600 BTU/ft^3.

The daily biogas flow rate to the IC engine was also measured and recorded. The daily biogas extraction rate, not necessarily the biogas generation rate, depends mainly on two operating factors. First, keeping the dome level and pressure in the domes below the recommended value of the membrane cover manufacturer; and second, making sure that there is enough gas to run the IC engine during the peak power window, 12 to 6 pm, until October 31 when the window period ends. As shown in Table 4.4, the daily biogas flow rate is 212,800 ft^3/day. The corresponding biogas generation rate is 10.2 ft^3 biogas/lb TS applied or 6.4 ft^3 CH_4/lb TS applied, which is within the range, 6 to 8.5 ft^3 CH_4/lb TS applied for food waste as reported in literature, while the corresponding value for the municipal wastewater sludge is 5 ft^3 CH_4/lb TS applied (EBMUD, 2008). On the basis of VS destruction, the biogas generation rate is 18.5 ft^3 biogas/lb VS destructed, or 11.6 ft^3 CH_4/lb VS destructed. The average hydrogen sulfide (H_2S) concentration in the raw biogas is 127±75 ppmv.

Table 4.4: Daily Biogas Production Rate and Composition

		Raw Biogas			Post H_2S Adsorbers			Post Siloxanes Adsorbers		
Date	**Biogas flow rate (ft^3/day)**	**CH_4 (%)**	**CO_2 (%)**	**H_2S (ppm)**	**CH_4 (%)**	**CO_2 (%)**	**H_2S (ppm)**	**CH_4 (%)**	**CO_2 (%)**	**H_2S (ppm)**
Count	52	52	52	52	52	52	52	45	45	45
Maximum	330,079	64.3	37.2	323	64.8	37.5	43	64.8	37.0	0
Minimum	112,098	61.3	33.2	0	61.3	34.4	0	61.9	34.9	0
Median	199,827	62.7	36.4	133	62.8	36.3	0	63.6	36.1	0
Average	212,811	62.6	36.1	127	62.8	36.3	7	63.6	36.0	0
Std. Dev.	46,997	0.7	0.7	75	0.7	0.6	13	0.5	0.4	0

During a similar period in 2011 (08/18/11 to 11/07/11) when the anaerobic digesters only received PS and TWAS, the average biogas generation rate was 131,800±26,800 ft^3/day. With current codigestion of FOG, food waste, PS, and TWAS, the daily biogas yield has increased from 131,800 to 212,800 ft^3/day, a 61% increase. On the mass loading basis, the biogas yield has increased from 8.75 to 12.1 ft^3/lb VS entered the digesters, a 38% increase. The fact, that the increase in biogas production (61%) is larger than that in VS loading rate (38%), supports the argument that volatile solids in FOG and food waste are more readily biodegradable than those in the municipal wastewater sludge.

The raw biogas from the two anaerobic digesters goes through the H_2S removal system, the condenser, and the siloxane removal system for conditioning before being fed to the IC engine. The biogas from the H_2S removal system and from the siloxane removal system were also surveyed twice daily for CH_4, CO_2, O_2, and H_2S. As shown in Table 4.4, the average CH_4 concentrations are 62.6±0.7%, 62.8±0.7%, and 63.6±0.5% in the raw biogas, effluent from the H_2S adsorbers, and effluent from the siloxanes adsorbers, respectively. The apparent slight increase in methane concentration in the effluent from the siloxane adsorbers is plausibly due to the removal of moisture by the condenser ahead of the siloxane adsorbers. These values are essentially the same which implies that these two biogas conditioning systems have no, or insignificant, effects on methane concentrations of the biogas. On the other hand, the H_2S concentrations dropped from 127±75 ppmv to 7±13 ppmv by the H_2S removal system. As mentioned in Section 3.1.4, the system was design to yield an effluent H_2S concentration of 15 ppmv. The system appears to meet the design specifications. Hydrogen sulfide was not detected in the effluent of the siloxane adsorbers. Since the media contained in the two siloxane adsorbers are GAC, the additional removal of H_2S should be from the GAC in the adsorbers.

Samples of raw biogas, biogas in the effluent of the H_2S adsorbers, and biogas in the effluent of the siloxanes adsorbers were grabbed on October 29, 2014 and analyzed by an outside certified laboratory, (Atmospheric Analysis and Consulting, Ventura, CA) using EPA Method 3C, *Determination of Carbon Dioxide, Methane, Nitrogen, and Oxygen from Stationary Sources*. This served as a QA/QC check for the measurements of the portable biogas analyzer. The results are summarized in Table 4.5. The values from the portable biogas analyzer and the certified lab are comparable, as shown in Tables 4.4 and 4.5.

Table 4.5: Results of EPA Method 3C Testing

Compound	Raw Biogas	Post H_2S Adsorbers	Post Siloxanes Adsorbers
H_2	<1.3	<1.3	<1.3
O_2	<0.1	<0.1	<0.1
N_2	0.7	0.6	0.4
CO	<0.1	<0.1	<0.1
CO_2	34.9	34.7	34.4
CH_4	64.3	64.6	65.1

4.2.2 Performance of the hydrogen sulfide removal system

Detailed specifications of the two H_2S adsorbers can be found in Section 3.1.4. The media in the adsorbers are a synthetic blend of iron oxide (SulfaTreat® 410). As discussed in the previous section, the readings from the portable biogas analyzer indicate that these two adsorbers reduced the H_2S

concentration in the raw biogas from 127±75 ppmv to 7±13 ppmv, which meets the design specifications of the system.

Samples of raw biogas, biogas in the effluent of the H_2S adsorbers, and biogas in the effluent of the siloxane adsorbers were grabbed on October 29, 2014 and sent to Atmospheric Analysis and Consulting (Ventura, CA) for analysis of reduced sulfur compounds. As shown in Table 4.6, H_2S and n-propyl mercaptan were the only two compounds detected, out of 22 reduced sulfur compounds (the detection limit is 0.065 ppmv). The concentration of total reduced sulfur compounds as H_2S in the raw biogas was 164 ppmv, and was reduced to 14.6 ppmv by the two H_2S adsorbers. It was further reduced to 10.4 ppmv by the siloxane adsorbers. This serves as a QA/QC check for the H_2S measurements by the portable biogas analyzer. As shown in Table 4.4 and Table 4.6, the measured values between the portable biogas analyzer and the certified lab are comparable.

Table 4.6: Removal of the Sulfur Compounds in Biogas by the Conditioning Systems (ppmv)

Compound	**Raw Biogas**	**Post H_2S Adsorbers**	**Post Siloxanes Adsorbers**
Hydrogen Sulfide	163	14.0	10.0
Carbonyl Sulfide	<0.065	<0.065	<0.065
Sulfur Dioxide	<0.065	<0.065	<0.065
Methyl Mercaptan	<0.065	<0.065	<0.065
Ethyl Mercaptan	<0.065	<0.065	0.076
Dimethyl Sulfide	<0.065	<0.065	<0.065
Carbon Disulfide	<0.065	<0.065	<0.065
Isopropyl Mercaptan	<0.065	<0.065	<0.065
tert-Butyl Mercaptan	<0.065	<0.065	<0.065
n-Propyl Mercaptan	0.824	0.604	0.367
Methylethylsulfide	<0.065	<0.065	<0.065
sec-Butyl Mercaptan	<0.065	<0.065	<0.065
Thiophene	<0.065	<0.065	<0.065
iso-Butyl Mercaptan	<0.065	<0.065	<0.065
Diethyl Sulfide	<0.065	<0.065	<0.065
n-Butyl Mercaptan	<0.065	<0.065	<0.065
Dimethyl Disulfide	<0.065	<0.065	<0.065
2-Methylthiophene	<0.065	<0.065	<0.065
Tetrahydrothiophene	<0.065	<0.065	<0.065
Bromothiophene	<0.065	<0.065	<0.065
Thiophenol	<0.065	<0.065	<0.065
Diethyl disulfide	<0.065	<0.065	<0.065
Total Unidentified Sulfur	<0.065	<0.065	<0.065
Total Reduced Sulfur as H_2S	**164**	**14.6**	**10.4**

4.2.3 Performance of the siloxane removal system

Detailed specifications of the two siloxane adsorbers can be found in Section 3.1.4. The media in the siloxane adsorbers is GAC. Samples of raw biogas, biogas in the effluent of the H_2S adsorbers, and biogas in the effluent of the siloxanes adsorbers were grabbed on 10/08/14 and 10/29/14 and sent to Atmospheric Analysis and Consulting (Ventura, CA) for analysis of the following siloxanes: hexamethyldisiloxane (L2), hexamethylcyclotrisiloxane (D3), octamethyltrisiloxane (L3), octamethylcyclotetrasiloxane (D4), decamethyltetrasiloxane (L4), decamethylcyclopentasiloxane (D5), and dodecamethylpentasiloxane (L5).

As shown in Table 4.7, only D3, D4, and D5 were detected in the raw biogas (the detection limit is 13.0 ppbv). The siloxane adsorbers reduced the D3 and D5 concentrations to below or close to the detection limit. D4 concentrations decreased 80% or more. However, it should be noted that the concentrations of D3 in the effluent of the H_2S adsorbers were higher than those in the raw biogas on both days (295 vs. <13.0 and 270 vs. 204 ppbv). In addition, the concentrations of L2 in the effluent of the siloxane adsorbers were higher than those in the effluent of the H_2S adsorbers on both days (84 vs. <13.0 and 63.4 vs. 13.0 ppbv). The causes for these increases were not identified. One plausible reason is that these samples were not taken in a synchronized manner. The total effluent siloxane concentrations were 99.1 ppbv on 10/08/14 and 117.9 ppbv on 10/29/15, which are either at or slightly above the design specification of 100 ppbv.

Table 4.7: Removal of Siloxanes in Biogas by the Conditioning Systems (ppbv)

	10/8/2014			10/29/2014		
	Raw Biogas	**Post H_2S Adsorbers**	**Post Siloxanes Adsorbers**	**Raw Biogas**	**Post H_2S Adsorbers**	**Post Siloxanes Adsorbers**
Hexamethyldisiloxane (L2)	<13.0	<13.0	84	<13.0	<13.0	63.4
Hexamethylcyclotrisiloxane (D3)	<13.0	295	<13.0	204	270	<13.0
Octamethyltrisiloxane (L3)	<13.0	<13.0	<13.0	<13.0	<13.0	<13.0
Octamethylcyclotetrasiloxane (D4)	161	225	15.1	202	202	41.6
Decamethyltetrasiloxane (L4)	<13.0	<13.0	<13.0	<13.0	<13.0	<13.0
Decamethylcyclopentasiloxane (D5)	1160	570	<13.0	523	334	13.9
Dodecamethylpentasiloxane (L5)	<13.0	<13.0	<13.0	<13.0	<13.0	<13.0

Samples of raw biogas, biogas in the effluent of the H_2S adsorbers, and biogas in the effluent of the siloxane adsorbers were grabbed on 10/08/14 and 10/29/14 and sent to Atmospheric Analysis and Consulting (Ventura, CA) for analysis using EPA Method TO-15, *Determination of Volatile Organic Compounds (VOCs) in Air Collected in Specially-Prepared Canisters and Analyzed by Gas Chromatography/Mass Spectrometry (GC/MS).*

Out of a long list of compounds analyzed, only one alkene (propene), four alkanes (cyclohexane, 2,2,4-trimethylpentane, hexane, and heptane), two ketones (2-butanone and 4-methyl-2-pentanone), four aromatics (benzene, toluene, ethylbenzene, and xylenes) and tetrahydrofuran were detected. Table 4.8 summarizes the concentrations of those compounds detected in the raw biogas, effluent of the H_2S adsorbers, and effluent of the siloxanes adsorbers. The GAC in the siloxane adsorbers should have some capability to remove VOCs. However, the concentrations in their effluent are often higher than those in their influent. This is probably because of the high moisture content of the biogas prior to the condenser,

and/or because the adsorbers are designed only for siloxane removal and may not provide sufficient empty bed contact time for removal of those VOCs.

Table 4.8: Removal of VOCs in Biogas by the Conditioning Systems (ppbv)

	10/8/2014			10/29/2014		
Compound	**Raw Biogas**	**Post H_2S Adsorber**	**Post Siloxanes Adsorber**	**Raw Biogas**	**Post H_2S Adsorber**	**Post Siloxanes Adsorber**
Propene	1,730	1,700	1,590	1,150	1,180	1,140
Cyclohexane	<6.5	<6.5	9.9	<6.5	<6.5	<6.5
2,2,4-Trimethylpentane	<6.5	7.2	84.4	<6.5	<6.5	49.9
Hexane	29.8	29.7	110	17.1	16.4	52.4
Heptane	130	106	238	53.2	54.1	140
2-Butanone	31.2	35.8	39.2	<13.0	<13.0	<13.0
4-Methyl-2-pentanone	<6.5	<6.5	13.7	<6.5	<6.5	10.6
Benzene	20.5	21.4	72.1	17.4	17.9	35.3
Toluene	735	690	1,860	1,430	1,430	2,130
Ethylbenzene	19.4	17.0	55.7	18.4	20.9	41.8
m & p-Xylenes	18.4	16.0	20.8	14.7	15.7	22.7
o-Xylene	6.7	<6.5	<6.5	<6.5	<6.5	<6.5
Tetrahydrofuran	88.5	<6.5	10.3	<6.5	<6.5	<6.5

The VOCs that were not detected in these two sampling events are listed below along with their detection limits. The raw data can be found in Appendix C.

- <6.5 ppb
  1,1,1-trichloroethane, 1,1,2,2-tetrachloroethane, 1,1,2-trichloroethane, 1,1-dichloroethane, 1,1-dichloroethene, 1,2,4-tirmethylbenzene, 1,2,4-trichlorobenzene, 1,2-dibromomethane, 1,2-dichlorobenzene, 1,2-dichloroethane, 1,2-dichloropropane, 1,3,5-trimethylbenzene, 1,3-butadiene, 1,3-dichlorobenzene, 1,4-dichlorobenzene, 1,4-dioxane, 2,2,4-trimethylpentane, 2-hexanone, 4-ethyl toluene, 4-methyl-2-pentanone, allyl chloride, benzyl chloride, bromodichloromethane, bromoform, bromomethane, carbon tetrachloride, chlorobenzene, chlorodifluoromethane, chloroethane, chloroform, chloromethane, cis-1,2-dichloroethene, cis-1,3-dichloropene, cyclohexane, dibromochloromethane, dichlorodifluoromethane, dichlorofluoromethane, dichlorotetrafluoroethane, ethyl acetate, hexachlorobutadiene, methyl tert-butyl ether, styrene, tetrachloroethene, trans-1,2-dichloroethene, trans-1,3-dichloropropene, trichloroethene, trichlorofluoromethane, trichlorotrifluoroethane, vinyl bromide, vinyl chloride
- <13 ppb
  acrylonitrile, methylene chloride, vinyl acetate
- <26.1 ppb
  2-propanol, acetone, ethanol
- <65.2 ppb
  methanol

4.3 IC Engine Emissions

The IC engine at the site is a Waukesha Model P48GLD, by GE Power & Water, powering a Kato 750 kW electrical generator.

4.3.1 Historic source test results on IC engine emissions

Since the biogas generated at the site is not sufficient for around-the-clock power generation, the engine is fueled by natural gas when biogas is not available. The IC engine has been source-tested by BAAQMD annually to check for compliance. For each test, the IC engine was fueled by biogas as well as by natural gas. The results from these official source tests provide a valuable opportunity to compare the emissions from the same engine on the same day while using biogas and natural gas.

Table 4.9 provides statistics for the annual source test results from 2008 to 2014 (the raw data can be found in Appendix D). The permit conditions for the exhausts are also listed in the table. The source test results indicate that the IC engine has been in compliance. As shown, the average emissions from natural gas (NG) fueled and biogas fueled operations are: NO_x @ 15% O_2 (38±19 vs. 37±20 ppm); CH_4 (692±83 vs. 1,065±224 ppm); non-methane organic carbon (NMOC) as C_1 (45±33 vs. 18±6 ppm); total organic carbon (TOC) as C_1 (735±65 vs. 1,075±227 ppm); CO_2 (7.5±0.5 vs. 12.8±1.6%); CO @15% O_2 (122±9 vs. 142±14 ppm); O_2 (7.9±0.4 vs. 6.9±0.7%); and SO_2 (4±3 vs. 7±5 ppm).

The NO_x concentrations in the exhausts using NG and biogas are essentially the same (38 vs. 37 ppmv). With regards to emissions of organic compounds, NG-fueled operations emit less CH_4 (692 vs. 1,065 ppmv), but higher NMOC (45 vs. 18 ppmv). The average CO_2 emission from using biogas is higher (12.8 vs. 7.5%), probably due to the higher CO_2 concentration in the biogas. The average CO concentration from biogas-fueled combustion was higher (142 vs. 122 ppmv). The average SO_2 concentration from biogas-fueled combustion was also higher (7 vs. 4 ppmv), probably due to the presence of reduced sulfur compounds in the biogas.

4.3.2 Daily monitoring of IC engine emissions

During the study period, exhausts from the IC engine were surveyed twice per day using the portable emission analyzer, EMCON J2KN Pro Industrial OCNX-IR by ECOM America, Ltd.

Table 4.10 provides statistics for the IC engine emission data from the daily monitoring (the raw data can be found in Appendix E). As shown, the average emissions from natural gas fueled and biogas fueled operations are: NO_2 (30±3 vs. 23±4 ppm); NO (17±4 vs. 10±3 ppm); CH_4 (1,200±170 vs. 1,680±200 ppm); CO_2 (7.2±0.1 vs. 7.7±0.1%); CO (122±9 vs. 142±14 ppm); O_2 (8.0±0.1 vs. 7.2±0.1%); and SO_2 (0±0 vs. 0±0 ppm). The data from daily monitoring are comparable to those from the source tests. For example the NO_x concentrations are in the range of 30 to 50 ppmv. The trends are also valid (i.e., higher methane concentration, high CO concentration, and lower O_2 concentration from biogas-fueled operations. It should be noted that SO_2 was not detected by the portable emission analyzer.

Table 4.9: Statistics of IC Engine Emission Data Using Natural Gas versus Biogas (Official Source Test Results from 2008-2014)

	Natural Gas					Biogas					Permits	
	Max	Min	Median	Avg.	Std. Dev.	Max	Min	Median	Avg.	Std. Dev.	Regulation NG/Biogas	Permit NG/Biogas
Output (kW)	650	538	590	601	42	649	550	620	612	30		
Flow rate (SCFM)	2,140	1,390	1,720	1,717	227	1,810	1,340	1,590	1,583	176		
CO (ppm)	292	246	263	269	17	381	286	329	334	28		
CO (ppm), converted to 15% O_2	138	106	121	122	9	157	114	142	142	14	2,000/2,000	
CO (gm/Hp-hr)	1.56	0.78	1.14	1.14	0.21	1.58	0.87	1.28	1.29	0.21		2.75/2.65
NO (ppm)	129	20	29	49	37	118	11	46	55	42		
NO_2 (ppm)	49	24	33	36	8	43	18	36	33	8		
NO_x (ppm), converted to 15% O_2	77	24	28	38	19	66	13	38	37	20	65/70	
NO_x (gm/Hp-hr)	0.93	0.37	0.45	0.55	0.20	1.02	0.21	0.51	0.54	0.30		1.00/1.25
Methane (ppm)	799	561	686	692	83	1,400	762	1,070	1,065	224		
NMOC as C_1 (ppm)	90	10	34	45	33	26	10	18	18	6		
NMOC as C_1 (gm/Hp-hr)	0.21	0.02	0.08	0.10	0.07	0.07	0.02	0.04	0.04	0.02		1.00/1.00
TOC as C_1 (ppm)	799	639	760	735	65	1,418	778	1,070	1,075	227		
CO_2 (%)	8.3	6.8	7.3	7.5	0.5	15.1	10.7	12.7	12.8	1.6		
Oxygen (%)	8.5	7.2	8	7.9	0.4	8.2	6	6.8	6.9	0.7		
SO_2 (ppm)	11	2	2	4	3	16	2	6	7	5	300/300	
SO_2 (gm/Hp-hr)	0.08	0.01	0.02	0.03	0.03	0.15	0.02	0.05	0.06	0.04		0.30/0.30
Estimated Heat Input (MMBTU/d)						191	191	191	191	0		231/231
Heating Value of Biogas (BTU/scf)						634	424	560	542	65		

Table 4.10: Daily IC Engine Emission Data

	Natural Gas							Biogas						
	CH_4 (%)	**CO_2 (%)**	**CO (ppm)**	**NO_2 (ppm)**	**NO (ppm)**	**SO_2 (ppm)**	**O_2 (%)**	**CH_4 (%)**	**CO_2 (%)**	**CO (ppm)**	**NO_2 (ppm)**	**NO (ppm)**	**SO_2 (ppm)**	**O_2 (%)**
Count	38	38	38	38	38	38	38	54	54	54	54	54	54	54
Maximum	0.195	7.7	378	37	28	0	8.2	0.214	7.8	385	30	18	0	7.3
Minimum	0.092	7.1	224	21	10	0	7.2	0.127	7.6	160	17	4	0	7.0
Median	0.119	7.2	312.5	30	17	0	8.0	0.170	7.7	367	22.5	10.5	0	7.2
Mean	0.120	7.2	312	30	17	0	8.0	0.168	7.7	360	23	10	0	7.2
Std. Dev.	0.017	0.1	19	3	4	0	0.1	0.020	0.0	36	4	3	0	0.1

4.3.3 Toxics testing on the IC engine emissions for this project

Tests on the IC engine emissions, when the engine was fueled by biogas, were also conducted by Total Air Analysis (Carson, CA), a BAAQMD-certified source tester, on 10/29/14 and 10/30/14. On each day, samples were taken and analyzed for air toxics (i.e., formaldehyde, PAHs, polychlorinated dibenzodioxins (PCDDs), and VOCs).

Table 4.11 tabulates the emission test results from the source tester. When compared to Table 4.9, the values in Table 4.11 are similar to those of the official source tests in the past seven years. The concentrations of CH_4, CO_2, CO, NO_x, and O_2 are also similar to those measured by the portable emission analyzer in Table 4.10.

If the stringent 2016 regulations in the jurisdiction area of SCAQMD in southern California were enforced on this IC engine, the CO concentration (@15% O_2) of 157 ppmv would be less than the 250 ppmv standard; however, the NO_x concentration (@15% O_2) would be higher than the 11 ppmv standard (SCAQMD, 2012).

Table 4.11: IC Engine Emissions from Tests Conducted by the Source Tester

	10/29/2014	**10/30/2014**
Output (kW)	613	615
Measured flow rate (SDCFM)	1,886	1,898
Calculated flow rate (SDCFM)	1,972	2,190
CO (ppm)	362	361
CO (ppm), converted to 15% O_2	157	157
CO (gm/Hp-hr)	1.63	1.81
NO_x (ppm)	54.8	51.4
NO_x (ppm), converted to 15% O_2	23.8	22.3
NO_x (gm/Hp-hr)	0.33	0.35
Methane (ppm)	1,484	1,708
Methane (ppm), converted to 15% O_2	643	741
TOC as C_1 (ppm)	1,484	1,708
CO_2 (%)	11.3	11.3
O_2 (%)	7.23	7.24

With regards to air toxics, the formaldehyde concentrations were 31.7 ppbv (10/29/14) and 32.6 ppbv (10/30/14) in the IC engine exhausts. For the VOC analysis (EPA Method TO-14), two aromatics (benzene and toluene) and ten halogenated organic compounds (1,1,1-TCA, 1,2-dichloropropane, bromomethane, carbon tetrachloride, chloroethane, chloroform, cis-1,2-DCE, TCE, trichlorotrifluoroethane, and vinyl chloride) were detected. Table 4.12 summarizes the concentrations of these compounds that were detected in the IC engine exhausts. If the stringent 2016 regulations in the jurisdiction area of SCAQMD in southern California were enforced on this IC engine, the total VOC concentrations, which are in the level of a couple of ppmv or less, would be less than the 30 ppmv standard (SCAQMD, 2012).

Table 4.12: VOCs in the IC Engine Exhausts from Tests Conducted by the Source Tester (ppbv)

	10/29/2014	10/30/2014
Benzene	33	30
Toluene	12	11
1,1,1-Trichloroethane	0.1	0.1
1,2-Dichloropropane	1.4	0.9
Bromomethane	648	1,027
Carbon tetrachloride	0.1	0.1
Chloroethane	111	102
Chloroform	22	16
cis-1,2-Dichloroethene	17	23
Trichloroethene	0.2	0.4
Trichlorotrifluoroethane	0.5	<0.3
Vinyl chloride	167	604

The VOCs that were not detected in these two sampling events are listed below with their detection limits.

- <0.1 ppb
  1,2-dichlorotrtrafluoroethane, trichlorofluoromethane, 1,1-dichloroethene, tetrachloroethylene, 1,1,2,2-tetrachloroethane, hexachlorobutadiene
- <0.3 ppb
  1,1-dichloroethane
- <1.0 ppb
  dichlorodifluoromethane, chloromethane, 1,2-dichloroethane, 1,2-dibromomethane,
- <2.0 ppb
  methylene chloride
- <3 ppb
  cis-1,3-dichloropropene, trans-1,3 dichloropropene, chlorobenzene, ethylbenzene, o,m,p-xylenes, styrene, 1,3,5-trimethylbenzene, 1,2,4-trimethylbenzene, 1,2-dichlorobenzene, 1,3-dichlorobenzene, 1,4-dichlorobenzene, 1,2,4-trichlorobenzene.

The exhausts were also collected and analyzed for polychlorinated dibenzodioxins/furans (PCDD/F) using CARB Method 428. The exhausts were analyzed for compounds including 2,3,7,8-tetrachlorodibenzodioxine (TCDD), 1,2,3,7,8-pentachlorodibenzodioxine (PeCDD), three isomers of hexachlorodibenzodioxine (HxCDD), 1,2,3,4,6,7,8-heptachlorodibenzodioxine (HpCDD), octachlorodibenzodioxine (OCDD), 2,3,7,8-tetrachlorodibenzofuran (TCDF), two isomers of pentachlorodibenzofuran (PeCDF), four isomers of hexachlorodibenzofuran (HxCDF), two isomers of heptachlorodibenzofuran (HpCDF), and octachlorodibenzodioxine (OCDF). OCDD is the only single PCDD/F species detected. In one of the two sampling events the masses of total HpCDD, TCDF, PeCDF, HxCDF were also above the detection limits. Table 4.12 tabulate the masses of the detected compounds in the collected samples and the corresponding concentrations (in mg/dry standard cubic meter), calculated using the mass and the total sample volume (80.11 and 81.49 ft^3 for 10/29/14 and 10/30/14, respectively). As shown, the concentrations are relatively low, at 1.95×10^{-8} mg/dscm or less (No

specific discharge limits on these compounds were found from a literature search). The raw laboratory data can be found in Appendix F.

Table 4.13: Dioxins/Furans in the IC Engine Exhausts from Tests Conducted by the Source Tester

	10/29/2014		10/30/2014	
	pg/sample	**mg/dscm**	**pg/sample**	**mg/dscm**
OCDD	31.2	1.38E-08	11.7	5.07E-09
Total HpCDD	7.77	3.42E-09	<9.55	<4.14E-09
Total TCDF	44.2	1.95E-08	<8.72	<3.78E-09
Total PeCDF	39.1	1.72E-08	<7.98	<3.46E-09
Total HxCDF	7.65	3.37E-09	<3.95	<1.71E-09

The exhausts were collected and analyzed for polycyclic aromatic hydrocarbons (PAHs) using CARB Method 429. The compounds analyzed for, including naphthalene, 2-methylnaphthalene, acenaphthene, acenaphthylene, fluorine, phenanthrene, anthracenem fluoranthene, pyrene, benzo(a)anthracene, chrysene, benz(b)fluoranthene, benzo(k)fluoranthene, benzo(e)pyrene, benzo(a)pyrene, perlene, indeno(1,2,3-c,d)pyrene, dibenz(a,h)anthracene, and benzo(g,h,i)perylene. Table 4.13 tabulate the masses of the detected compounds in the collected samples and the corresponding concentrations (in mg/dscm), calculated using the mass and the total sample volume (80.11 and 81.49 ft^3 for 10/29/14 and 10/30/14, respectively). Ten PAH species were detected in the IC engine exhausts and naphthalene has the highest average concentration, at 6.1×10^{-3} mg/dscm (No specific discharge limits on these compounds were found from a literature search). The raw laboratory data can be found in Appendix F.

Table 4.14: PAHs in the IC Engine Exhausts from Tests Conducted by the Source Tester

	10/29/2014		20/30/2014	
	ng/sample	**mg/dscm**	**ng/sample**	**mg/dscm**
Naphthalene	13,300	5.86E-03	14,600	6.33E-03
2-Methynaphthalene	8,240	3.63E-03	11,100	4.81E-03
Acenaphthylene	773	3.41E-04	815	3.53E-04
Acenaphthene	357	1.57E-04	458	1.98E-04
Fluorene	698	3.08E-04	352	1.53E-04
Phenanthrene	2,470	1.09E-03	1,750	7.58E-04
Anthracene	128	5.64E-05	<20	8.67E-06
Fluoranthene	246	1.08E-04	142	6.15E-05
Pyrene	193	8.51E-05	108	4.68E-05
Chrysene	85.1	3.75E-05	47.7	2.07E-05

Two biogas samples (one from each testing day) were also analyzed for higher heating values by Quantum Analytical Services using ASTM 1945-03. The gross heating values are 639 BTU/ft^3 and the net heating values are 575 BTU/ft^3 for both samples.

CHAPTER 5:
Conclusion

A literature review on anaerobic digestion of food waste, biogas generation, and beneficial uses of biogas was conducted. Field data were collected, for a consecutive 12-week period in 2014, at the Central Marin Sanitation Agency (San Rafael, CA) which employs two anaerobic digesters for codigestion of FOG, food waste, PS, and TWAS and uses an IC engine to generate biopower using the biogas.

The findings from the experiments include the following:

(1) The digesters are being operated under stable conditions with FOG and food waste making up approximately 25% of the TS or VS loading to the anaerobic digesters.

(2) The biogas production rate is 18.5 ft^3 biogas/lb VS destructed or 11.6 ft^3 CH_4/lb VS destructed. With 33% percent more VS loading from FOG and food waste, the daily biogas production is 60% greater.

(3) Hydrogen sulfide (H_2S) is the dominant reduced sulfur compound in the raw biogas, while n-propyl mercaptan was also detected. The on-site H_2S removal system is capable of reducing the concentration of total reduced sulfur to the design specification of 15 ppmv.

(4) With regards to siloxanes, only hexamethylcyclotrisiloxane (D3), octamethylcyclotetrasiloxane (D4), and decamethylcyclopentasiloxane (D5) were detected in the raw biogas. The on-site activated carbon adsorbers reduced the D3 and D5 concentrations to below or close to the detection limit and 80% or more of D4 was removed.

(5) The EPA Method TO-15 analysis detected only one alkene (propene), four alkanes (cyclohexane, 2,2,4- trimethylpentane, hexane, and heptane), two ketones (2-butanone and 4-methyl-2-pentanone), four aromatics (benzene, toluene, ethylbenzene, and xylenes) and tetrahydrofuran in the raw biogas samples.

(6) The IC engine at the site used both NG and biogas on a daily basis. Results of official source tests over the past seven years show that NO_x concentrations (@15% O_2) in the exhausts from both NG and biogas were essentially the same (38 vs. 37 ppmv). With regards to emissions of organic compounds, NG-fueled operations emitted less CH_4 (692 vs. 1,065 ppmv), but higher NMOC (45 vs. 18 ppmv). The average CO_2 emission from biogas was higher (12.8 vs. 7.5%), probably due to the higher CO_2 concentrations in the digester gas. Average CO concentrations (@15% O_2) from biogas-fueled combustion was higher (142 vs. 122 ppmv) as were average SO_2 concentration from biogas-fueled combustion (7 vs. 4 ppmv), probably due to the presence of reduced sulfur compounds in the biogas.

(7) With regards to air toxics in the exhausts of IC engine emissions, formaldehyde concentration was 32 ppbv. Two aromatics (benzene and toluene) and ten halogenated organic compounds (1,1,1-TCA, 1,2-dichloropropane, bromomethane, carbon tetrachloride, chloroethane, chloroform, cis-1,2-DCE, TCE, trichlorotrifluoroethane, and vinyl chloride) were detected using EPA Method TO-14.

(8) The exhausts were also collected and analyzed for polychlorinated dibenzodioxins/furans (PCDD/F) using CARB Method 428. At an average concentration of 9.4×10^{-9} mg/dry standard cubic meter (dscm), octachlorodibenzodioxine (OCDD) was the only single PCDD/F species detected.

(9) The exhausts were also collected and analyzed for PAHs using CARB Method 429. Ten PAH species were detected in the IC engine exhausts while naphthalene having the highest concentration, at 6.1×10^{-3} mg/dscm.

Several concluding remarks can be drawn from this study:

(1) Codigestion of food waste and municipal wastewater sludge is a viable and stable process.A 25% contribution from food waste to the total volatile solids applied to the anaerobic digesters resulted in a 60% increase in daily biogas production.

(2) The IC engine fueled by biogas can meet stringent emission limits for CO @15% O_2 (250 ppmv) and VOCs (30 ppmv). However, additional emission controls may be needed to meet the low NO_x (@15% O_2) limit of 11 ppmv.

(3) Codigestion of food waste with municipal wastewater sludge would help divert organic wastes from landfills and increase the use of renewable fuels throughout the state and add to California's renewables portfolio.

GLOSSARY

Term	Definition
BAAQMD	Bay Area Air Quality Management District
BACT	Best Available Control Technology
CARB	California Air Resources Board
CHP	Combined heat and power
CNG	Compressed natural gas
COD	Chemical oxygen demand
CMSA	Central Marin Sanitation Agency
EBMUD	East Bay Municipal Utility District
EPA	U.S. Environmental Protection Agency
FOG	Fats, oils and grease
GAC	Granular activated carbon
GHG	Greenhouse gas
IC	Internal combustion
LNG	Liquified natural gas
MC	Moisture content
MCRT	Mean cell residence time
MGD	Million gallons per day
MSS	Marin Sanitary Service
MSW	Municipal solid waste
MW	Megawatt
NG	Natural gas
NMOC	Non-methane organic carbon
PAH	Polycyclic aromatic hydrocarbons
PS	Primary sludge
RPS	Renewable Portfolio Standard

SCAQMD	South Coast Air Quality Management District
SCR	Selective catalytic reduction
TOC	Total organic carbon
TS	Total solids
TWAS	Thickened waste activated sludge
VA	Volatile acids
VOC	Volatile Organic Compound
VS	Volatile solids
WWTP	Wastewater treatment plant

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APPENDIX A:
Raw Anaerobic Digestion Data

	Primary Sludge			TWAS			FOG			Food Waste			Combined Feed			Digestate TS						
Date	TS (%)	VS (%)	Loading Rate (gallons)	TS (%)	VS (%)	Loading Rate (gallons)	TS (%)	VS (%)	Loading Rate (gallons)	TS (%)	VS (%)	Loading Rate (tons)	TS (%)	VS (%)	COD (mg/L)	TS (%)	VS (%)	pH	Temp (^{o}F)	VA (mg/L)	Alk (mg/L)	NH_4^+-N (mg/L)
08/18/14	3.9	84	26,045	4.6	92	21,316	4.5	96		14.4	90	2.5				2.1	68	7.2	99.8	142	4,900	1,280
08/19/14	4.2	83	28,731	4.8	83	15,614	6.6	95	13,500	17.6	90	7.8				2.0	70	7.2	99.4	138	5,300	1,284
08/20/14	4.4	84	27,634	4.9	84	15,996	1.2	89	13,750	15.1	87	3.2				2.2	70	7.2	99.8	128	5,300	1,250
08/21/14	4.4	85	29,439	5.0	83	15,617	8.0	96	5,200	19.8	92	4.6	4.9	94.2		2.0	68	7.2	99.6	138	5,000	1,209
08/22/14	4.2	83	26,032	4.8	83	14,614	3.8	96	9,500	13.9	91	2.3	7.7	96.7		2.1	68	7.2	99.8	129	5,100	1,210
08/23/14			21,666			13,706				20.4	90	4.8										
08/25/14			26,330	5.1	82	12,454	3.5	98	4,500	21.0	92	2.6				2.2	69	7.2	100.0	120	5,000	1,322
08/26/14	4.1	84	28,402	5.2	83	11,290	4.2	96	13,500	19.2	90	8.2				2.2	70	7.2	99.3	142	5,100	1,274
08/27/14	4.0	83	31,041	5.1	83	14,089	4.2	95	5,000	19.4	91	3.4	16.4	97.5		2.2	69	7.2	99.7	137	5,100	1,224
08/28/14	3.9	82	23,752	5.3	83	14,408	5.7	94	4,000	18.9	92	4.0	8.0	93.5		2.1	68	7.2	99.4	133	5,000	1,209
08/29/14	4.3	82	23,385	5.0	83	12,345	4.6	94	7,500	22.7	91	2.9	5.7	94.9		2.1	68	7.2	99.6	124	5,000	1,289
08/30/14			23,295			12,624				19.9	88	4.8										
09/01/14			20,991			11,488				21.2	93	3.0										
09/02/14	4.1	82	27,898	4.8	84	11,350	2.7	92	4,500	21.9	92	7.8	8.6	91.1				7.2	100.2	124	5,000	
09/03/14	3.9	83	28,605	5.1	84	12,523	6.9	97	15,500	24.7	91	3.2	7.2	98.2		2.1	65	7.2	99.6	128	5,100	1,301
09/04/14	3.5	84	33,030	5.0	84	12,766	3.1	92	8,500	21.7	91	3.6				2.0	69	7.2	99.5	133	5,000	1,230
09/05/14	4.0	83	24,275	4.8	84	14,200	1.4	86	10,000			3.8	3.0	90.0		2.2	65	7.2	99.5	129	5,000	1,191
09/06/14			33,356			15,086				19.2	91	5.6										
09/08/14	4.6	84	28,905	4.7	82	14,527	1.2	90		22.8	91	2.6	4.8	90.8		2.0	65	7.2	99.6	138	5,000	
09/09/14			23,410	4.8	83	15,372	1.8	95	16,250	19.6	93	8.6	4.0	93.8		2.1	66	7.2	100.0	146	5,050	1,201
09/10/14	4.0	82	24,798	4.8	84	14,928	0.4	88	11,000	17.6	92	2.6	1.1	81.2	33,000	2.2	69	7.2	99.8	133	5,050	1,260
09/11/14	4.5	84	23,818	4.6	83	15,255	4.7	91	17,600	14.4	90	4.9	1.7	75.0	65,500	2.1	68	7.2	99.8	129	5,000	1,201
09/12/14	4.6	80	20,260	4.7	81	13,325	11.0	92	10,500	18.9	90	2.6	1.7	84.2	51,400	2.2	63	7.2	99.8	146	4,900	1,182
09/13/14										19.6	90	5.4										
09/15/14	4.6	83	28,929			16,103	3.7	93	9,300	21.5	90	2.7	6.0	94.6		2.1	65	7.2	99.5	137	5,000	1,168
09/16/14	4.4	83	25,233	4.4	84	16,016	5.2	97	9,750	20.8	91	7.6	8.1	95.4		2.0	65	7.2	99.8	146	4,850	1,134
09/17/14	4.3	85	21,778	4.3	84	13,318	6.8	93	15,400	14.8	91	2.7	6.2	88.7		2.1	70	7.2	99.4	158	4,850	1,190
09/18/14	4.3	82	24,821	4.3	81	16,104	1.5	88	9,000	17.8	91	4.3	4.9	96.1		2.1	64	7.3	99.6	142	5,000	1,196
09/19/14	4.3	84	38,571	4.3	82	16,032	2.2	89	10,300	26.3	93	2.7	2.6	85.0	71,200	2.1	66	7.2	100.0	154	4,950	1,117

	Primary Sludge			TWAS			FOG			Food Waste			Combined Feed			Digestate TS						
Date	TS (%)	VS (%)	Loading Rate (gallons)	TS (%)	VS (%)	Loading Rate (gallons)	TS (%)	VS (%)	Loading Rate (gallons)	TS (%)	VS (%)	Loading Rate (tons)	TS (%)	VS (%)	COD (mg/L)	TS (%)	VS (%)	pH	Temp (^{o}F)	VA (mg/L)	Alk (mg/L)	NH_4^+-N (mg/L)
09/20/14										18.9	89	5.2										
09/22/14	3.9	84	34,759	4.0	80	22,129	8.7	95	14,500	23.5	92	2.5	3.2	86.7	80,400	2.2	64	7.2	99.8	150	5,050	1,170
09/23/14	3.5	86	28,068	4.2	81	21,751	0.8	90	10,400	23.9	92	7.8	2.7	82.8		2.1	64	7.2	99.6	162	4,900	1,095
09/24/14	4.3	86	27,494	4.2	80	8,930	2.9	95	15,000	21.4	92	2.7	1.3	72.2		2.0	69	7.2	99.5	154	4,900	1,140
09/25/14	5.2	84	42,072	4.1	80	21,985	2.6	95	10,000	12.9	92	3.3	0.9	69.2		2.1	66	7.2	100.0	154	4,900	1,112
09/26/14	3.8	82	35,813	3.8	83	15,729	2.2	94	6,000	15.2	89	1.9	10.8	95.3		2.0	68	7.2	99.4	132	5,060	1,112
09/27/14										18.9	84	5.7	16.4	94.6								
09/29/14	4.4	85	17,630	4.4	82	26,685	1.5	85	6,000	26.8	93	2.0	4.4	89.5		2.0	68	7.2	99.7	120	4,700	1,120
09/30/14	4.3	85	28,995	4.4	83	17,482	1.5	85	9,000	21.4	93	7.5	4.8	89.5	85,200	2.0	69	7.2	99.6	120	4,800	1,114
10/01/14	4.6	85	29,474	4.4	83	16,123	2.3	93	13,500	19.9	92	3.1	4.0	91.5		2.0	66	7.2	99.5	116	4,700	1,092
10/02/14	4.0	83	25,058	4.5	82	15,981	2.0	94	8,500	18.6	92	4.1	4.0	82.4		2.0	68	7.2	100.1	111	4,600	1,120
10/03/14	4.0	82	35,361	4.2	82	15,690	1.5	90	15,100	24.8	90	2.1	2.9	91.8		2.0	68	7.2	100.0	111	4,750	1,030
10/04/14										20.4	90	4.3										
10/06/14	4.1	84	26,842	4.8	81	13,645	3.3	94	4,850	24.4	92	1.9				2.0	68	7.2	99.7	98	4,800	1,168
10/07/14	4.0	81	30,720	4.7	82	14,972	3.4	93	15,000	19.3	90	6.9	14.5	96.0	69,800	2.0	68	7.2	99.4	103	4,750	1,050
10/08/14	4.2	83	31,035	4.4	82	16,782	2.3	96	16,500	23.4	92	2.1	1.8	87.0		2.0	70	7.2	99.8	124	4,600	1,126
10/09/14	3.7	80	34,218	4.6	81	17,149	1.9	90	15,200	21.3	89	4.1	2.7	86.8		2.0	70	7.2	99.8	129	4,700	1,081
10/10/14	7.8	81	27,334	4.6	80	16,795	2.2	93	20,500	24.9	72	2.3	3.8	89.4		2.0	65	7.2	99.8	111	4,650	1,064
10/11/14										28.4	92	4.9										
10/13/14	4.4	83	41,706	4.6	81	16,128	2.1	85	10,200	22.2	92	1.9				2.0	65	7..2	100.3	116	4,600	1,095
10/14/14	4.1	82	24,580	4.6	82	16,353	0.8	77	11,000	22.6	90	5.8	2.0	81.5		2.0	65	7.2	100.0	107	4,850	1,070
10/15/14	4.7	82	27,423	4.5	84	17,187	2.5	90	15,200	18.0	89	2.3	3.3	89.4		2.0	67	7.2	100.5	90	4,750	1,086
10/16/14	5.2	84	34,218	4.4	83	17,383	2.5	94	14,900	19.8	90	4.0				2.0	66	7.2	99.8	107	4,700	1,061
10/17/14	5.3	83	34,747	4.3	85	16,718	2.7	94	18,950	22.5	90	2.4	1.5	86.4		2.0	66	7.2	100.0	107	4,650	1,109
10/18/14										16.3	86	4.0										
10/19/14																						
10/20/14	4.3	84	28,379	4.8	83	13,970	0.6	90	6,000	20.0	90	2.1	3.3	79.1		2.0	66	7.2	99.8	107	4,650	1,056
10/21/14	4.6	85	28,069	4.4	82	16,647	1.5	87	18,700	20.7	91	7.3	3.4	84.8		2.0	69	7.2	99.6	98	4,600	1,044
10/22/14	4.9	83	26,672	4.6	82	16,766	2.2	91	16,200	19.4	93	3.2				2.0	70	7.2	100.5	102	4,700	1,047
10/23/14	4.8	84	30,584	4.5	83	16,629	2.8	93	18,500	19.4	92	4.9	5.4	95.4		2.0	70	7.2	99.8	94	4,600	1,075
10/24/14	4.9	85	31,261	4.6	82	15,460	0.9	93	4,200	26.2	92	1.7	0.8	69.2		2.0	69	7.2	99.6	107	4,700	1,014
10/25/14										29.3	91	5.5										
10/27/14	4.5	85	27,416	4.5	82	19,444	1.8	89	8,400	21.1	92	1.8	7.6	93.8		2.0	68	7.2	99.6	108	4,700	1,086
10/28/14	5.1	85	29,223	5.1	82	17,083	2.2	92	9,000	19.8	91	6.3	6.0	91.8		2.0	67	7.2	100.7	111	4,650	1,039

	Primary Sludge			TWAS			FOG			Food Waste			Combined Feed			Digestate TS						
Date	**TS (%)**	**VS (%)**	**Loading Rate (gallons)**	**TS (%)**	**VS (%)**	**Loading Rate (gallons)**	**TS (%)**	**VS (%)**	**Loading Rate (gallons)**	**TS (%)**	**VS (%)**	**Loading Rate (tons)**	**TS (%)**	**VS (%)**	**COD (mg/L)**	**TS (%)**	**VS (%)**	**pH**	**Temp (^{o}F)**	**VA (mg/L)**	**Alk (mg/L)**	**NH_4^+-N (mg/L)**
10/29/14	3.8	84	25,204	3.8	83	18,226	4.2	90	9,800	17.4	90	2.4	3.0	89.1		2.0	68	7.2	99.7	111	4,650	1,039
10/30/14	4.8	85	33,114	4.8	83	16,478	1.1	88	14,700	23.2	86	4.2	2.7	89.1		2.0	68	7.2	99.3	111	4,700	1,168
10/30/14	4.8	85	33,114	4.8	83	16478	1.1	88	14,700	23.2	86	4.2	2.7	89.1	11,267	2.0	68	7.2	99.3	111	4700	1168
10/31/14	3.9	84	32,341	4.3	83	14880	1.5	88	8,700	23.5	91	1.8	1.5	84.0	9,666	2.0	68	7.2	99.6	103	4800	1053
11/02/14	4.6	85	22,997			17713				20.4	90	3.3										
11/03/14	4.9	86	27,323	4.5	83	19052	3.0	87	10,500	22.2	87	6.5	5.7	92.1	11,520	2.0	68	7.2	99.8	111	4800	1008
11/04/14	4.6	88	29,654	4.3	84	20011	2.1	88	14,000	21.8	91	6.4	2.3	75.9	12,677	2.0	70	7.2	99.6	111	4850	1092
11/05/14	5.1	88	26,932	4.4	83	20282	5.0	96	9,000	18.6	94	2.5	36.1	96.8	9,064	1.9	68	7.2	99.4	107	4650	1011
11/06/14	4.1	86	31,781	4.4	82	19975	2.6	92	17,250	24.3	91	5.7	12.9	96.6	11,882	1.9	65	7.2	99.3	115	4750	1014
11/07/14	5.2	85	32,167	4.6	83	19182	2.2	84	15,500				1.8	89.7	36,109	2.0	67	7.2	99.4	115	4700	1095
Count	59	59	65	59	59	65	60	60	58	70	70	71	51	51	14	59	59	59	60	60	60	58
Maximum	7.8	88	42,072	5.3	92	26,685	11.0	98	20,500	29.3	94	8.6	36.1	98.2	85,200	2.2	70	7.3	100.7	162	5,300	1,322
Minimum	3.5	80	17,630	3.8	80	8,930	0.4	77	4,000	12.9	72	1.7	0.8	69.2	9,064	1.9	63	7.2	99.3	90	4,600	1,008
Median	4.3	84	28,069	4.6	83	16,016	2.4	92	10,500	20.4	91	3.6	4.0	89.5	34,555	2.0	68	7.2	99.7	122	4,850	1,119
Mean	4.4	84	28,588	4.6	83	16,098	3.1	91	11,543	20.6	90	4.1	5.5	88.6	39,906	2.0	67	7.2	99.7	124	4,853	1,137
Std. Dev.	0.6	2	4,769	0.7	11	2,967	2.1	4	4,316	3.3	3	1.9	5.7	7.2	28,576	0.1	2	0.0	0.3	18	179	83

APPENDIX B:
Raw Biogas Data

		Raw Biogas				Post H_2S Adsorbers				Post Siloxanes Adsorber			
Date	Biogas flow rate (ft^3/day)	CH_4 (%)	CO_2 (%)	O_2 (%)	H_2S (ppm)	CH_4 (%)	CO_2 (%)	O_2 (%)	H_2S (ppm)	CH_4 (%)	CO_2 (%)	O_2 (%)	H_2S (ppm)
08/18/14	330,079	62.8	36.9	0.0	255	62.0	36.8	0.0	41				
08/19/14	196,632	62.1	36.8	0.0	260	61.8	37.1	0.0	39				
08/20/14	235,008	62.7	36.9	0.0	268	61.3	37.5	0.0	43				
08/21/14	242,276	62.0	36.7	0.0	190	62.0	36.9	0.0	35				
08/22/14	227,807	62.7	36.4	0.0	235	62.0	36.9	0.0	33				
08/25/14	178,774	62.2	36.8	0.0	245	62.1	36.9	0.0	36				
08/26/14	177,265	62.3	36.7	0.0	210	62.2	36.9	0.0	32				
09/08/14	155,707	63.8	36.0	0.0	48	62.8	36.9	0.0	0	63.8	35.9	0.0	0
09/09/14	170,110	62.0	35.5	0.0	63	62.1	36.2	0.0	0	63.5	36.2	0.0	0
09/10/14	216,270	62.3	36.2	0.0	73	62.4	36.2	0.0	0	62.5	36.2	0.0	0
09/11/14	147,718	63.9	36.9	0.0	98	62.7	37.5	0.0	0	63.3	36.2	0.0	0
09/12/14	330,079	62.0	36.7	0.0	115	62.1	36.4	0.0	0	63.3	36.3	0.0	0
09/15/14	173,800	62.3	36.5	0.0	130	62.7	36.5	0.0	0	64.0	36.0	0.0	0
09/16/14	209,180	63.0	35.0	0.0	98	63.0	36.3	0.0	0	63.3	35.5	0.0	0
09/17/14	267,640	63.4	36.4	0.0	100	63.5	35.6	0.0	0	64.0	35.7	0.0	0
09/18/14	327,667	62.9	33.3	0.0	128	63.7	34.8	0.0	0	64.2	35.6	0.0	0
09/19/14	260,148	63.6	33.2	0.0	148	64.3	34.4	0.0	0	64.5	35.3	0.0	0
09/22/14	186,943	62.4	35.7	0.0	205	62.8	36.3	0.0	0	63.3	35.9	0.0	0
09/23/14	200,875	61.7	36.3	0.0	323	62.9	36.3	0.0	0	63.8	35.9	0.0	0
09/24/14	112,098	61.7	35.8	0.0	115	63.2	35.7	0.0	0	64.1	35.7	0.0	0
09/25/14	268,174	62.0	35.7	0.0	113	62.3	36.0	0.0	0	63.3	36.3	0.0	0
09/29/14	149,630	61.3	36.2	0.0	110	62.3	36.3	0.0	0	63.5	36.1	0.0	0
09/30/14	190,887	61.3	36.2	0.0	83	62.1	36.5	0.0	0	63.3	36.2	0.0	0
10/01/14	181,578	61.9	36.4	0.0	60	62.5	36.1	0.0	0	63.4	36.1	0.0	0
10/02/14	171,569	62.0	35.9	0.0	60	62.6	35.9	0.0	0	63.6	36.1	0.0	0
10/03/14	259,365	62.0	36.4	0.0	48	61.9	36.8	0.0	0	61.9	36.8	0.0	0
10/06/14	165,654	62.0	36.2	0.0	0	62.9	36.5	0.0	0	63.5	35.9	0.0	0
10/07/14	195,423	62.8	36.5	0.0	28	63.1	36.5	0.0	0	63.4	36.3	0.0	0
10/08/14	308,536	63.4	36.3	0.0	23	63.0	36.1	0.0	30	63.9	36.1	0.0	0
10/09/14	242,888	64.3	34.9	0.0	25	64.8	34.8	0.0	8	64.8	34.9	0.0	0
10/10/14	249,998	63.0	36.0	0.0	60	63.8	36.2	0.0	0	64.2	35.9	0.0	0
10/13/14	192,319	62.8	36.2	0.0	45	63.4	36.3	0.0	0	64.0	36.9	0.0	0
10/14/14	167,526	62.4	36.1	0.0	53	62.8	36.4	0.0	20	63.2	36.3	0.0	0
10/15/14	175,187	63.0	36.6	0.0	115	63.1	36.5	0.0	0	63.2	36.3	0.0	0
10/16/14	188,691	63.0	36.8	0.0	135	63.0	36.4	0.0	0	64.0	35.8	0.0	0
10/17/14	199,307	61.8	37.2	0.0	218	62.0	37.1	0.0	0	63.0	36.9	0.0	0
10/20/14	230,383	62.4	36.7	0.0	125	62.9	36.6	0.0	0	63.8	36.1	0.0	0
10/21/14	207,226	63.2	35.8	0.0	135	63.3	35.9	0.0	0	64.2	35.8	0.0	0
10/22/14	240,531	63.5	35.8	0.0	153	63.6	35.9	0.0	0	64.2	35.7	0.0	0

		Raw Biogas				Post H_2S Adsorbers				Post Siloxanes Adsorber			
Date	**Biogas flow rate (ft^3/day)**	**CH_4 (%)**	**CO_2 (%)**	**O_2 (%)**	**H_2S (ppm)**	**CH_4 (%)**	**CO_2 (%)**	**O_2 (%)**	**H_2S (ppm)**	**CH_4 (%)**	**CO_2 (%)**	**O_2 (%)**	**H_2S (ppm)**
10/23/14	228,666	63.4	36.2	0.0	160	63.4	36.2	0.0	0	64.1	35.9	0.0	0
10/24/14	257,832	63.6	35.7	0.0	158	63.6	35.7	0.0	0	64.4	35.3	0.0	0
10/27/14	177,748	63.3	36.4	0.0	165	63.4	36.5	0.0	0	63.6	35.6	0.0	0
10/28/14	187,235	62.6	36.4	0.0	0	63.2	36.0	0.0	0	63.7	36.1	0.0	0
10/29/14	162,944	62.0	36.1	0.0	168	62.3	36.6	0.0	0	63.4	36.7	0.0	0
10/30/14	231,109	62.3	36.4	0.0	160	62.8	36.7	0.0	0	63.4	36.6	0.0	0
10/31/14	183,906	63.0	36.1	0.0	170	63.4	36.0	0.0	0	63.7	36.2	0.0	0
11/02/14	213,593	62.7	36.6	0.0	185	62.8	35.4	0.0	0	63.1	36.4	0.0	0
11/03/14	225,318	62.2	37.1	0.0	193	62.2	37.4	0.0	0	63.0	37.0	0.0	0
11/04/14	200,347	62.9	36.4	0.0	208	63.3	36.1	0.0	0	63.8	36.0	0.0	0
11/05/14	190,099	63.0	36.6	0.0	208	63.4	36.1	0.0	0	64.0	36.3	0.0	0
11/06/14	176,616	63.7	36.6	0.0	195	62.7	36.2	0.0	0	63.6	36.3	0.0	0
11/07/14	241,296	62.5	36.6	0.0	205	63.3	36.3	0.0	0	64.1	35.8	0.0	0
Count	52	52	52	52	52	52	52	52	52	45	45	45	45
Maximum	330,079	64	37.2	0.0	323	64.8	37.5	0	43	64.8	37.0	0.0	0
Minimum	112,098	61	33.2	0.0	0	61.3	34.4	0	0	61.9	34.9	0.0	0
Median	199,827	63	36.4	0.0	133	62.8	36.3	0	0	63.6	36.1	0.0	0
Mean	212,811	63	36.1	0.0	127	62.8	36.3	0	7	63.6	36.0	0.0	0
Std. Dev.	46,997	0.7	0.7	0.0	75	0.7	0.6	0	13	0.5	0.4	0	0

APPENDIX C:
VOC Concentrations in the Biogas

	10/8/2014			10/29/2014		
Compound	**Raw Biogas**	**Post H_2S Adsorber**	**Post Siloxanes Adsorber**	**Raw Biogas**	**Post H_2S Adsorber**	**Post Siloxanes Adsorber**
Chlorodifluoromethane	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
Propene	1,730	1,700	1,590	1,150	1,180	1,140
Dichlorodifluoromethane	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
Chloromethane	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
Dichlorotetrafluoroethane	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
Vinyl Chloride	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
Methanol	<65.2	<65.2	<65.2	<65.2	<65.2	<65.2
1,3-Butadiene	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
Bromomethane	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
Chloroethane	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
Dichlorofluoromethane	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
Ethanol	<26.1	<26.1	<26.1	<26.1	<26.1	<26.1
Vinyl Bromide	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
Acetone	<26.1	<26.1	<26.1	<26.1	<26.1	<26.1
Trichlorofluoromethane	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
2-Propanol	<26.1	<26.1	<26.1	<26.1	<26.1	<26.1
Acrylonitrile	<13.0	<13.0	<13.0	<13.0	<13.0	<13.0
1,1-Dichloroethene	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
Methylene Chloride	<13.0	<13.0	<13.0	<13.0	<13.0	<13.0
Allyl Chloride	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
Trichlorotrifluoroethane	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
trans-1,2-Dichloroethene	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
1,1-Dichloroethane	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
Methyl Tert Butyl Ether	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
Vinyl Acetate	<13.0	<13.0	<13.0	<13.0	<13.0	<13.0
2-Butanone	31.2	35.8	39.2	<13.0	<13.0	<13.0
cis-1,2-Dichloroethene	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
Hexane	29.8	29.7	110	17.1	16.4	52.4
Chloroform	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
Ethyl Acetate	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
Tetrahydrofuran	88.5	<6.5	10.3	<6.5	<6.5	<6.5
1,2-Dichloroethane	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
1,1,1-Trichloroethane	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
Benzene	20.5	21.4	72.1	17.4	17.9	35.3
Carbon Tetrachloride	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
Cyclohexane	<6.5	<6.5	9.9	<6.5	<6.5	<6.5
1,2-Dichloropropane	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
Bromodichloromethane	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
1,4-Dioxane	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5

	10/8/2014			10/29/2014		
Compound	**Raw Biogas**	**Post H_2S Adsorber**	**Post Siloxanes Adsorber**	**Raw Biogas**	**Post H_2S Adsorber**	**Post Siloxanes Adsorber**
Trichloroethene	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
2,2,4-Trimethylpentane	<6.5	7.2	84.4	<6.5	<6.5	49.9
Heptane	130	106	238	53.2	54.1	140
cis-1,3-Dichloropene	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
4-Methyl-2-pentanone	<6.5	<6.5	13.7	<6.5	<6.5	10.6
trans-1,3-Dichloropropene	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
1,1,2-Trichloroethane	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
Toluene	735	690	1,860	1,430	1,430	2,130
2-Hexanone	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
Dibromochloromethane	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
1,2-Dibromomethane	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
Tetrachloroethene	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
Chlorobenzene	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
Ethylbenzene	19.4	17.0	55.7	18.4	20.9	41.8
m & p-Xylenes	18.4	16.0	20.8	14.7	15.7	22.7
Bromoform	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
Styrene	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
1,1,2,2-Tetrachloroethane	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
o-Xylene	6.7	<6.5	<6.5	<6.5	<6.5	<6.5
4-Ethyl toluene	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
1,3,5-Trimethylbenzene	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
1,2,4-Tirmethylbenzene	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
Benzyl Chloride	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
1,3-Dichlorobenzene	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
1,4-Dichlorobenzene	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
1,2-Dichlorobenzene	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
1,2,4-Trichlorobenzene	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5
Hexachlorobutadiene	<6.5	<6.5	<6.5	<6.5	<6.5	<6.5

APPENDIX D:
Historical Data from IC Engine Source Tests

	5/22/2008		4/29/2009		4/16/2010		5/3/2001		4/19/2012		9/17/2013		4/17/2014	
	NG*	**Biogas**	**NG**	**Biogas**	**NG**	**Biogas**	**NG**	**Biogas**	**NG**	**Biogas**	**NG**	**Biogas**	**NG**	**Biogas**
Output (kW)	590	640	590	620	555	620	643	649	650	600	538	550	641	603
Flow rate (SD CFM)	2,140	1,710	1,750	1,780	1,530	1,440	1,390	1,340	1,720	1,590	1,610	1,410	1,880	1,810
CO (ppm)	292	381	263	337	286	359	246	286	288	329	259	321	252	322
CO (ppm), converted to 15% O_2	138	157	121	157	128	147	106	114	127	139	118	137	118	142
CO (gm/Hp-hr)	1.56	1.58	1.15	1.42	1.16	1.22	0.78	0.87	1.12	1.28	1.14	1.21	1.09	1.42
NO (ppm)	20	113	20	46	71	118	129	63	44	19	29	17	29	11
NO_2 (ppm)	32	38	33	36	46	43	49	39	37	27	33	27	24	18
NO_x (ppm), converted to 15% O_2	24	62	24	38	53	66	77	40	35	19	28	19	25	13
NO_x (gm/Hp-hr)	0.45	1.02	0.37	0.57	0.78	0.91	0.93	0.51	0.52	0.29	0.45	0.27	0.38	0.21
Methane (ppm)	799	847	799	1,070	605	762	561	886	686	1,400	720	1,220	677	1,270
NMOC as C_1 (ppm)	<10	24	<10	<10	34	16	90	<10	18	18	72	<25	84	26
NMOC as C_1 (gm/Hp-hr)	<0.03	0.06	<0.02	<0.02	0.08	0.03	0.16	<0.02	0.04	0.04	0.18	<0.05	0.21	0.07
TOC as C_1 (ppm)	799	870	799	1,070	639	778	651	866	704	1,418	791	1,230	760	1,290
CO_2 (%)	8.0	14.6	8.1	15.1	7.2	12.7	8.3	13.8	7.3	11.8	7.0	11.2	6.8	10.7
Oxygen (%)	8.3	6.5	8.5	8.2	8.0	6.4	7.2	6.0	7.4	6.8	7.9	7.0	8.3	7.5
SO_2 (ppm)	<5	16	2	2	<2	9	11	11	2	6	<2	3	<2	<2
SO_2 (gm/Hp-hr)	<0.07	0.15	0.02	0.02	<0.02	0.07	0.08	0.08	0.01	0.05	<0.02	0.03	<0.02	<0.02
Estimated Heat Input (MMBTU/d)													187	191
Heating Value of Biogas (BTU/scf)		596		560		560		540		424		479		634

Note: NG = Natural Gas

APPENDIX E:
Daily Monitoring Data for IC Engine Emissions

	Natural Gas								Biogas							
Date	**CH_4 (%)**	**CO_2 (%)**	**CO (ppm)**	**NO_2 (ppm)**	**NO (ppm)**	**SO_2 (ppm)**	**O_2 (%)**	**kW**	**CH_4 (%)**	**CO_2 (%)**	**CO (ppm)**	**NO_2 (ppm)**	**NO (ppm)**	**SO_2 (ppm)**	**O_2 (%)**	**kW**
08/18/14									0.179	7.6	353	18	12	0	7.2	
08/19/14									0.186	7.7	349	19	13	0	7.2	
08/20/14									0.164	7.6	201	18	9	0	7.3	
08/21/14									0.164	7.7	371	17	12	0	7.2	
08/22/14									0.200	7.6	362	17	10	0	7.3	
08/25/14									0.169	7.7	366	18	14	0	7.2	
08/26/14									0.132	7.7	350	20	15	0	7.1	
08/27/14									0.189	7.7	360	19	13	0	7.1	
08/28/14									0.178	7.7	360	17	10	0	7.2	
08/29/14									0.183	7.7	363	17	12	0	7.2	
09/02/14									0.194	7.7	353	20	7	0	7.2	
09/03/14									0.190	7.7	354	20	8	0	7.1	
09/04/14									0.172	7.7	358	18	9	0	7.2	
09/05/14									0.182	7.7	367	20	11	0	7.1	
09/08/14									0.127	7.6	381	23	15	0	7.3	
09/09/14									0.168	7.7	375	21	12	0	7.2	
09/10/14									0.201	7.7	377	20	7	0	7.1	
09/15/14	0.148	7.2	313	25	16	0	8.0		0.182	7.6	385	22	12	0	7.3	580
09/16/14	0.140	7.2	313	26	13	0	8.0	531	0.176	7.7	377	22	12	0	7.2	613
09/17/14	0.195	7.7	378	21	12	0	7.2	612	0.168	7.6	380	21	11	0	7.3	555
09/18/14									0.214	7.6	382	25	18	0	7.3	571
09/19/14	0.128	7.2	304	27	14	0	8.0	553	0.174	7.6	369	22	11	0	7.3	563
09/22/14	0.121	7.2	314	28	16	0	8.1	552	0.141	7.7	353	28	5	0	7.2	590
09/23/14	0.115	7.2	312	31	17	0	8.0	603	0.171	7.7	367	23	10	0	7.2	576
09/24/14	0.121	7.2	309	28	12	0	8.1	537								
09/25/14	0.100	7.1	317	28	21	0	8.2	654	0.140	7.7	372	22	15	0	7.2	617

	Natural Gas								Biogas							
Date	**CH_4 (%)**	**CO_2 (%)**	**CO (ppm)**	**NO_2 (ppm)**	**NO (ppm)**	**SO_2 (ppm)**	**O_2 (%)**	**kW**	**CH_4 (%)**	**CO_2 (%)**	**CO (ppm)**	**NO_2 (ppm)**	**NO (ppm)**	**SO_2 (ppm)**	**O_2 (%)**	**kW**
09/26/14	0.129	7.2	224	24	21	0	8.1		0.160	7.7	367	26	9	0	7.1	613
09/29/14	0.110	7.2	315	27	17	0	8.0	640	0.157	7.7	370	21	13	0	7.2	588
09/30/14	0.113	7.2	312	27	18	0	8.0	586	0.142	7.7	372	21	11	0	7.2	592
10/01/14	0.119	7.2	314	29	20	0	8.0	589	0.162	7.7	384	29	17	0	7.1	551
10/02/14	0.124	7.2	322	32	28	0	8.0	611	0.192	7.6	368	25	8	0	7.3	690
10/03/14	0.133	7.3	319	37	24	0	7.9	550	0.202	7.6	371	25	6	0	7.3	620
10/06/14									0.198	7.7	368	24	9	0	7.1	590
10/07/14	0.119	7.2	322	30	19	0	8.0	589	0.171	7.7	367	23	11	0	7.2	567
10/08/14	0.120	7.2	315	29	18	0	8.0	561	0.186	7.7	365	24	6	0	7.2	541
10/09/14	0.117	7.2	311	30	20	0	8.0	638	0.174	7.7	365	26	9	0	7.2	620
10/10/14	0.119	7.2	314	30	19	0	8.0	553	0.160	7.7	372	25	11	0	7.2	570
10/13/14	0.121	7.2	316	31	19	0	8.0	594	0.180	7.8	379	28	16	0	7.0	633
10/14/14	0.122	7.2	310	27	14	0	8.1	612	0.171	7.7	365	24	9	0	7.2	592
10/15/14	0.136	7.2	307	27	10	0	8.1	583	0.174	7.6	370	20	6	0	7.3	621
10/16/14	0.092	7.2	317	31	16	0	8.1	575	0.163	7.7	371	27	11	0	7.2	586
10/17/14	0.129	7.2	315	28	14	0	8.0	597	0.154	7.6	369	21	7	0	7.3	611
10/20/14	0.130	7.2	302	26	12	0	8.0	636	0.175	7.7	368	23	8	0	7.2	597
10/21/14	0.116	7.2	309	28	16	0	8.0	597	0.153	7.7	370	29	15	0	7.2	681
10/22/17	0.108	7.2	304	35	17	0	8.0	607								
10/23/14	0.107	7.2	307	31	13	0	8.0	558								
10/24/14	0.114	7.3	312	31	20	0	7.9	603	0.154	7.7	363	27	7	0	7.2	592
10/27/14	0.098	7.3	324	35	23	0	7.9	594	0.129	7.7	370	30	15	0	7.1	643
10/28/14	0.107	7.2	304	34	18	0	8.0	641	0.129	7.7	364	29	13	0	7.2	605
10/29/14	0.114	7.2	307	32	16	0	8.0	605	0.155	7.7	366	29	12	0	7.1	566
10/30/14	0.110	7.2	309	33	18	0	8.0	611	0.150	7.7	364	26	6	0	7.2	595
10/31/14	0.113	7.2	309	32	16	0	8.0	656	0.142	7.7	363	25	10	0	7.2	662
11/03/14	0.115	7.3	319	33	23	0	7.9	611	0.143	7.7	160	24	9	0	7.2	578
11/04/14	0.094	7.2	307	29	17	0	8.0	579	0.161	7.7	360	22	6	0	7.2	643
11/05/14	0.123	7.2	320	30	18	0	8.0	578	0.152	7.7	361	26	10	0	7.1	632
11/06/14	0.119	7.2	320	32	20	0	8.0	623	0.156	7.7	362	24	8	0	7.2	607

	Natural Gas								Biogas							
Date	**CH_4 (%)**	**CO_2 (%)**	**CO (ppm)**	**NO_2 (ppm)**	**NO (ppm)**	**SO_2 (ppm)**	**O_2 (%)**	**kW**	**CH_4 (%)**	**CO_2 (%)**	**CO (ppm)**	**NO_2 (ppm)**	**NO (ppm)**	**SO_2 (ppm)**	**O_2 (%)**	**kW**
11/07/14	0.105	7.2	311	30	13	0	8.0	600	0.171	7.7	363	22	4	0	7.2	589

Count	38	38	38	38	38	38	38	36	54	54	54	54	54	54	54	37
Maximum	0.195	7.7	378	37	28	0	8.2	656	0.214	7.8	385	30	18	0	7.3	690
Minimum	0.092	7.1	224	21	10	0	7.2	531	0.127	7.6	160	17	4	0	7.0	541
Median	0.119	7.2	313	30	17	0	8.0	597	0.170	7.7	367	23	11	0	7.2	592
Mean	0.120	7.2	312	30	17	0	8.0	595	0.168	7.7	360	23	10	0	7.2	601
Std. Dev.	0.017	0.1	19	3	4	0	0.1	32	0.020	0.0	36	4	3	0	0.1	34

APPENDIX F:
Results from Air Toxics Testing

	10/29/2014		10/30/2014	
	pg/sample	**mg/dscm**	**pg/sample**	**mg/dscm**
2,3,7,8-TCDD	<5.75	<2.53E-09	<4.89	<2.12E-09
1,2,3,7,8-PeCDD	<3.52	<1.55E-09	<3.65	<1.58E-09
1,2,3,4,7,8-HxCDD	<7.41	<3.27E-09	<6.96	<3.02E-09
1,2,3,6,7,8-HxCDD	<8.39	<3.70E-09	<7.87	<3.41E-09
1,2,3,7,8,9-HxCDD	<6.95	<3.06E-09	<6.52	<2.83E-09
1,2,3,4,6,7,8-HpCDD	<6.67	<2.94E-09	<7.84	<3.40E-09
OCDD	31.2	<1.38E-08	11.7	<5.07E-09
2,3,7,8-TCDF	<8.09	<3.57E-09	<4.89	<2.12E-09
1,2,3,7,8-PeCDF	<3.42	<1.51E-09	<4.29	<1.86E-09
2,3,4,7,8-PeCDF	<5.64	<2.49E-09	<4.37	<1.89-09
1,2,3,4,7,8-HxCDF	<3.16	<1.39E-09	<1.48	<6.41E-10
1,2,3,6,7,8-HxCDF	<3.05	<1.34E-09	<1.42	<6.15E-10
2,3,4,6,7,8-HxCDF	<3.30	<1.45E-09	<1.54	<6.67E-10
1,2,3,7,8,9-HxCDF	<2.61	<1.15E-09	<1.78	<7.71E-10
1,2,3,4,6,7,8-HpCDF	<5.86	<2.58E-09	<3.78	<1.64E-09
1,2,3,4,7,8,9-HpCDF	<3.88	<1.71E-09	<5.00	<2.17E-09
OCDF	<6.66	<2.94E-09	<8.41	<3.64E-09
Total TCDD	<5.75	<2.53E-09	<4.89	<2.12E-09
Total PeCDD	<5.54	<2.44E-09	<3.65	<1.58E-09
Total HxCDD	<10.5	<4.63E-09	<11.2	<4.85E-09
Total HpCDD	7.77	3.42E-09	<9.55	<4.14E-09
Total TCDF	44.2	1.95E-08	<8.72	<3.78E-09
Total PeCDF	39.1	1.72E-08	<7.98	<3.46E-09
Total HxCDF	7.65	3.37E-09	<3.95	<1.71E-09
Total HpCDF	<6.68	<2.94E-09	<9.29	<4.03E-10

	10/29/2014		20/30/2014	
	ng/sample	**mg/dscm**	**ng/sample**	**mg/dscm**
Naphthalene	13,300	5.86E-03	14,600	6.33E-03
2-Methynaphthalene	8,240	3.63E-03	11,100	4.81E-03
Acenaphthylene	773	3.41E-04	815	3.53E-04
Acenaphthene	357	1.57E-04	458	1.98E-04
Fluorene	698	3.08E-04	352	1.53E-04
Phenanthrene	2,470	1.09E-03	1,750	7.58E-04
Anthracene	128	5.64E-05	<20	8.67E-06
Fluoranthene	246	1.08E-04	142	6.15E-05
Pyrene	193	8.51E-05	108	4.68E-05
Benz(a)anthracene	<20	<8.82E-6	<20	<8.67E-06
Chrysene	85.1	3.75E-05	47.7	2.07E-05
Benzo(b)fluoranthene	<20	<8.82E-6	<20	<8.67E-06
Benzo(k)fluoranthene	<20	<8.82E-6	<20	<8.67E-06
Benzo(e)pyrene	<20	<8.82E-6	<20	<8.67E-06
Benzo(a)pyrene	<20	<8.82E-6	<20	<8.67E-06
Perylene	<20	<8.82E-6	<20	<8.67E-06
Indeno(1,2,3-c,d)pyrene	<20	<8.82E-6	<20	<8.67E-06
Dibenz(a,h)anthracene	<20	<8.82E-6	<20	<8.67E-06
Benzo(g,h,i)perylene	<20	<8.82E-6	<20	<8.67E-06