FINAL REPORT

Renewable Energy Production from DoD Installation Solid Wastes By Anaerobic Digestion

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14. ABSTRACT

Food waste generation and disposal is a significant source of greenhouse gas emissions and lost opportunity for energy recovery. Anaerobic digestion of food waste and purification of methane-rich biogas was conducted at the US Air Force Academy. Cost and performance of the technology with respect to renewable energy efficiency; biogas purification; digester capacity and stability; waste sludge generation and characteristics; operational reliability, safety, and ease of use; and greenhouse accounting were evaluated. Demonstration results indicated the process was capable of meeting or exceeding most performance objectives. The technology was capable of significant reductions in the solid waste stream while at the same time recovering energy that can be used as vehicle fuel or a variety of other uses. Cost-effectiveness of the technology was comparable or better to landfilling and composting especially for larger installations. The technology was also demonstrated to have favorable greenhouse gas offsets compared to composting and landfilling. An engineering guidance document was prepared that provides installations practical approaches for technology evaluation and implementation.

15. SUBJECT TERMS

Food waste, FOG, solid waste, anaerobic digestion, methane, biogas, biomethane, biogas purification, vehicle fuel, renewable energy, net zero, greenhouse gas, food-to-fuel.

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ACRONYMS

ADM1	Anaerobic Digestion Model 1
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ATP	adenosine triphosphate
BEC_5	five day biological energy conversion
Biogas	methane byproduct
BMP	biochemical methane potential
BTU	British Thermal Units
CDPHE	Colorado Department of Public Health and the Environment
C_{COD}^{feed}	feed COD concentration
CHP	combined heat and power
CO_2e	carbon dioxide equivalents
COD	chemical oxygen demand
CTS	co-thickened sludge
DoD	Department of Defense
EBMUD	East Bay Municipal Utility District
EDDs	electronic data deliverables
ESTCP	Environmental Security Technology Certification Program
EPA	US Environmental Protection Agency
EPACT	Energy Policy Act of 2005
EO	Executive Order
F/M	food-to-microorganism
FOG	fats, oils and grease
GGE	gasoline gallon equivalents
GHG	greenhouse gases
LEED	Leadership in Energy and Environmental Design
NDAA	National Defense Authorization Act
NEC	National Electrical Code
NFPA	National Fire Protection Association
NOx	nitrogen oxides
NPDES	National Pollutant Discharge Elimination System
O&M	operations and maintenance

OSHA	Occupational Safety and Health Administration
PSA	pressure swing adsorption
PVC	polyvinylchloride
Q	flow rate
QAC	quaternary amine compound
RCRA	Resource Conservation and Recovery Act
rpm	revolutions per minute
RTD	resistance temperature device
SELR	specific energy loading rate
SOP	Standard Operating Procedure
SOx	sulfur oxides
SRT	solids retention time
TALK	total alkalinity
USAFA	U.S. Air Force Academy
VFA	volatile fatty acids
V	volume
VS	volatile solids
VSA	vacuum swing adsorption
VSD	volatile solids destruction
VSS	volatile suspended solids
VSSD	volatile suspended solids destruction
WERF	Water Environment Research Foundation
WRA	Water Reclamation Authority
WRRF	water resource recovery facilities
WWTP	wastewater treatment plant
X_{VSS}	volatile solids concentration

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Point of contact for the demonstration are included in Appendix A.

EXECUTIVE SUMMARY

BACKGROUND AND TECHNOLOGY DESCRIPTION

The Department of Defense (DoD) is a significant consumer of energy and generator of solid waste. During fiscal year 2009 the DoD consumed 209 trillion British Thermal Units (BTUs) of energy (2.2×10^{17} J), excluding vehicle fuel. Further, during the same period the DoD generated 5.2 million tons of solid waste. The consumption of energy and the generation of waste place economic, environmental and social burdens on the DoD.

Food waste is generated worldwide at a rate of about 0.3 kg person^{-1} d^{-1}. In 2011, 164 million tons of municipal solid waste was discarded comprising that contained 21.3% food waste. The energy content is about 130 trillion BTU or about 60% of the FY2009 DoD energy use. Much of this highly biodegradable waste is disposed in landfills where it is anaerobically digested into the greenhouse gases (GHG) methane and carbon dioxide. The methane produced in landfills is substantial and only a fraction is recovered. Anaerobic digestion of food waste in engineered reactors to produce methane-rich biogas offers a sustainable alternative to current practices and a source of energy. Furthermore, this biogas can be purified to produce vehicle fuel and provide greenhouse gas offsets. A simple schematic (**Figure ES-1**) shows in general terms how this technology could be implemented at DoD installations and elsewhere.

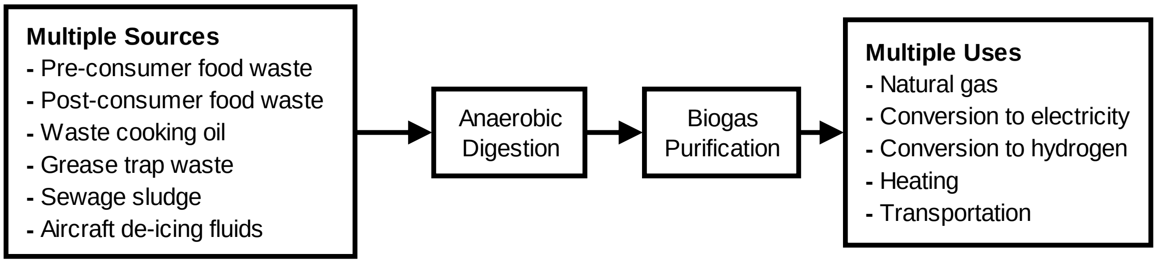

Multiple Sources
- Pre-consumer food waste
- Post-consumer food waste
- Waste cooking oil
- Grease trap waste
- Sewage sludge
- Aircraft de-icing fluids
Anaerobic Digestion
Biogas Purification
Multiple Uses
- Natural gas
- Conversion to electricity
- Conversion to hydrogen
- Heating
- Transportation

Figure ES-1. Food to fuel.

Anaerobic digestion plus biogas purification was used to convert food waste to biomethane fuel (food-to-fuel). Anaerobic digestion is a process where a community of anaerobic microorganisms biodegrade organic matter and produce biogas – a mixture of methane (CH_4) and carbon dioxide (CO_2). While anaerobic digestion of sewage sludge is a well-established process, use of anaerobic digestion to treat food waste and other energy-rich wastes such as fats, oils and grease (FOG); deicing fluids; and green waste has only recently been studied. Biogas treatment is any process used to improve the quality of the anaerobic digester gas. Biogas purification to produce high purity biomethane for vehicle fueling is relatively new. Two technologies were demonstrated for biogas purification biomethane. Hydrogen sulfide (H_2S) and organosulfur compounds were removed using a mixed metal oxide media (SulfaTrap™). A triple-bed vacuum swing adsorption (VSA) unit was used for CO_2 and moisture removal.

PERFORMANCE OBJECTIVES AND RESULTS

The demonstration was conducted at the U.S. Air Force Academy (USAFA) in Colorado Springs, Colorado. Four phases were conducted including I) equipment shakedown, II) startup, III) stable operation with diluted digester feed, and IV) modified process with concentrated digester feed. The performance objectives of this demonstration included various aspects of renewable energy conversion efficiency; digester capacity and stability; biogas purification, solids destruction and minimization of process residuals; operational reliability; and accounting of GHG emissions. Both quantitative and qualitative performance objectives were evaluated during the demonstration.

Renewable Energy Efficiency

Energy conversion efficiency of food waste and canola oil (a surrogate for USAFA grease trap waste) to methane was 73±13% (Goal ≥70%). When parasitic energy losses for the process (e.g., heating, pumping, and gas purification) were considered, the efficiency was 62% (goal ≥50%). Methane yields were 360±70 L/kg-volatile solids (goal ≥310) and 270±75 L/kg-chemical oxygen demand (COD) (goal ≥190). Biogas composition was 59±4.6% (goal ≥60%). While all of the above goals were met, volumetric methane production rate was not met (0.82±0.22 L/L/d [goal ≥2]). This was a result of a dilute food waste/canola oil feed (i.e., Phase III) which was rectified later in the demonstration (i.e., Phase IV) resulting in a rate of 2 L/L/d being observed at the end of the demonstration.

Biogas Purification

Methane recovery during biogas purification by the VSA was 94±2.9% (goal ≥80%). H_2S in the treated biogas was 0.030±0.035 ppm (goal <4). CH_4 in the treated biogas was 98±0.5% (goal ≥95%) after correction for likely air contamination during sampling. N_2 was 3.1±2.0 (goal <3%), CO_2 was 2.1±0.4% (goal <3%), and O_2 was 1.2±0.6 (goal <0.2%). The nitrogen and oxygen results appear to be elevated because of air contamination during sampling.

Digester Capacity/Stability

The digester capacity objective is related to the digester loading rate which in turn drives cost and space requirements. The volumetric loading rates based on volatile solids (VS) and COD were not met in Phase III (2.4±0.6 g-VS/L/d [goal ≥3.2] and 3.0±1.0 g-COD/L/d [goal ≥4.8]) but were possibly met near the end of Phase IV as a result of the modified feeding process (2.9±0.8 g-VS/L/d and 5.3±1.8 g-COD/L/d). When the COD loading rate was normalized to volatile suspended solids (VSS) concentration as a surrogate for the active microorganism mass in the digester to yield the specific energy loading rate (SELR), the loading rate goals were met (0.44±0.17 g-COD/g-VSS/d in Phase III and 0.47±0.30 g-COD/g-VSS/d in Phase IV [goal ≥0.26 g-COD/g-VSS/d]). Digester stability indicators included (pH 7.8±0.1 [goal 6.8 to 7.8]) and the ratio of total volatile fatty acids (VFA) to total alkalinity (TALK) (0.15±0.09 g-acetate equivalents/g-$CaCO_3$ [goal < 0.2 g-acetate equivalents/g-$CaCO_3$]).

Waste Sludge Generation and Characteristics

Reduction of food waste mass and generation of a reusable or safely disposable digestate were evaluated. Total solids reduction was 78±3.4% (goal ≥60%). Digestate sulfide was 71 mg/L (goal <500 mg/L). Hazardous metals concentrations were less than US Environmental Protection Agency (EPA) Resource Conservation and Recovery Act (RCRA) toxicity characteristic thresholds. While not directly applicable, digester treatment of the food waste met Class B biosolids requirements for treatment of sewage sludge: The solids retention time (SRT) was 40±14 d [goal ≥15) and the Volatile Solids destruction (VSD) was 81±3.0% (goal ≥38%). The digestate was a liquid with low total suspended solids, high ammonia and VFA concentrations, moderate concentrations of pathogens and poor dewaterability. Compost amendment is possible though odor could be a concern. The digestate may be useful as a liquid fertilizer considering the concentrations of ammonia and metal nutrients.

Operational Reliability, Safety, & Ease of Use

The process was 93% available during Phase III and 100% available during Phase IV (goal ≥95%). Mechanical malfunctions during Phase III were related to a digester mixer shaft seal that leaked. While there were no Occupational Safety and Health Administration (OSHA)-reportable accidents during the demonstration, the operator was exposed to H_2S gas that leaked from the malfunctioning digester shaft seal. Safety was addressed during the design process by specifying National Electrical Code (NEC) Class 1 Division 1 and Class 1 Division 2 areas that required specialized equipment, instrumentation, and electrical systems (e.g., explosion proof or intrinsically safe). The facility was successfully operated by a single operator that was not on-site 24 hours a day. After start-up issues were resolved, the system was easily operated by a single operator working one shift per day, five days per week. However, two issues that would need to be addressed in a full-scale facility are food waste debris and gas leaks. The food waste contained much debris that was manually segregated. Commercially available systems are available that can automate the process. Gas leaks that led to operator exposure to H_2S would need to be eliminated.

Greenhouse Gas Accounting

The calculated greenhouse gas emissions from nominally scaled food waste digester treating about 38,000 tons/yr of food waste were -470 tons per year (i.e., GHG offset due to use of purified biomethane as vehicle fuel). By comparison, landfilling and composting would generate 530 and 180 tons/year, respectively. Thus, food waste disposal in anaerobic digesters represents a significant greenhouse gas savings compared to landfilling and composting.

PERFORMANCE EVALUATION

Anaerobic digestion of food waste and a surrogate for grease trap waste (i.e., canola oil) was demonstrated to be capable of recovering potential energy content, reducing solid waste, and potentially producing a valuable, nutrient-rich end product. Biogas purification was demonstrated to be capable of high methane recovery and production of biomethane that was sufficiently pure to be compressed and used as vehicle fuel. When the processes are considered together they provide a solid waste reduction technology that recovers energy, creates a greenhouse gas offset, and produces an end product. The process provides distinct advantages over landfilling and composting with respect to energy recovery and greenhouse gas offsets.

The demonstration highlighted that feeding the digester with a concentrated food waste was necessary to facilitate high organic loading rates and volumetric methane production rates. A practical method for feeding high solids content food waste (e.g., >20% total solids) was employed that involved recycling and mixing with the digestate to create a pumpable slurry (i.e., < 10% total solids). Even when the high solids content feed was used, the digestate total solids concentration remained low and mixable because of the high digestibility of the food waste. The demonstration highlighted the need to amend with metal nutrients that have the potential to be deficient. This was especially true for cobalt and nickel. Ammonia concentrations can be quite high especially when a protein-rich food waste is the primary feed. The observed concentrations were not as toxic as expected, however upper limits were not identified. Fat, oil, and grease (FOG) also has the potential to be toxic however acclimation strategies were identified that can prevent toxicity to a certain extent. The elevated ammonia concentrations may have led to elevated concentrations of VFAs. These elevated concentrations of ammonia and VFAs did not inhibit food waste digestion and methane production, however, they were high when compared to conventional anaerobic waste activated sludge digestion at wastewater treatment plants (WWTP). Additionally the high VFA concentrations can lead to odor concerns when considering potential use of the digestate as a compost amendment or liquid fertilizer.

Use of standard wastewater engineering metrics and observations were found to not necessarily be applicable to food waste digestion. For example, digester feeding was better monitored and controlled using the SELR rather than a volumetric organic loading rate. Furthermore, when the energy loading rate (measured in terms of chemical oxygen demand) was limited to the protein+fat content a better prediction of methane production rates was observed when compared to the total COD.

The capital and operations and maintenance costs (O&M) of a green field food waste digester and gas purification system was determined for three installation sizes (10,000; 20,000; and 40,000 personnel). Capital costs ranged from $0.93 (10,000 personnel) to $2.44 million (40,000 personnel). Net annual revenues (i.e., income from vehicle fuel minus operating and maintenance costs) ranged from –$20,000 (10,000 personnel) to $120,000 (40,000 personnel). When capital costs, O&M, and revenues were considered, the net present cost ranged from $1.28 million (10,000 personnel) to $280,000 (40,000 personnel). The costs for food waste digestion and vehicle fueling were as low as $4/wet ton (40,000 personnel) to $50/wet ton (10,000 personnel). Compare these costs to average landfilling costs of $50/wet ton and composting costs ranging from $29 to $52/wet ton. Thus, even at the smaller 10,000 personnel base the technology is cost competitive with landfilling and off-site composting. For installations serving a population of 20,000, food waste disposal through anaerobic digestion and biogas recovery either as a vehicle fuel or in a CHP facility is cost competitive with institutional on-site composting. At larger bases of around 40,000 personnel, disposal of food waste via anaerobic digestion and biogas purification appears to have economic advantages compared to traditional food waste disposal methods. This economic advantage combined with the minimized GHG emissions and dependence of petroleum-based fuels suggests that food waste digestion and biogas purification is advantageous. For example, the estimated biomethane production from food waste generation alone at USAFA is 6,000 to 10,000 gasoline gallon equivalents (GGE)/year. For installations that have on-site WWTP with anaerobic digestion such as USAFA, co-digestion of food waste becomes an even more valuable proposition.

1.0 INTRODUCTION

The purpose of this demonstration was to validate anaerobic digestion of DoD wastes including pre- and post-consumer food waste, waste cooking oil, and grease trap waste as a viable means of disposal and renewable energy generation. The project demonstrated the ability to digest these wastes in a controlled and predictable manner to maximize the generation of biogas, a methane-rich, high energy byproduct. The project also studied biogas treatment to remove the non-methane portion of the gas including H_2S (and carbon dioxide, with the goal to produce treated product gas equivalent in quality to natural gas and suitable for numerous end-use applications and reduce mass of waste disposed by at least 60%. The pilot system was installed at the USAFA in Colorado Springs, Colorado and demonstration activities were conducted for one year. A laboratory treatability study was also conducted in advance of the field demonstration.

1.1 BACKGROUND

The DoD is a significant consumer of energy and generator of solid waste. During FY 2009 the DoD consumed 209 trillion BTUs of energy (2.2×10^{17} J), excluding vehicle fuel (DoD 2010). Further, during the same period the DoD generated 5.2 million tons of solid waste. The consumption of energy and the generation of waste place economic, environmental and social burdens on the DoD. In recognition of the burden that these activities place on the Department, the DoD has initiated programs and policies to reduce energy consumption and waste generation.

- The Energy Policy Act of 2005 (EPACT) mandates that federal facilities receive at least 7.5% of their electricity from renewable resources by 2013. If the energy is generated on site from renewable resources the facilities receive double credit toward attainment of this goal.
- The 2008 National Defense Authorization Act (NDAA) implemented a renewable energy goal of 25% for the DoD.
- Executive Order 13423 ([EO] 13423) requires that at least half of the statutorily required renewable energy consumed by the agency in a fiscal year comes from a new renewable source and to the extent feasible, the agency implement renewable energy generation projects on agency property for agency use. Further, the order requires increased diversion of solid waste as appropriate and maintenance of cost effective waste prevention and recycling programs in its facilities (USDOE 2008).
- The DOD Integrated (Non-Hazardous) Solid Waste Management Policy set minimum standards of 40% waste diversion of non-hazardous, non-construction and demolition integrated solid waste (Beehler 2008).

Food waste is generated worldwide at a rate of about 0.3 kg $person^{-1}$ d^{-1} (USEPA 2008). The DoD is a major producer of solid waste of which a significant fraction is food waste (see Appendix B). In 2011, 164 million tons of municipal solid waste was discarded comprising that contained 21.3% food waste (USEPA 2013a). We estimate that energy content of this annual food waste generation amounts to 130 trillion BTU (1.4×10^{17} J) which is about 60% of the FY2009 DoD energy use exclusive of vehicle fuel). Much of this highly biodegradable waste is disposed in landfills where it is anaerobically digested into greenhouse gases (GHG) such as methane and carbon dioxide. The methane produced in landfills is significant and only a fraction is recovered. Food waste and related wastes, including spent cooking oil, has a high energy value (Lenahan and Kirwan 2001; Wolk et al. 2007). Anaerobic digestion of food waste in engineered reactors offers a sustainable alternative to current practices and a source of energy.

Co-digestion of food waste is increasingly being conducted at WWTP. Less is known about mono-digestion of food waste. Learning more about mono-digestion will complement our knowledge of co-digestion (Parry 2014). A significant challenge in implementing food waste digestion is the lack of quantitative data on digestibility of food waste, kinetics of food waste digestion, stability, and energy and material balances. Previous research has identified several critical success factors for mono-digestion of food waste at the laboratory scale (Amador et al. 2012; Evans et al. 2012; Stallman et al. 2012). These included presence of supplemental nutrients (e.g., Co, Ni, and Mo). The objectives of this research were to demonstrate solids reduction and biomethane production from anaerobic digestion mono-food waste/FOG digestion (i.e., not co-digestion) and associated solids reduction.

This project demonstrated anaerobic digestion as a means of treating DoD wastes and producing renewable energy to partially offset an installation's energy demands and reduce waste disposal. Anaerobic digestion is a biological treatment process that uses bacterial populations capable of degrading organic wastes while generating a methane byproduct (biogas). The bacterial population is preferentially selected by maintaining favorable environmental conditions including a mesophilic (37 °C) or thermophilic (55 °C) temperature, the absence of oxygen, and a pH between 6.5 and 8.0.

Biogas generated by the digestion process can be used in an untreated state for energy generation (i.e., combined heat and power [CHP]); however impurities in the biogas can cause excessive wear to equipment and does not necessarily provide the best value (see Appendix C). To maximize the opportunities for biogas utilization the gas can be purified to biomethane which can be used as a natural gas substituted or compressed for vehicle fueling. A simple schematic (**Figure 1**) shows in general terms how the subject technology would be implemented at DoD installations to support attainment of the EPACT and NDAA goals.

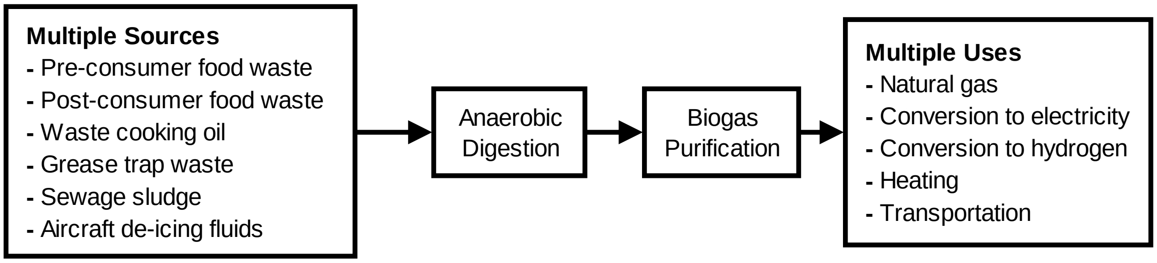


Figure 1. Anaerobic digestion of wastes to produce fuel.

Combining waste treatment with renewable energy production provides a number of benefits that are not provided by the conventional practices of fossil fuel utilization and landfilling of wastes. The benefits of the subject technology are listed below:

- Production of a high energy product with numerous end uses
  - Provides a significant contribution towards EPACT and NDAA goals of increased renewable energy production and utilization
  - Decreases total energy procurement costs as purified biogas is substituted for natural gas
  - Reduces greenhouse gas and pollutant emissions as fossil fuel energy sources are avoided

- Reduced landfilling of a high water content waste
  - Reduces waste disposal costs
  - Reduces leachate formation and preserves groundwater quality
  - Extends landfill life and delays construction of new landfills

1.2 OBJECTIVE OF THE DEMONSTRATION

The objective of the research reported here was to demonstrate stable anaerobic mono-digestion of food waste at the pilot scale. An additional objective was to demonstrate two innovative technologies for biogas purification to natural gas-quality methane. The technical objectives of this demonstration/validation project included:

- Demonstrate anaerobic digestion of food waste and FOG at a DoD installation to produce methane-rich biogas.
- Demonstrate biogas purification to biomethane that could be used for vehicle fueling.
- Determine the extent to which the technology can cost-effectively recover energy, reduce solid waste generation, produce a valuable end product, and offset GHG emissions.
- Determine the operating conditions that lead to stable digester operation and document associated engineering design parameters that can guide technology implementation at DoD installations.
- Document cost and performance of the technology.

1.3 REGULATORY DRIVERS

Regulatory drivers for this technology include:

- The DoD Strategic Sustainability Performance Plan provides an approach towards meeting these requirements which includes a focus on: 1) reducing energy needs and reliance on fossil fuels; and 2) water resources management.
- American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) 189.1-2009, Leadership in Energy and Environmental Design (LEED) and various Energy Policy Acts all have required more sustainable use of energy.

- The Army has implemented a Net-Zero installations policy seeking to increase and improve sustainability on installations.
- In addition, several other orders and acts promote energy sustainability and minimization of waste generation including:
    - EPACT 2005
    - EO 13423
    - 10 United States Code 2577
    - Energy Independence and Security Act 2007
    - FY2008 NDAA
    - Pollution Prevention Act of 1990
    - DoD Instruction 4715.4 “Pollution Prevention”
    - DoD Integrated Solid Waste Management Policy

2.0 TECHNOLOGY

This section provides an overview of the technology anaerobic digestion and biogas purification technologies.

2.1 TECHNOLOGY DESCRIPTION

For simplicity of discussion the anaerobic digestion and biogas treatment portions of the technology will be discussed separately.

2.1.1 Anaerobic Digestion

Anaerobic digestion is a process where a community of anaerobic microorganisms biodegrade organic matter and produce a mixture CH_4, CO_2, and other gases such as H_2S, albeit in smaller concentrations. While the biochemical reactions are complex, the general mechanisms involve solids biohydrolysis followed by fermentation of complex organics to hydrogen and VFAs including acetic, propionic, and butyric acids. These simpler compounds are subsequently converted to methane by methanogenic microorganisms. The process generally performs most efficiently at mesophilic (37 ^{o}C) and thermophilic (55 ^{o}C) temperatures and at or near neutral pH. Stable operation is dependent on feeding the digester organic material at a rate that does not exceed the metabolic capacity of the methanogenic bacteria. If the metabolic capacity of the methanogens is exceeded, VFA can build up, consume alkalinity and cause a drop in the digester's pH. As the pH drops, an acidic/toxic environment can develop in the digester and the active microbial can be inhibited or killed, halting the digestion process.

A schematic representation of the anaerobic digestion process is presented in **Figure 2**. A photo of an industrial anaerobic digestion facility is shown in **Figure 3.**

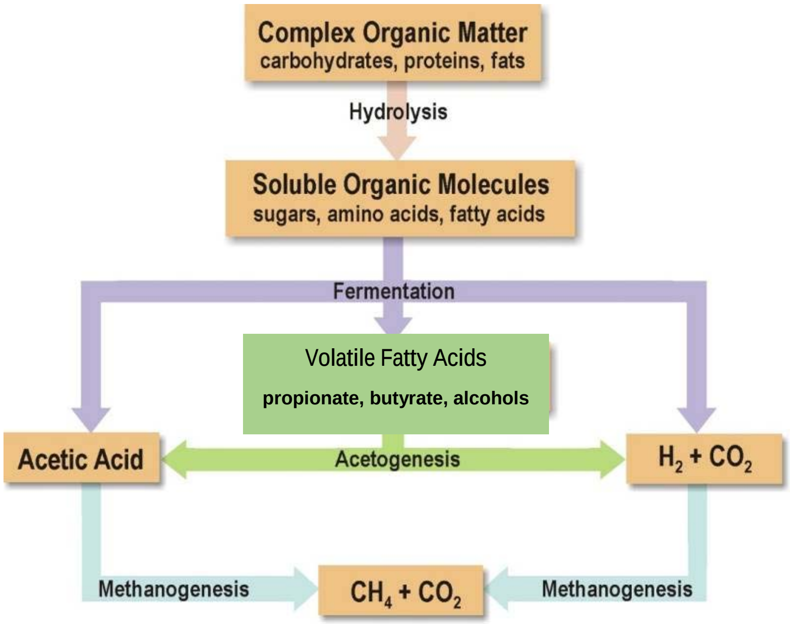

Complex Organic Matter
carbohydrates, proteins, fats
Hydrolysis
Soluble Organic Molecules
sugars, amino acids, fatty acids
Fermentation
Volatile Fatty Acids
propionate, butyrate, alcohols
Acetic Acid
Acetogenesis
$H_2 + CO_2$
Methanogenesis
$CH_4 + CO_2$
Methanogenesis

Figure 2. Simplified anaerobic digestion schematic (USEPA 2011).

Figure 3. Anaerobic digester.

Anaerobic digestion of sewage sludge is a well-established process, having been used for over a century in wastewater treatment for the purpose of treating wastewater sludge and for energy generation. Recently there has been increased interest in using anaerobic digestion to treat other organic wastes including food waste, rendering waste, FOG, deicing fluids, and green waste. Anaerobic digestion has been targeted for these activities because of its established history and its ability to turn a waste product in an energy source. A brief timeline of the development of anaerobic digestion is provided below (Burton and Turner 2003; Meynell 1976).

1808	Sir Humphrey Davy determines that methane gas can be generated from cow manure
1859	First anaerobic digester is built in a leper colony in India
1895	Anaerobic digesters used in Exeter, England to fuel street lamps
1912	Birmingham, England and Baltimore, Maryland use first large scale commercial digesters for sewage sludge
1926	First modern digester in Antigo, Wisconsin (covered, heated, mixed, continuously fed, methane collected)
1950's	Most large central sewage treatment plants incorporate anaerobic digestion into their treatment process
1970's	Clean Water Act spurs WWTP construction across the United States and widespread implementation of anaerobic digestion
1970's	Oil crisis increases interest in anaerobic digestion for energy generation. Large scale farm digesters constructed in Europe
1990's	Over 200 organic waste digestion systems are installed in Europe, predominantly in Scandinavian countries
1993	Regulations are instituted regulating digestion processes and disposal of biosolids from WWTP (USEPA 1993)
2002	City of Toronto begins testing anaerobic digestion of source separated food waste
2003	East Bay Municipal Utility District (EBMUD) begins co-digestion of sewage sludge with food and slaughter house wastes
2006	EPA studies controlled co-digestion systems for increased stability and throughput
2008	WERF initiates study on co-digestion of food waste with wastewater solids

Research on the digestibility of food waste has increased significantly in the past ten years as indicated by the volume of papers and reported published on the subject (Alatriste-Mondragon et al. 2006; Amador et al. 2012; Bailey 2007; Carucci et al. 2005; Chung et al. 2007; Heo et al. 2003b; Heo et al. 2003a; Evans et al. 2015; Gray (Gabb) 2008; Jayaraman et al. 2015; Kabouris et al. 2007; Kabouris et al. 2009; Kilian et al. 2007; Kim et al. 2003; Li et al. 2002; Parry and Evans 2012; Parry 2012, 2014; Rizk et al. 2007; Schafer et al. 2007; Speece 1996; Stallman et al. 2012; Strehler et al. 2007; Tsang et al. 2007; USEPA 2014; Vandenburgh et al. 2007; Zhang et al. 2007; Zitomer and Adhikari 2005). This work has demonstrated several important principles summarized here:

- Various food and oil/grease wastes are very suitable for biogas production
- Addition of food and oil/grease wastes to existing wastewater treatment plant digesters significantly enhances biogas production rates
- Solids loading to the digester is an important optimization variable
- Off-gas impurities including H_2S will be present and must be managed

- Proper control of carbon-nitrogen-phosphorous ratios and micronutrients is critical to stable digester operation must be managed

2.1.2 Biogas Treatment

Biogas treatment is any process used to improve the quality of the anaerobic digester gas. Typically, biogas treatment is employed to reduce air emissions and to protect equipment that utilize the biogas as well as increase the opportunities to utilize the gas for a beneficial means. The use of a specific gas treatment technology is based on the source quality of the biogas, the desired end product, and based on economic and operational considerations. A brief timeline showing the development of gas treatment follows.

1895	Anaerobic digesters used in Exeter, England to fuel street lamps - no gas treatment used
1950's	Biogas used for digester and space heating, moisture and H_2S removal
1970's	Advanced gas treatment technologies are developed (membranes, specialized media, scrubbers), but rarely implemented
1980's	Biogas utilization for heat and power generation becomes commonplace at large-scale WWTP. Gas treatment for hydrogen sulfide, moisture and particulates dominates
1986	First large scale WWTP in the United States upgrades biogas to natural gas quality with water tower scrubber
1990's	Gas quality requirements for boilers and engines become more stringent.
1990	SulfaTreat® developed for H_2S removal
1996	Specialized media and packaged filter systems for siloxane treatment are commercialized
1997	Pressure swing adsorption (PSA) units are commercialized for CO_2 removal
2000's	Advanced gas treatment technologies are commonplace for all major biogas utilization projects.
2001	Molecular sieve commercialized for CO_2 removal
2002	Chemical adsorption for removal of CO_2 from biogas commercialized in Europe by Purac
2003	Water tower scrubber for removal of CO_2 from biogas commercialized in Europe by Ros Roca

One of the demonstration objectives was to demonstrate the ability to clean biogas to natural gas standards. To achieve this, a pilot plant was developed to remove H_2S and CO_2 from the gas. H_2S was removed with a proprietary SulfaTrap. A VSA unit was used for CO_2 removal.

PSA and VSA systems take advantage of the ability of specialized media, like zeolites and activated carbon, to adsorb and desorb CO_2 as gas pressure is raised and lowered. A PSA uses a cyclic process in which media packed vessels are successively pressurized and depressurized to produce a continuous stream of purified gas. CO_2 laden biogas is introduced to depressurized vessels. The pressure in the vessel is raised to between 90 and 150 psig. The CO_2 adsorbs to the media while the purified methane is purged from the vessel. The vessels pressure is dropped back down to atmospheric conditions. The CO_2 desorbs from the media and is purged to an exhaust system. This cycle is repeated in a series of vessels to produce a continuous supply of product gas. A VSA is similar but adsorbs at a relatively low pressure close to atmospheric pressure and uses a vacuum to regenerate the media.

2.1.3 Application of Technology

While these technologies are being used increasingly around the world, there is no known installation that combines these technologies to generate a natural gas quality product solely from food waste. The project will build off of previous research to demonstrate, validate, promote the technology to encourage its transfer and implementation across the DoD and the United States. Possible applications for the food waste digestion technology include:

- Implementation at permanent installations to reduce food waste disposal costs and generate renewable energy
- Use on forward operating bases to reduce waste disposal demands while providing a grid-independent and mobile energy supply
- Implementation at any site with a food waste disposal burden including universities, towns, cities, grocery stores, farms, schools, etc.
- Enhancement of waste activated sludge digestion (i.e., co-digestion)

2.2 TECHNOLOGY DEVELOPMENT

Significant technology development has been conducted over the past two centuries as was described in the previous section. The Water Environment Research Foundation (WERF) funded project number OWSO5R07 to evaluate co-digestion which is summarized below. Additional technology development included the treatability study described in Section 5. The follow text is excerpted from the Executive Summary of the WERF report (Parry 2014).

The primary goal of the WERFs Optimization Challenge is to enable the wastewater sector to reduce overall treatment and solids management operation costs by at least 20%. In some cases, wastewater treatment facilities with anaerobic digesters can increase their production of biogas through co-digestion of organic waste with wastewater solids. Co-digestion is loosely defined as the addition of non-municipal wastewater organic wastes to anaerobic sludge digesters. Biogas produced from the additional wastes can be used to generate heat, power, electricity, or biomethane. An estimated 216 water resource recovery facilities (WRRFs) located in the United States import organic waste for co-digestion with wastewater solids. This accounts for approximately 17% of WRRFs that process solids using anaerobic digesters. As co-digestion has been implemented, some municipalities have observed other benefits, including increased VS destruction and biogas production from the municipal wastewater solids components. There can also be impacts from co-digestion on the amount and characteristics of the biosolids, sidestream nutrient concentrations from digestate (the material remaining after anaerobic digestion) dewatering, potential upset of the digestion process, and difficulty in handling the additional organic wastes.

The intention of this project was to further the understanding of co-digestion of organic waste, to quantify the benefits of co-digestion, and to provide answers to some key questions to help overcome barriers associated with greater implementation of co-digestion programs at municipal WRRFs. Greater implementation of co-digestion at municipal WRRFs would be significant progress towards meeting the goals of the Optimization Challenge while setting the stage to move closer to a net-zero energy goal in the near future.

Based on research conducted by WERF, co-digestion has been shown to be an economically feasible food waste management approach. However, there are still several important and frequently asked questions regarding co-digestion of organic wastes. This research project sought to answer to the following questions:

- What are the economic impacts of co-digestion on the operation of a WRRF?
- How much additional biogas will be produced from adding different organic wastes?
- What is the allowable organic loading rate for stable digestion?
- What fraction of the digester loading can be from FOG?

The literature review documents that co-digestion is being investigated worldwide and with success for many co-substrates reported at all levels from benchtop studies to full-scale systems. There is good potential for co-digestion of a variety of organic waste streams with municipal sewage sludge, under both mesophilic and thermophilic conditions. However, there is far less literature available on co-digestion under thermophilic conditions. Perhaps the most important finding from the literature review is that there remains a need for structured and standardized testing procedures to support co-digestion research and data reporting.

The waste characterization phase of the research was performed to determine background information of potential co-digestion feedstocks with regards to chemical, physical, and biogas production characteristics. The five day biological energy conversion (BEC_5) appears to indicate that all the organic wastes tested are more readily converted to biogas than co-thickened sludge (CTS) alone and would make good co-digestion feedstocks. On the basis of the metal content of the waste sources, there does not appear to be any significant issues with most feedstocks. FOG in the form of restaurant grease, canola oil, and biodiesel glycerol showed the highest BEC_5 in the bench-scale batch tests in the waste characterization analyses.

As a result, extended laboratory experiments were conducted on restaurant grease and biodiesel glycerol as co-digestion feedstock with CTS. The results show that restaurant grease and biodiesel glycerol are suitable co-digestion feedstocks for anaerobic digestion on a continuously fed basis. The test data also suggest that it is possible to achieve high VS reductions for the added grease, thus providing both a significant increase in biogas production with a minimal increase in biosolids mass.

The pilot-scale tests analyzed the effects of co-digesting FOG and glycerol with wastewater solids in separate trials. The results of this phase showed that an anaerobic digester fed FOG could potentially produce twice the volume of biogas compared to a control digester fed biosolids alone.

Testing the co-digestion of FOG under mesophilic and thermophilic conditions was successful in achieving expected levels of VS destruction and biogas production. VS reduction in both the mesophilic and thermophilic tests at COD loadings between 30 and 120% were consistently higher than the baseline loading condition, indicating that digestion successfully degraded the co-substrates at all loading conditions.

There is a limited amount of data reporting when failure of a co-digestion system may occur. The results of this study suggests failure of a fully loaded anaerobic digester, operating at a 20-day SRT from wastewater solids, may be susceptible to failure when FOG addition by volume reaches 5% of the volume of wastewater solids. The SELR presented in this study could be another tool to assess when failure of a digestion system may occur. Ultimately, these results suggest that FOG and glycerol are good co-digestion substrates to add to wastewater solids to achieve enhanced biogas production.

Anaerobic digesters operating at full load, with a 20-day SRT, can potentially be operated at twice the organic loading rate through the introduction of FOG. While the SELR is an effective tool that can be used to determine COD loading rates for anaerobic digestion, comprehensive waste characterizations are recommended for all new feedstocks to prevent digester upsets. The full-scale evaluation portion of the project analyzed data and evaluated the overall performance of the Des Moines, Iowa Water Reclamation Authority's (WRA) co-digestion program that began accepting and processing offsite organic waste in 1994. Overall, the Des Moines WRA has demonstrated that the difficulties of operating a co-digestion program are manageable and the benefits outweigh the difficulties. By handling and processing offsite hauled wastes, the WRA benefits from increased biogas production, receiving revenue from tipping fees and the sale of biogas. Not only does the WRA meet all of its plant process and space heating demands using biogas, but it also offsets a significant amount of the plant power demand with a biogas fueled CHP system.

Finally, an easy-to-use Economic Model was developed in spreadsheet format to facilitate high-level decisions regarding the economics of handling and treating different organic wastes in municipal anaerobic digesters. As demonstrated with the model, economic feasibility is strongly dependent upon waste characteristics, energy costs (electricity and natural gas), and biosolids residuals costs. Most waste streams (with the exception of FOG) require a tipping fee to achieve economic viability. The value of the additional biogas produced increases with level of treatment (e.g., biomethane has a higher value than raw biogas since biomethane can be used in lieu of natural gas). However, additional treatment steps are required to obtain higher energy products, such as biomethane. Production of higher energy biogas products is most favorable in scenarios when electricity or natural gas rates are high. The model takes these considerations into account and can help generate a foundation for high-level decision and considerations.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Advantages and limitations of the subject technology have been summarized in **Table 1**.

Table 1. Advantages and limitations of the technology.

Advantages
Combines waste handling and renewable energy generation
Reduces waste disposal of organics by at least 60%
Is scalable and can be combined with other waste handling practices like composting, gasification and pyrolysis
Generates a renewable energy product with numerous proven end uses
Relies on technologies that have been used and proven for over 100 years
Operation is simple and effective
Anaerobic digestion and biogas treatment are proven processes operated at hundreds of full scale facilities around the world
Limitations
Is capable of treating only biodegradable solid wastes
Requires sorting of organic wastes from mixed waste stream

For comparative purposes prominent alternative technologies have also been identified. A matrix comparison of these technologies identifying some of their advantages has been provided in **Table 2**. Items with an "X" indicate that technology has generally demonstrated this capability, while blank boxes indicate a deficiency and a potential limitation of the technology. A brief description of each technology follows the table.

- **Landfilling:** This is considered the conventional means of waste disposal. Landfilling of waste is typically carried out by a contracted party. Landfilling is an established technology that requires limited labor on site for distributing and covering waste. It has the potential to generate renewable energy through landfill gas collection, but this is infrequently employed.
- **Incineration:** Incineration of food waste is limited because of the high water content. There is limited renewable energy generation, typically limited to heat recovery for on-site process requirements. Electrical power generation is possible and has been employed. However, under current economic conditions, power generation from incineration is significantly more expensive than traditional method for power generation and is therefore not considered economically feasible under most conditions.
- **Composting:** This is an established technology that can be carried out on site or at a central facility. There is no renewable energy generation associated with the process, but a valuable end product is produced and the process has a high level of public acceptance.

Table 2. Alternative technologies.

Criteria	Landfilling	Incineration	Composting	Co-Digestion	Hog and Fish Feed	Pyrolysis	Gasification
Established Technology	X	X	X	X	X		
Limited operator input (on-site)	X	X	X	X	X		
Renewable Energy Generation	X	X		X		X	X
Produces Valuable End Product			X		X		
Low land requirement		X	X	X	X	X	X
Good Public Acceptance			X	X	X		
Treat Large Volumes	X	X	X	X		X	X
Scalable and Portable			X	X			

- **Co-digestion:** Digesting food waste with sewage sludge requires the availability of a wastewater treatment plant and its anaerobic digesters. The process can generate a substantial amount of energy in the form of biogas.
- **Hog and Fish Feed:** Food waste can be used as a food source for livestock and aquaculture. This process does not generate renewable energy, but it does produce a valuable end product. The process is limited by proximity to end users and by limited scale.
- **Pyrolysis:** This technology uses heat and pressure in the absence of oxygen to reduce waste to an oil-like fuel that can be used for heat and power or can be anaerobically digested. A distinct advantage of pyrolysis is that it can accept almost any feedstock; however, it suffers from high temperature inputs, lack of scale and limited installations to prove the concept.
- **Gasification:** This is a high temperature process that uses oxygen-starved combustion to convert dry organic matter to a syngas. Syngas is a low BTU fuel that can be used as fuel. Gasification has limited applications for wet feed stocks as the heat required to evaporate the water reduces the overall efficiency of the system. There are no known successful installations of gasification systems on a wet feed stock.

3.0 PERFORMANCE OBJECTIVES

Quantitative and qualitative performance objectives were developed to evaluate the technology and to guide the development of a testing plan. The objectives provided the basis for evaluating the cost and performance of the technology. The performance objectives along with the corresponding metrics, data requirements and success criteria are summarized in **Tables 3** and **Table 4**.

3.1 PERFORMANCE OBJECTIVE: RENEWABLE ENERGY CONVERSION

Generation of a renewable energy source a primary driver for the demonstration technology. To accurately estimate the total value of the energy produced, its quality, quantity, and conversion efficiency was monitored and documented. Parasitic losses (e.g., energy inputs for digester heating, pumping, biogas purification, etc.) were also considered to evaluate net energy generation.

3.1.1 Data Requirements

Data was collected to estimate the quantity of biogas produced, the quality of the biogas produced (methane, carbon dioxide, H_2S and siloxane concentrations) and the energy conversion efficiency. Energy conversion efficiency was measured by biogas generated per unit of COD added.

3.1.2 Success Criteria

As identified in **Table 3**, the following criteria were met during this pilot study:

- Energy conversion was 73±13% in Phase III and similar to the goal of ≥70%
- Energy conversion adjusted for parasitic loads was 63% in Phase III, which is greater than the goal of 50%
- Methane production:
  - Methane per mass of VS loaded was 360±70 L/kg, which is greater than the goal of 310 L/kg
  - Methane per mass of COD loaded was 270±75 L/kg, which is greater than the goal of 190 L/kg
  - Methane production per unit digester volume (2 L/L/d) was met at only at the end of Phase IV
- Biogas composition in Phases III and IV were 59±4.6% and 61±6.6%, respectively, and similar to the goal of 60%

Methane production per unit digester volume was not met during Phase III and most of Phase IV because of low microbial concentrations (based on low VSS concentrations). This was a result of a dilute food waste/canola oil feed in Phase III and insufficient time to reach stable operation in Phase IV.

Table 3. Quantitative performance objectives.

Performance Objective	Data Requirements	Success Criteria	Phase III Result	Phase IV Result	Criterion Met?
Quantitative Performance Objectives					
Renewable energy conversion	Energy Conversion	≥ 70% energy conversion at 24 day-SRT (not accounting for parasitic demands)	73±19	62±40	**Yes** during Phase III. **No** during Phase IV however energy conversion increased over time and operation had not reached steady state. Note SRT was greater than 24 days.
		≥ 50% energy conversion at 24 day-SRT (including parasitic demands and conversion to CNG)	63	NA	**Yes**
	Methane production	≥ 310 L CH_4/kg VS loaded (5 ft^3/lb)	360±70	490±140	**Yes**
		≥ 190 L CH_4/kg COD loaded (3 ft^3/lb)	270±75	230±150	**Yes**
		≥ 2 L CH_4/L digester/day (2 ft^3/ft^3/d)	0.82±0.22	1.1±0.65	**No** in Phase III. **No** during Phase IV. **Yes** at end of Phase 4 when methane production was 2.0 L/L/d.
	Biogas composition	≥ 60% CH_4 in biogas	59±4.6	61±6.6	**Yes**
Gas Purification	Natural Gas Specifications	≥ 80% CH_4 recovery	NA	94±2.9	**Yes**
		< 4ppm H_2S	NA	0.030±0.0.5	**Yes**
		≥ 95% CH_4 in treated biogas	NA	98±0.5	**Yes** after data corrected for air contamination during sampling. Result prior to correction is 94±2.9%.
		< 3% N_2 and CO_2 in treated biogas	NA	3.1±2.0 N_2 2.1±0.4 CO_2	**Partly** - atmospheric exposure appears to have occurred during sampling.
		< 0.2% O_2 in treated biogas	NA	1.2±0.6	**No** - atmospheric exposure appears to have occurred during sampling.

Performance Objective	Data Requirements	Success Criteria	Phase III Result	Phase IV Result	Criterion Met?
Digester capacity/ stability	Volumetric VS loading rate	≥ 3.2 g VS/L/d (0.2 lb VS/ft^3/d)	2.4±0.6	2.0±1.2	**No** in Phase III. **Possibly** in Phase IV during last 20 days = 2.9±0.8 g/L/d.
	Volumetric COD loading rate	≥ 4.8 g COD/L/d (0.3 lb COD/ft^3/d)	3.0±1.0	4.4±2.7	**No** in Phase III. **Possibly** during the last 20 days of Phase IV (5.3±1.8 g/L/d).
	Specific energy loading rate (SELR)	≥ 0.26 g-COD/g-VSS/day (0.26 lb/lb/d)	0.44±0.17	0.47±0.30	**Yes**
	pH	6.8 to 7.8	7.8±0.1	7.6±0.1	**Yes**
	VFA/TALK	VFA/TALK < 0.2 g-acetate equivalents/g-$CaCO_3$	0.15±0.09	0.12±0.09	**Yes**
Waste Sludge	TS Reduction	≥ 60% TS reduction – at 24 day SRT	78%±3.4%	92%±2.1%	**Yes** although SRT was greater than 24 d. The Phase IV result is likely overestimated because less than 1 SRT occurred.
	Total sulfide	< 500 mg/kg reactive sulfide	NA	71	**Yes** - Result is for the liquid digestate in units of mg/L.
	Leachable metals	Passes TCLP	NA	See Text	**Yes**
Class 503(b)	SRT	≥ 15 days	40±14	130±91	**Yes**
	VS destruction	≥ 38%	81%±3.0%	93%±1.8%	**Yes** based on both soluble and suspended VS. In Phase III the result based on VSS was 92±2.7%. The Phase IV result is likely overestimated because less than 1 SRT occurred.
Operational Reliability	Operations hours	≥ 95% availability of process equipment	93%	100%	**No** during Phase III due to a leaking mixer shaft seal. **Yes** during Phase IV.

Table 4. Qualitative performance objectives.

Performance Objective	Data Requirements	Success Criteria	Criteria Met?
Qualitative Performance Objectives			
Safety	OSHA Accident report forms	Zero lost-time accidents	**Yes** - no zero-lost time accidents. However exposure to hydrogen sulfide did occur due to a leaking mixing shaft seal.
		Elimination of all relevant ignition and fire hazards	**Yes** - The process equipment was designed in accordance with the National Electrical Code for Class 1, Division 2.
Capacity/Stability	Operating data under a variety of conditions	Capable of stable operation under a range of realistic operating scenarios	**Yes** - Food waste composition varied widely and the digesters were stable.
		Identify limits of QAC and FOG loading	**No** - Upper limits of FOG were not determined, however the amount of FOG that was used was quantified and resulted in stable operation. Quaternary amine compound (QAC) sanitizers were no longer used at USAFA and limits could not be quantified.
Residuals Characteristics	Pathogens, HPC, microbial characterization	Suitability for composting	**Yes** - Digestate contained *E. coli* and fecal coliforms. Presence of other pathogens not determined.
	BOD, TSS, ammonia	Determine residual handling requirements	**Yes** - COD and ammonia were high and TSS was low. Residual was a liquid rather than a solid and may be suitable as a fertilizer or compost amendment. BOD was not measured but can be assumed to be half of the COD.
Market compatibility	Feedback from composters and USAFA base	Acceptable as feedstock for compost	**Possibly** - Digestate was rich in COD and nutrients but the high VFA content could lead to odor complaints.
Ease of use	Feedback from operators	Safe and reliable operation by a single operator	**Yes** - Provided automated food waste handling and foreign debris segregation is implemented.
	Shutdown report		NA
GHG Accounting	Carbon balance on food waste digestion	Documentation of direct emissions associated with food waste digestion and gas treatment activities	**Yes** - See text for discussion.

3.2 PERFORMANCE OBJECTIVE: GAS PURIFICATION

Upgrading biogas from a relatively low quality fuel to a high quality fuel equivalent to natural gas drastically improves its value ability to be used for a variety of uses including vehicle fueling.

3.2.1 Data Requirements

To track the efficiency of the biogas upgrading process, the treated biogas was tested to determine its constituent makeup and compared with natural gas standard metrics. Additionally, methane recovery was determined.

3.2.2 Success Criteria

As identified in **Table 3**, the following criteria were met during this pilot study:

- Methane recovery in Phase IV was 94±2.9%, in excess of the goal of 80%
- The methane concentration in the treated biogas was 98±0.5% compared to the goal of 95% after correction for likely air contamination during sampling
- H_2S in the treated biogas was less than 0.030±0.035 ppm; the goal was 4 ppm
- CO_2 in the treated biogas was 2.1±0.4% compared to the goal of <3%

Although, the system did not meet the criteria of less than 3% N_2 and less than 0.2% O_2, this appears to be an artifact of atmospheric contamination. It is virtually impossible that biogas generated by the digester would contain any oxygen.

3.3 PERFORMANCE OBJECTIVE: DIGESTER CAPACITY/STABILITY

From a design and operation standpoint one of the most important factors regarding the technology is its capacity and stability. A high capacity per unit volume and stable operation minimizes capital costs and reduces the required operator attention.

3.3.1 Data Requirements

Digester capacity was evaluated using four different but related metrics. The volumetric VS loading rate (g VS/L/day), the volumetric COD loading rate (g COD/L/day), and the specific COD loading rate (g-COD/g-VSS/d) also referred to as the SELR.

In addition to loading rates, digester pH, VFA and TALK and the ratio VFA/TALK were monitored. These are traditional values used to determine digestion stability. Typically, as digesters tend toward an upset, the VFA concentration increases, the alkalinity decreases, and the pH decreases to inhibitory levels.

3.3.2 Success Criteria

As identified in **Table 3**, the following criteria were met during this pilot study:

- The volumetric VS loading rate was possibly met in the last 20 days of Phase IV where it was 2.9±0.8 g-VS/L/d compared to the goal of 3.2 g-VS/L/d.
- The volumetric COD loading rate was possibly met in the last 20 days of Phase IV where it was 5.3±1.8 g-COD/L/d compared to the goal of 4.8 g-COD/L/d.
- The SELR goal of ≥0.26 g-COD/g-VSS/d was met in both phases. The SELR was 0.44±0.17 g-COD/g-VSS/d in Phase III and 0.47±0.30 g-COD/g-VSS/d in Phase IV.
- The pH was routinely within the goal of 6.8 to 7.8, with the average being 7.8±0.1 and 7.6±0.1 in Phases III and IV, respectively.
- The average VFA:TALK ratio was maintained < 0.2. In Phase III, the average ratio was 0.15±0.09 and in Phase IV it was 0.12±0.09.

The system did not meet the volumetric VS and COD loading rate goals during Phase III and the initial part of Phase IV.

3.4 PERFORMANCE OBJECTIVE: WASTE SLUDGE

Food waste total solids destruction is another technology benefit because it reduces an installation's solid waste stream. Waste sludge from the technology has the potential to be used or disposed in a variety of ways. Waste sludge characterization was conducted to determine options for reuse and disposal.

3.4.1 Data Requirements

The treated sludge was tested for its total solids content and compared with the total solids content of the raw food waste to estimate total solids destroyed by the process. Additionally the treated sludge was tested for its reactive sulfide concentration, and its concentration of leachable metals. Destruction of solids is an important metric as it will determine the mass and volume of solids that must be transported for use or disposal. Limits on sulfide and leachable metals were set as these concentrations can dictate what disposal methods are allowed.

3.4.2 Success Criteria

As identified in **Table 3**, all the criteria were met during this pilot study:

- TS reduction was 78±3.4% in Phase III and greater than the goal of 60%. The value reported for Phase IV also exceeded the goal, but is a likely overestimate because less than one SRT had occurred.
- The total sulfide in the digestate was 71 mg/L; less than the 500 mg/kg of reactive sulfide goal.

- Leachable metals were quantified as total metals and all detections were less than EPA RCRA toxicity characteristic thresholds as defined in 40CFR261.24.

3.5 PERFORMANCE OBJECTIVE: CLASS 503(b)

EPA regulations (i.e., 40CFR503 Part b) are used to regulate disposal of waste activated sludge from WWTPs. These regulations also specify requirements for anaerobic digestion of sewage sludge prior to beneficial use via land application. The beneficial product is termed “biosolids”. Biosolids are classified as Class A or B with Class A being higher quality (USEPA 1993). The regulations are not directly applicable to food waste digestion systems. Nevertheless, a comparison was made considering that the digester was initially seeded with WWTP anaerobic digester sludge and results from this study are potentially applicable to co-digestion. Comparison to Class B requirements were made for the purpose of this study.

3.5.1 Data Requirements

Class B biosolids can be produced through a variety of processes, but the most common is mesophilic anaerobic digestion in a complete mix reactor with a minimum SRT of 15 days and a minimum VSD of 38%. This level of destruction is established as a process to significantly reduce pathogens and is believed to reduce the pathogen vector attraction of the biosolids to acceptable levels. The SRT and VSD were monitored throughout the demonstration.

3.5.2 Success Criteria

As identified in **Table 3**, both criteria were met during this pilot study:

- SRT time in Phase III and Phase IV, were both in excess of the 15-day goal. The SRTs were 40±14 d and 130±19 d in Phase III and IV, respectively.
- VSD was in excess of the 38% goal. VSDs were 81±3.0% and 93±1.8% in Phases III and IV, respectively.

3.6 PERFORMANCE OBJECTIVE: OPERATIONAL RELIABILITY

Operational reliability helps to ensure that the subject technology is available to perform as expected. Reliable operation will help encourage adoption and utilization of the technology.

3.6.1 Data Requirements

Operational reliability was assessed by tracking the number of days the demonstration system was operational during Phases III and IV. Lost time as result of equipment malfunction and maintenance was documented to determine the percent of total time that the technology was operational.

3.6.2 Success Criteria

The availability goal of 95% was met in Phase IV (100% available) and was nearly met in Phase III (93%). During Phase III a digester mixer shaft seal was leaking which required significant maintenance time. The seal was old, in need of replacement, and not representative of new equipment.

3.7 PERFORMANCE OBJECTIVE: SAFETY

Safety is the first of the identified qualitative performance objectives. Qualitative performance objectives are summarized in **Table 4**.

3.7.1 Data Requirements

To monitor safety OSHA-reportable accidents were tracked.

3.7.2 Success Criteria

There were no OSHA-reportable accidents during the demonstration. However, the operator was exposed to H_2S gas that leaked from the malfunctioning digester shaft seal. This digester was removed from service at the end of Phase III. Safety was also addressed during the design process by specifying NEC Class 1 Division 1 and Class 1 Division 2 areas that required specialized equipment, instrumentation, and electrical systems (e.g., explosion proof or intrinsically safe).

3.8 PERFORMANCE OBJECTIVE: CAPACITY/STABILITY

Capacity and stability are also included within the qualitative performance objectives to capture design data associated with these performance objectives. Specifically, the goal is to demonstrate that the technology is stable over a range of realistic operating scenarios and to identify the limits of Quaternary amine compound (QAC) and FOG in the form canola oil. This objective is intended to demonstrate the flexibility of the technology.

3.8.1 Data Requirements

Operating data including loading rate, pH, VFA/TALK ratios, canola oil loading, food waste composition (i.e., fat, protein, and carbohydrates), gas flow rate (Q), and methane concentration were monitored over the duration of the project during varying operating conditions. This data, in addition to operator observations were used to determine digester stability in response to varying feed composition and operating conditions. QACs were no longer contained in sanitizers used by USAFA and thus could not be evaluated.

3.8.2 Success Criteria

The digesters were stable over a wide range of feed compositions that led to high concentrations of potentially inhibitory ammonia. The digesters initially were thought to be unstable based on high concentrations of VFAs and sludge color (i.e., brown rather than black). However, further data evaluation demonstrated the digesters were stable. Limits of canola oil addition leading to digester failure were not established, however stable operation in the presence of ~10% canola oil as a percentage of VS was observed. Section 6 presents further discussion on digester capacity and stability.

3.9 PERFORMANCE OBJECTIVE: RESIDUALS CHARACTERISTICS

Residuals included the waste digestate which must be characterized to determine disposal costs and operational requirements.

3.9.1 Data Requirements

In addition analyses associated with the quantitative performance objective of Waste Sludge, the digestate was analyzed for pathogens, heterotrophic plate counts, ammonia, COD (as a surrogate for BOD), and TSS. Dewaterability was also determined.

3.9.2 Success Criteria

The digestate was a liquid with low TSS, high ammonia and VFA concentrations, and moderate concentrations of pathogens. Compost amendment is possible though odor could be a concern. The sludge was not easily dewatered.

3.10 PERFORMANCE OBJECTIVE: MARKET COMPATIBILITY

Market compatibility refers to the suitability and acceptability of using the digestate for other beneficial means including as a soil amendment or as part of compost.

3.10.1 Data Requirements

The digestate was evaluated with respect to the previously mentioned parameters and potential reuse as a compost amendment or fertilizer.

3.10.2 Success Criteria

The liquid nature of the digestate may limit its use as a compost amendment. It may be useful as a liquid fertilizer considering the concentrations of ammonia and metal nutrients.

3.11 PERFORMANCE OBJECTIVE: EASE OF USE

The relative ease with which the subject technology is incorporated and operated will help to increase market acceptance and adoption. The simpler the operation, the more likely the technology is to succeed commercially.

3.11.1 Data Requirements

Ease of operation will be determined based on operator experience.

3.11.2 Success Criteria

The facility was successfully operated by a single operator that was not on-site 24 hours a day. During the initial shakedown (Phase I) the facility suffered problems associated with equipment malfunctions. After these start-up issues were resolved the operator proved to be easy to operate by a single operator working one shift per day. However, two issues that would need to be addressed in a full-scale facility are food waste debris and gas leaks. The food waste contained much debris that needed to be manually segregated. Commercially available systems are available that can automate the process. Gas leaks that led to operator exposure to H_2S would also need to be eliminated in a full-scale system.

3.12 PERFORMANCE OBJECTIVE: GHG ACCOUNTING

In anticipation of future GHG regulations and in recognition that GHG emissions already drive technology selection and evaluation, documentation of GHG emissions was conducted.

3.12.1 Data Requirements

GHG documentation was based on projected emissions from a nominally sized facility. The calculations assume that the facility operates at a 40-day SRT and produces 270 L of methane per kg COD fed (from study results) and is fed 120,000 mg/L COD (based on study food waste characteristics. Calculations were also based on 94% methane recovery by the VSA process. Power for the process were estimated. Electrical power was assumed to emit 1.34 pounds of CO_2 per kWh electricity consumed (Energy Information Administration 2002).

3.12.2 Success Criteria

The calculated greenhouse gas emissions from a food waste digester is -470 tons per year (i.e., a GHG offset). By comparison, previous research demonstrated that the greenhouse gas emissions from landfilling and composting were 0.15 and 0.05 kg carbon dioxide equivalents (CO_2e) per kg food waste (Parry 2012). Using the food waste characteristics of this study that would be an equivalent of 530 and 180 ton per year for landfilling and composting, respectively. Thus, food waste disposal in anaerobic digesters represents a significant greenhouse gas savings compared to landfilling and composting.

4.0 SITE DESCRIPTION

4.1 FACILITY/SITE SELECTION

The minimum requirements for the demonstration of the subject project were as follows:

- Available source of food waste and grease trap waste that can be used as feedstock for the digesters.
- Willingness to support the demonstration by providing site access and space, coordination of food waste collection, permitting assistance, and connection to utilities.
- Ability to permit gas (biogas) and liquid (digested sludge) discharges as required.
- Access to water, electricity, and sewer utilities.

USAFA had many characteristics making it an excellent site for the Environmental Security Technology Certification Program (ESTCP) demonstration. These characteristics included:

- Educates 4,500 cadets who eat 3 meals per day/7 days per week at Mitchell Hall. Thus a readily available source of food waste existed. A review of billing statements and operating procedures revealed generation rates of 5 tons of food waste and 170 pounds of fats oils and grease per week.
- Food waste is sluiced off of plates and containers, ground, and dewatered prior to being bagged and dropped into roll off containers for landfilling. This pretreatment makes transport and handling of the digester feed stock efficient. The ground and dewatered food waste can be collected in 5-gallon buckets and transported to the digester.
- Analysis of food waste and grease trap waste and treatability studies (Section 5.2) indicated it was an excellent feedstock for the digester. Quaternary amine compounds were used as a sanitizer during food waste pulping and this toxicity was evaluated during the treatability study. However, quaternary amine compounds were no longer used at the time of the field demonstration.
- An operational WWTP is on-base and provided an excellent location for the demonstration. An open area north of the existing full-scale digesters (see **Figure 4** and **Figure 5**) was available for demonstration equipment. This location provided utilities including electricity, natural gas, and non-potable/potable water. Digestate from the pilot digesters was capable of being discharged into USAFA digester 1 (i.e., the primary digester). Demonstration digester off-gas was able to be routed to an existing flare that is currently used to burn full-scale digester biogas. The full-scale digesters were also a source of seed for the demonstration digesters.

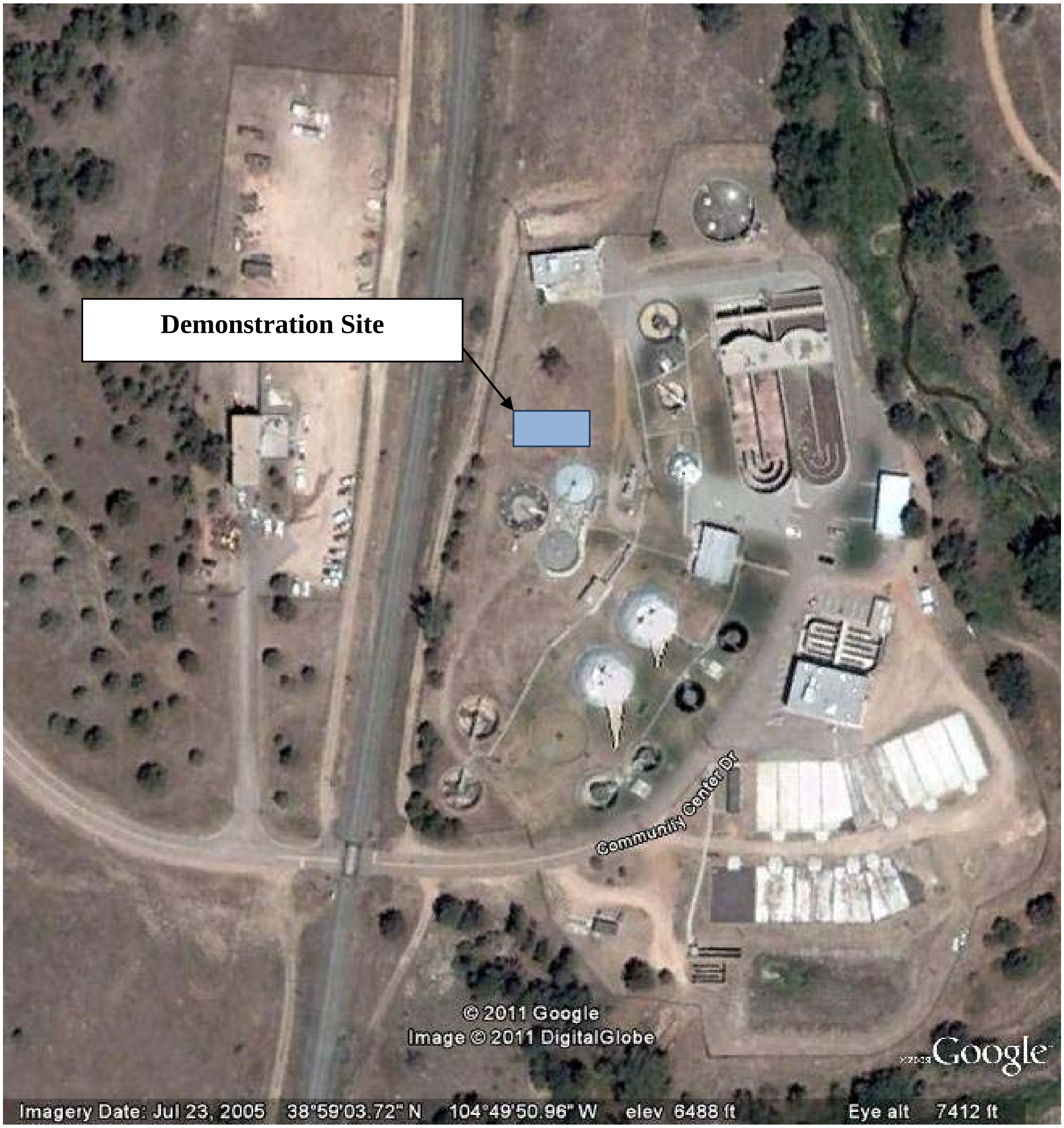

Demonstration Site
Community Center Dr
© 2011 Google
Image © 2011 DigitalGlobe
Google
Imagery Date: Jul 23, 2005
38°59'03.72" N
104°49'50.96" W
elev 6488 ft
Eye alt 7412 ft

Figure 4. Aerial view of demonstration site.

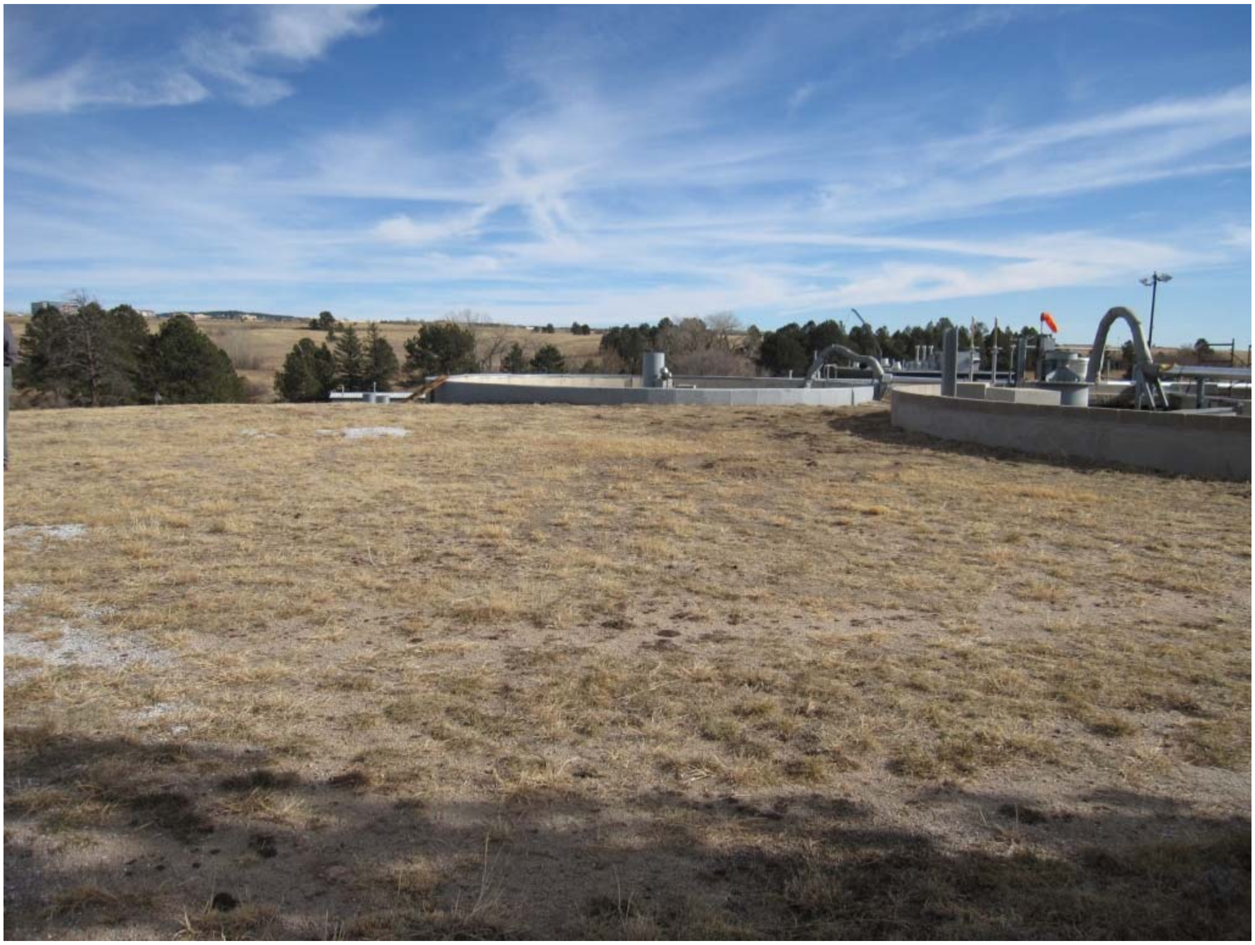


Figure 5. Grade view of demonstration site showing USAFA digesters.

4.2 FACILITY/SITE LOCATION AND OPERATIONS

The pilot plant was installed at the USAFA WWTP located approximately ten miles north of downtown Colorado Springs off Stadium Boulevard and Community Center Drive. The unit was installed on the north end of the plant's anaerobic digesters as this space was easily accessible for construction, it had nearby utilities that were tapped for connections, the existing digesters and biogas flare were available for management of the digested waste and excess biogas, and the site is reasonably close to Mitchell Hall, the source of the food waste feedstock. An aerial photograph showing the proposed site is provided in **Figure 4**. A photograph of the installation site at ground level is provided in **Figure 5**. A map showing the location of Mitchell Hall and the WWTP is provided in **Figure 6**.

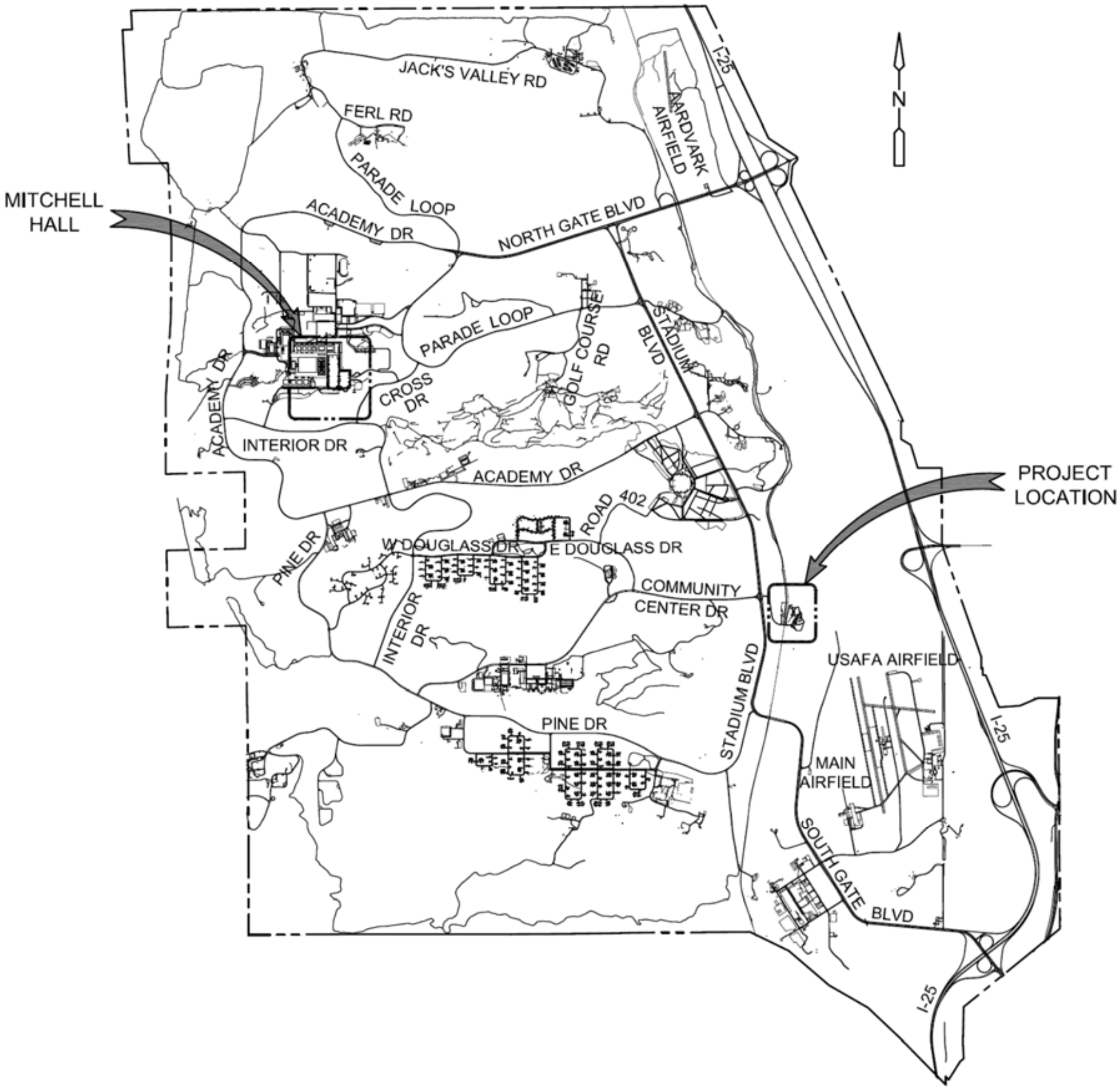

JACK'S VALLEY RD
FERL RD
PARADE LOOP
MITCHELL HALL
ACADEMY DR
NORTH GATE BLVD
AARDVARK AIRFIELD
I-25
N
PARADE LOOP
GOLF COURSE RD
STADIUM BLVD
CROSS DR
ACADEMY DR
INTERIOR DR
ACADEMY DR
ROAD 402
PROJECT LOCATION
PINE DR
W DOUGLASS DR
E DOUGLASS DR
COMMUNITY CENTER DR
INTERIOR DR
USAFA AIRFIELD
STADIUM BLVD
PINE DR
MAIN AIRFIELD
I-25
SOUTH GATE BLVD
I-25

Figure 6. Map of demonstration site.

4.3 FACILITY/SITE CONDITIONS

Two facility/site conditions were identified that could impact the demonstration of the technology. These included: 1) times when the food waste feedstock was not available due to breaks from school and 2) potential freezing temperatures in the winter that could damage equipment and halt operations. During Phase I – system shakedown – a shortage of food waste was experienced but it was short term and did not affect Phases II through IV of the demonstration. Freezing winter temperatures also resulted in mechanical failures during Phase I. Additional modifications were conducted to prevent further problems.

4.4 SITE-RELATED PERMITS AND REGULATIONS

During the site selection process it was determined that the operation of the pilot plant could potentially impact the existing National Pollutant Discharge Elimination System (NPDES) permit, the biosolids disposal requirements (40 CFR 503.b), the Colorado Department of Public Health and the Environment (CDPHE) air permit, and the operator requirements at the USAFA wastewater treatment plant. Each one of these potential impacts were investigated to ensure the least impact and conformity with the applicable regulations.

4.4.1 NPDES Permit

NPDES permits are issued to regulate point source discharges into the waters of the United States. The pilot plant was not a point source and thus is not subject to an individual permit. However, because the pilot discharged to a permitted wastewater treatment plant, the impact on an existing permit was an important consideration. Ultimately, it was determined that the relative low flow of the discharged waste (less than 50 gallons per day) and the chosen discharge location (into the plant's anaerobic digester) would mitigate any potential loading impact to the plant and help them to maintain their history of compliance.

4.4.2 Biosolids Handling 40 CFR 503(b)

Biosolids handling and disposal are regulated by 40 CFR 503(b). This regulation stipulates standards for sewage sludge handling including minimum detention time, temperature and destruction rates. With the digesters selected as the preferred disposal point for the pilot waste there was initial concern that the disposed waste could contaminate the existing treatment process and result in a lack of compliance. There was the potential that the pilot waste would not meet the minimum detention time standards prior to discharge if the waste was injected into a secondary digester just before it was wasted. To address this concern, waste discharged from the pilot was only sent to the plant's primary digester.

4.4.3 CDPHE Air Permit

The wastewater treatment plant holds a permit (95EP691-6) for the plant and a point source air permit waiver for their biogas flare and biogas boiler. Regulations regarding the existing permit and permit waivers were reviewed to ensure that the biogas generated by the pilot plant would not require a permit modification or substantially change the existing requirements. Due to the low flows of biogas anticipated to be generated by the pilot plant, it was determined that the impact of the pilot plant on the existing emissions was minimal and that no permit modifications would be required. A graphical representation of the pilot plant's air emissions impact is provided in **Figure 7.** Even with the addition of the pilot plant gas, the emissions from the biogas flare was able to stay below the regulatory threshold of 2 tons per year for nitrogen oxides (NOx), volatile organic compounds VOCs), sulfur oxides (SOx), and carbon monoxide (CO), and 50 pounds per year of H_2S.

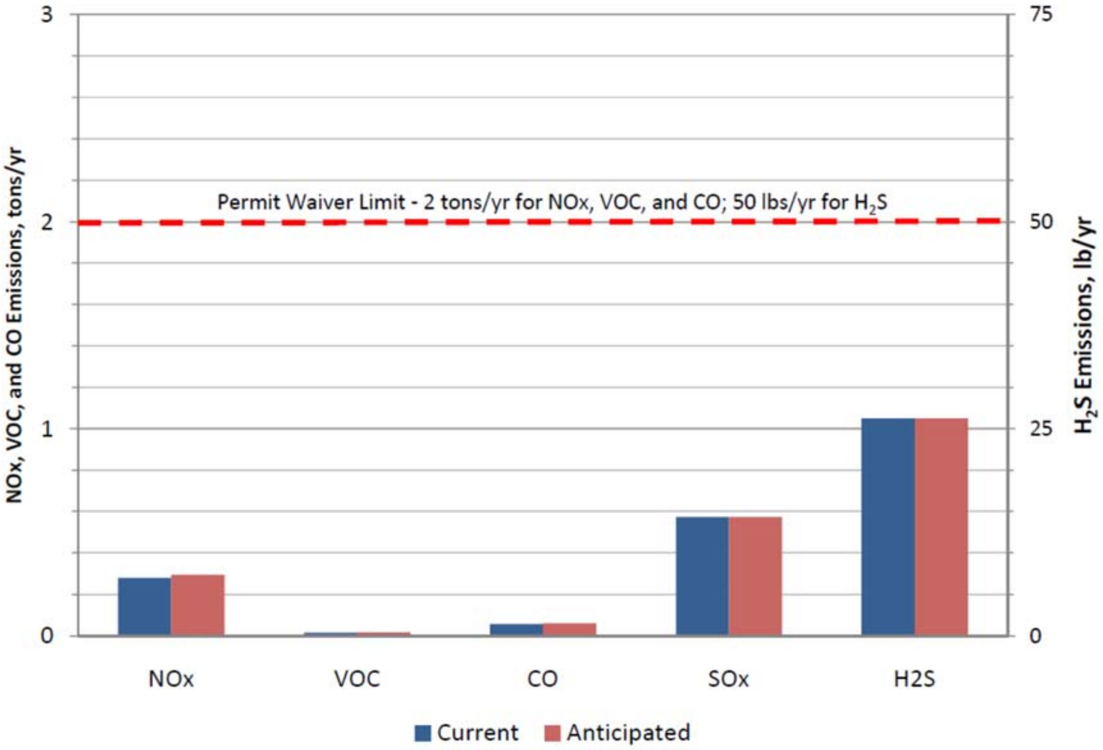


Figure 7. Potential air emissions impact.

4.4.4 Operator Permit

Licensed operators are required by the CDPHE for any point source that has been issued a permit to discharge to any of the State's waters. As the pilot plant is not a permitted discharger and was not be treating wastewater for discharge to a body water, rather the wastewater treatment plant, a licensed operator was not required.

5.0 TEST DESIGN

This section provides the detailed description of the demonstration design and testing conducted to address the performance objectives described in Section 3.0.

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

Testing including an initial laboratory treatability test followed by the field demonstration at USAFA. The treatability test is summarized in Section 5.2 (report included in Appendix D) and the remainder of Section 5 focuses on the field demonstration.

The field demonstration involved anaerobic digestion of a food waste/canola oil mixture to produce biogas and purification of the biogas with a sorbent for sulfur compounds and a VSA system for removal of CO_2 and moisture from the biogas in order to meet natural gas specifications. The demonstration included four phases. Two replicate digesters were operated in Phases I through III and a single digester was operated in Phase IV.

Phase I focused on troubleshooting mechanical problems associated with the equipment plus refining digester feeding and sampling and analysis protocols to improve operations and increase data reliability. Phase II involved restarting the digesters and establishment of stable operating conditions. Phase III involved a period of stable operation during which food waste/canola oil digestion and biogas production was studied and optimized. At the end of Phase III performance objectives with respect to organic loading rates and volumetric methane production rates were not met; the feeding strategy was hypothesized to have been the cause. The feeding strategy used in Phases I through III involved mixing food waste and canola oil with tap water to obtain a pumpable slurry that contained about 10% total solids or less. Feeding this diluted food waste/canola oil mixture limited the VSS concentration and associated concentration of microorganisms in the digester which effectively limited the ability to increase the organic loading rate. The feeding process was modified for Phase IV to allow feeding of a more concentrated food waste/canola oil mixture to the digester. The modification involved elimination of tap water for dilution. Rather, a portion of digestate was mixed with the food waste/canola oil and the resultant mixture was pumped back into the digester. This approach resulted in effectively feeding the digester with an "undiluted" food waste/canola oil mixture that contained over 20% solids. Biogas purification testing was conducted during Phase IV.

5.2 TREATABILITY STUDY RESULTS

A laboratory treatability study was conducted in CDM Smith's Environmental Technologies Laboratory between May, 2010 and May, 2011. The treatability study focused on: 1) food waste and grease trap waste characterization, 2) quantification of biochemical methane potential (BMP), 3) operation of semi-continuous digesters to determine operating limits, collect performance data, and establish demonstration performance objectives, 4) measurement of hydrolysis kinetics, and 5) adaptation of Anaerobic Digestion Model 1 (ADM1) to a MathCad platform and simulation of food waste digestion. The results of the treatability study are presented in Appendices D and E and are summarized below and elsewhere (Amador et al. 2012; Evans et al. 2012; Stallman et al. 2012).

5.2.1 Food Waste and Grease Trap Waste Characterization

Characterization results for the 15 food waste samples and a single grease trap waste sample are presented in **Table 5**. The average VS/TS ratios for the food waste and grease trap waste were high, indicating a high potential for digestion as expected. Nitrogen and phosphorous nutrients in the grease trap waste were significantly lower than in the food waste suggesting these elements may be limiting. The various parameters for the food waste samples varied greatly as indicated by the high standard deviations relative to the means. The reason for the variability is likely attributable to different amounts of meat, green vegetables, and starches present in the individual samples.

Table 5. Summary of characterization of food waste (15 samples) and grease trap waste.

Analysis	Food Waste (Average ± Std. Dev.)	Grease Trap Waste
Volatile Solids (% Wet Weight)	26±6	67
Total Solids (% Wet Weight)	33±15	68
VS/TS	0.85±0.18	0.98
TKN (% Dry Weight)	4.9±2.5	0.06
Total Phosphorus (mg/kg Dry Weight)	300±220	40
COD (g/kg Dry Weight)	1400±340	1500
Protein (% Dry Weight)	31±16	0.3
Fat (% Dry Weight)	18±8	91
Ash (% Dry Weight)	3.2±1.5	0.3
Total Carbohydrates (% Dry Weight)	48±22	8.7

5.2.2 Biochemical Methane Potential (BMP)

The methane accumulation trends for BMP tests with individual food waste samples and the grease trap waste sample are shown in **Figure 8**. These trends are corrected for the average methane production by the inoculum alone in bottles without food or grease trap waste. The majority of methane generation was observed in the first 10 days, however some generation continued for another 10 to 20 days. The average net methane yield for the food wastes was 390±90 mL CH_4 per g of food waste COD fed, with values ranging from 190 to 570 mL/g COD. The theoretical value, based on assuming 5% of the COD used ends up in cell mass, is 380 mL/g COD. The observed methane production from the grease trap waste sample was much higher, at 700 mL/g COD^{-}fed. Some of the variation in the specific methane production is from applying the same average inoculum correction to all bottles. Some of the variation may also be attributable to different biodegradability of individual samples and/or enhancement of inoculum sludge digestion.

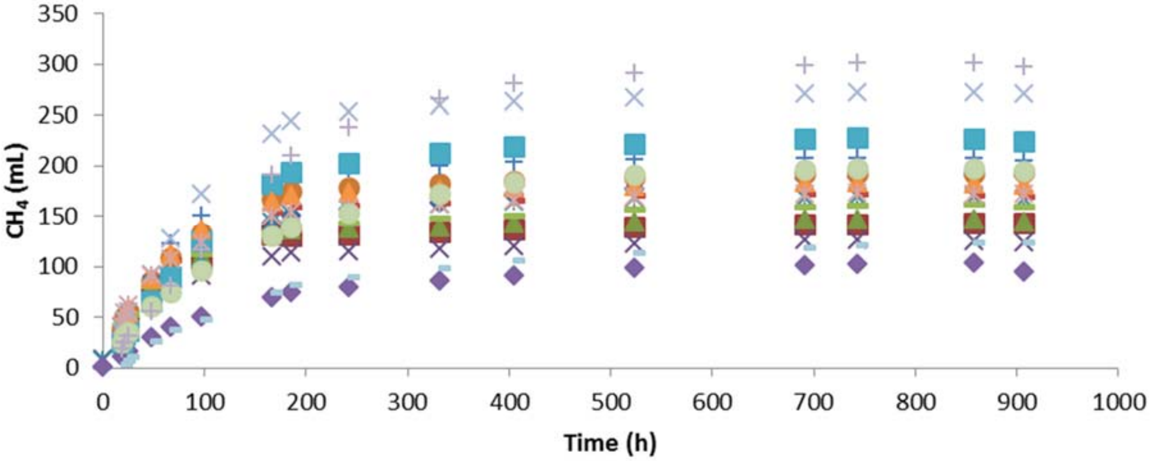


Figure 8. Methane production trends for different food waste and grease trap waste samples during BMP tests based on subtracting average methane production by the digester seed sludge-only controls.

Due to the wide range of methane yields observed in the BMP tests, the food waste characteristics were examined for any correlations with the methane yields in order to assess differences in degradability. Of the food waste characteristics, the sum of the fat and protein contents was found to best correlate with variations in the methane yields as shown by a trend line in **Figure 9**. The ratio of methane to COD increased with the combined fat and protein content. The correlation was not perfect and the results for three of the food waste samples did not fit the correlation. None of the characteristics for these three samples explained the deviation of these three from the pattern shown by the other wastes. Nevertheless, the data suggest that organic wastes with greater content of fat plus protein digest to yield more methane per unit COD fed. One possible explanation for these data is greater degradability of fat and protein relative to carbohydrates with the carbohydrates containing more non-biodegradable COD. The carbohydrate fraction includes cellulosic and potentially humic materials which are less biodegradable than fat and protein. Another explanation is that fat and protein enhanced digestion of the sewage sludge used to seed the BMP tests. Such enhancements have been observed in other studies (Kabouris et al. 2007; Kabouris et al. 2009). In any event, this correlation is a useful engineering parameter for feed stock characterization and digester design.

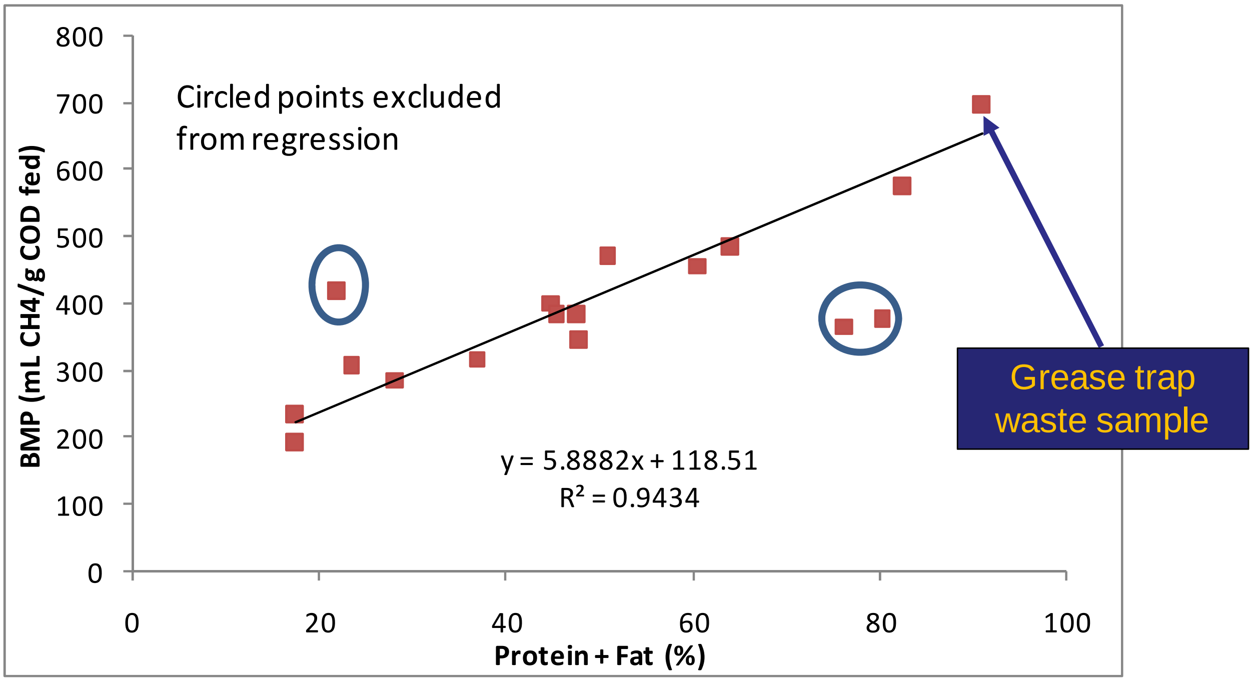


Figure 9. Biochemical methane potential relationship to protein-plus-fat content of various food wastes and a grease trap waste.

5.2.3 Volatile Solids Concentration in Food Waste Fed to the Digesters

Over 80% of the food waste VS was biodegradable such that digester VS concentration was much lower than that typically found in municipal anaerobic sludge digesters unless the feed VS concentration was above 10% (**Figure 10**). In addition, digesters fed with less than 5% VS developed instability in the form of elevated VFA/TALK ratios, decreased pH, and poor methane production. The cause was due to the dilute feed providing insufficient alkalinity to the digesters via protein hydrolysis and de-amination rather than the volumetric COD load which was modest at approximately 2.2 g-COD L^{-1} d^{-1}. Digesters fed 10 to 15% VS in the feed were stable. These digesters had COD loadings that ranged from 0.5 to 3.3 g-COD L^{-1} d^{-1}, which were both above and below the failed digester loadings.

The VS concentrations were significantly greater in the stable digesters compared to the unstable digesters. When the feed contained 4 percent VS by weight, the digester contained less than 1 percent VS and was unstable. Therefore, a more concentrated food waste VS was fed to the digester to increase digester VS. Feed concentrations greater than 10 percent VS increased digester VSS concentrations to 4 percent and improved digester stability. The observed VS concentrations in the digesters compare well with theoretical VS concentrations calculated with the following formula:

$$\begin{aligned} Reactor\ VS = {} & Feed\ VS * undegradable\ VS\ fraction \\ & + Feed\ VS * degradable\ VS\ fraction * cell\ yield \end{aligned} \quad (1)$$

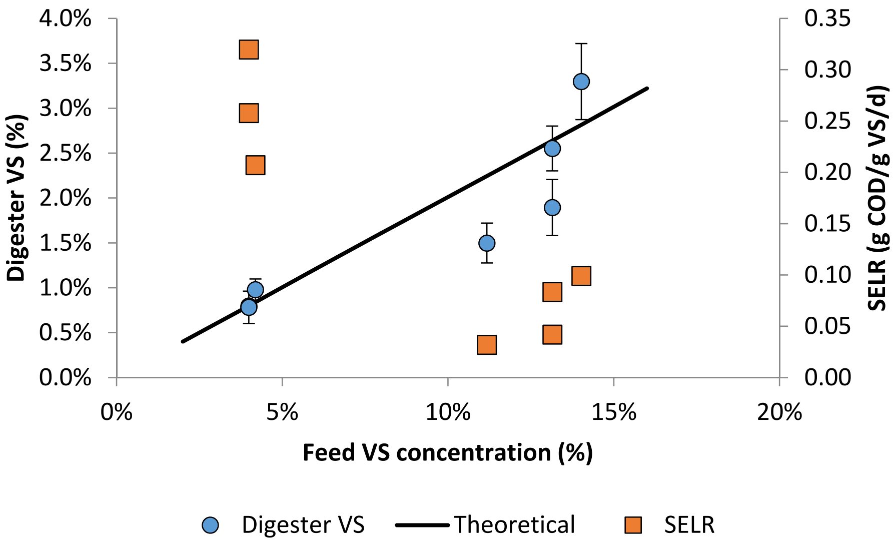


Figure 10. Effect of food waste/FOG VS concentration in the digester feed on digester stability.

Where the non-biodegradable VS fraction was assumed to be 15%, and the cell yield was assumed to be 0.12 g biomass VS per g VS consumed. The high biodegradability of the food waste (e.g., 85%) led to an operational requirement that the digesters be fed concentrated food waste with VS greater than 10%.

A VS loading rate per unit of digester volume is a common design and operating parameter for anaerobic digestion of municipal sludge (Tchobanoglous et al. 2003). However, it was not as useful of a parameter for determining stability of the laboratory digesters fed with highly digestible food waste. An alternative metric termed the SELR (g-COD d^{-1} g-VSS^{-1}) is proposed as a unifying design parameter for digester loading rather than VS (Evans et al. 2012). This metric is based on two general concepts. First, methanogenesis has a certain kinetic capacity for energy conversion following hydrolysis and fermentation of biodegradable organics to VFAs. If this capacity is exceeded, the digester becomes unstable and the rate of acidogenesis outpaces the rate of methanogenesis. By using energy loading rather than mass loading, the different specific energy contents of various organic wastes can be normalized. Second, instead of defining loading on a volumetric basis, we propose defining loading on an active biomass basis. The SELR is analogous to the specific activity of an enzyme. Whereas the specific activity measures the substrate concentration consumed per unit time per unit mass of enzyme (Lehninger 1975), the SELR relates the energy loading rate per unit of methanogenic biomass. The SELR is also somewhat analogous to the food-to-microorganism (F/M) ratio in the activated sludge process (Tchobanoglous et al. 2003). To ensure the SELR is a practical parameter, it must be based on readily available analytical methods. We propose COD as a surrogate for energy content. We also propose VS or VSS as a surrogate for active biomass. The SELR is then calculated as follows:

$$SELR = \frac{R_{COD}}{M_{VSS}} = \frac{QC_{COD}^{feed}}{VX_{VSS}} \qquad (2)$$

R_{COD} is the rate of energy fed to the digester based on feed flow rate (Q) and feed COD concentration (C_{COD}^{feed}). M_{VSS} is the amount of biomass in the digester estimated as the digester volume (V) multiplied by the VS concentration (X_{VSS}). COD is a reasonable surrogate for energy. VS or VSS may not be the best surrogate for biomass especially if the feed contains a large portion of non-biodegradable solids and the digester is not at steady state. Alternative approaches involve measuring another parameter in the digester that is more directly related to biomass or estimating the biomass concentration based on methane production rate measurements. Direct measurements of biomass indicators such as adenosine triphosphate (ATP) (Velten et al. 2007) may be conducted and should be more accurate, but VS and VSS were used for this analysis.

The SELR was calculated for these digesters and was also greater in the unstable region (less than 5% VS feed) than in the stable region (greater than 10% VS feed) (**Figure 10**). These data indicate that while the volumetric energy loading rates were similar (2.2 g-COD L^{-1} d^{-1} compared to 0.5 to 3.3 g-COD L^{-1} d^{-1}), different digester VS concentrations (i.e., active biomass concentrations) determined whether the digesters were stable or not – lower digester feed VS (e.g., 5%) led to too high a SELR.

5.2.4 Trace Metal Nutrient Requirements

Despite increased feed VS concentrations and increased digester VS concentrations, the digesters continued to experience some instability. As part of a process to identify causes of the instability, the trace metals content of the food waste was tested. Metal nutrient deficiency has been observed previously during food waste digestion (Hawkes et al. 1992). **Figure 11** compares the trace metal nutrient content of the food waste to required concentrations for methanogens (Scherer et al. 1983). The required concentrations in the food waste were calculated from the range of values reported for metals concentrations in methanogens and an assumed cellular yield of 0.05 g cells per g food waste). **Figure 11** indicates the food waste was deficient in nickel, cobalt, and possibly molybdenum. After the trace nutrient limitations were identified, these three nutrients were added to the feed along with boric acid. Although the biochemical need for boron is not well-established, it is recommended in anaerobic culture media.

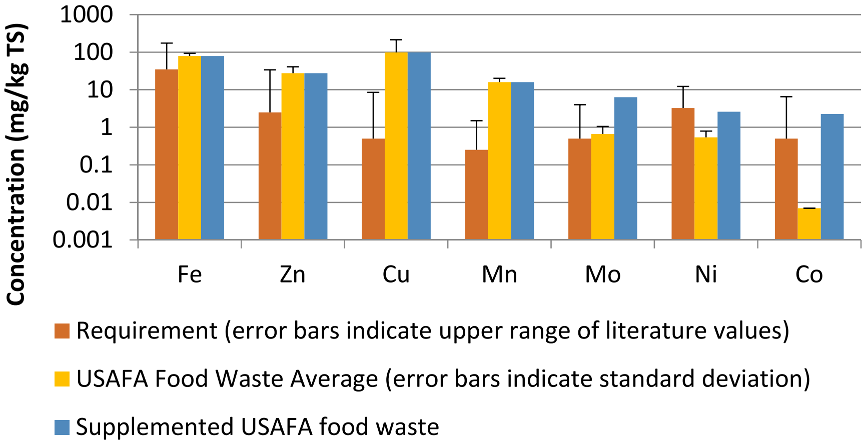


Figure 11. Comparison of trace metal nutrient requirements to USAFA food waste composition.

5.2.5 Grease Trap Waste Inhibition

During early tests of digester loading, digesters started at a loading of 10 g-COD L^{-1} d^{-1} failed when grease trap waste was included as 10% of the COD load. The remainder of the COD load was food waste. In contrast, digesters started at that same COD loading rate but without grease trap waste were stable. In order to determine whether the grease trap waste was inherently inhibitory, the performance of digesters fed grease trap waste plus food waste was compared to that of digesters fed canola oil plus food waste. As shown in **Figure 12**, the digesters receiving 10% of their COD as either grease trap waste or canola oil failed immediately: gas production was consistently low in these digesters, VFAs accumulated rapidly, and pH dropped below 6.5 within one week of operation. In contrast, the digesters receiving 5% of their COD load as either grease trap waste or canola performed stably, and with methane production rates similar to those seen in the control with no grease trap waste or canola oil. These results clearly demonstrated that this specific grease trap waste was not inherently inhibitory. Rather, digester failure was due to elevated concentrations of FOG fed at a high COD loading rate.

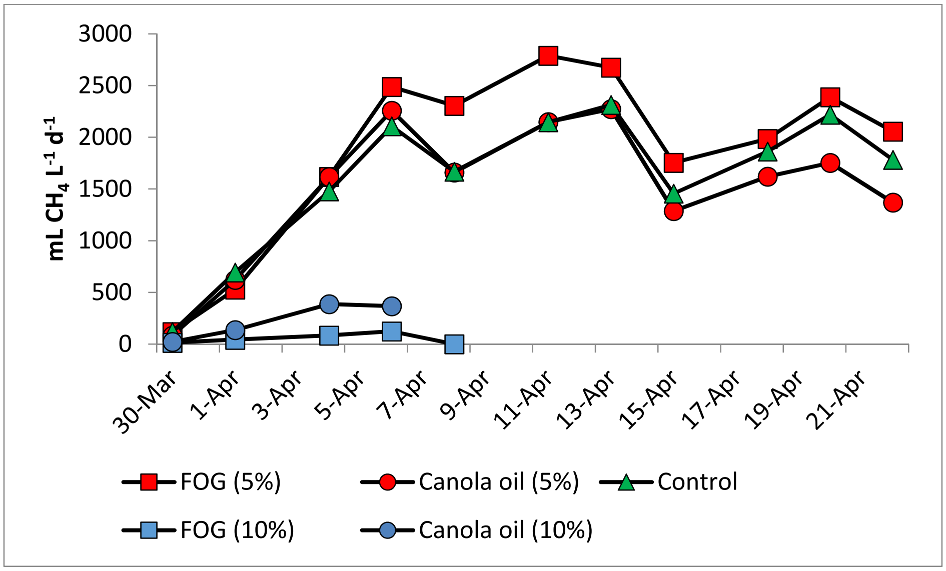


Figure 12. Methane production from digesters receiving FOG and canola oil. Percentages are the fraction of total COD loading comprised by the grease trap waste or canola oil.

While grease trap waste had a relatively high BMP per unit COD (**Figure 9**), it is potentially inhibitory because hydrolysis will liberate toxic long-chain fatty acids (Koster and Cramer 1987; Li et al. 2002). Nevertheless, strategies that led to successful digester acclimation and start-up were identified (**Figure 13**). Four conditions were compared: immediate loading of 10 g-COD L^{-1} d^{-1} without grease trap waste, immediate loading of 10 g-COD L^{-1} d^{-1} with 10% grease trap waste, immediate loading of 10 g-COD L^{-1} d^{-1} with ramping of grease trap waste from 0% to 10%, and ramping a 10% grease trap waste COD feed from 4 g-COD L^{-1} d^{-1} to 10 g-COD L^{-1} d^{-1}. The methane production rates from these digesters are shown in **Figure 13**. As expected, immediate feeding of 10 g-COD L^{-1} d^{-1} of food waste without grease trap waste was stable but addition of grease trap waste at this COD loading rate was unstable. Both ramping approaches (i.e., gradual increase of COD loading or grease trap waste percentage) led to stable digestion of a 10 g-COD L^{-1} d^{-1} loading with 10% grease trap waste. These data demonstrate that stable digestion with 10% grease trap waste COD at a total COD loading rate of 10 g-COD L^{-1} d^{-1} is possible, but startup must include a ramping procedure. These results demonstrate that acclimation is critical if high-lipid wastes, such as grease trap waste, are to be successfully digested.

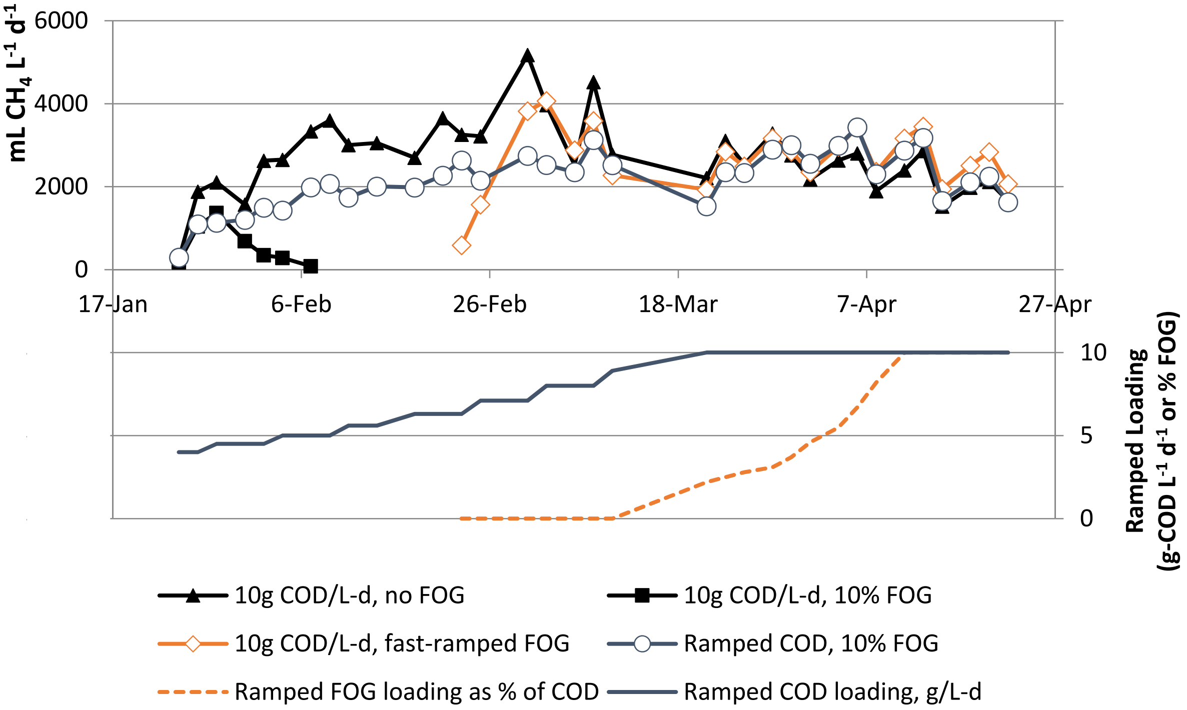


Figure 13. Effect of startup strategy on digester stability.

5.2.6 Effect of Varying SELR on Digester Performance

In order to assess the utility of the SELR as a guideline for stable digester loading rates, the VFA/TALK ratios observed during digester operation were compared to the SELR. A VFA/TALK ratio of greater than 0.1 has been suggested as an indicator of digester instability. **Figure 14** shows the relationship between SELR and this ratio. Digesters with a SELR of <0.4 g-COD $g\text{-}VS^{-1}$ d^{-1} generally maintained VFA/alkalinity values well below 0.1, although those loaded at more than 0.38 approached that threshold. At SELRs from 0.4 to 0.5, the VFA/TALK ratios were generally higher than at lower SELRs, with a few excursions well above 0.1. Greater SELR led to increased ratios of VFA/TALK and ultimately to digester failure.

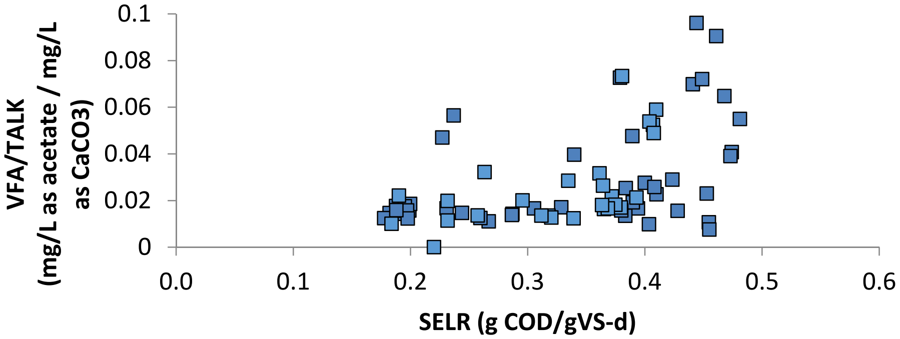


Figure 14. Ratio of VFAs to alkalinity in relation to the SELR.

Several further experiments were conducted to define the limits of reactor operation. Addition of QACs was tested because these compounds were contained in sanitizers used at Mitchell Hall at the time of the treatability test. Different sanitizers that did not include QACs were in use during the field demonstration. Therefore, the treatability study results on sanitizer toxicity were not applicable to the field demonstration. The QACs were found to cause reactor failure at concentrations about 2,000 to 3,000 mg QAC/kg of food waste dry solids. Limited data from USAFA are available to estimate the QAC concentration in Mitchell Hall food wastes. Nevertheless, the QAC concentration in Mitchell Hall food waste was conservatively estimated to range from 1,300 to 2,700 mg/kg on a dry weight basis. Therefore, QACs previously in Mitchell Hall food waste may or may have been at inhibitory concentrations.

5.2.7 Steady State Digester Performance

Figure 15 summarizes the methane yields and VS destruction rates observed in digesters receiving steady loadings of either 4 g-COD L^{-1} d^{-1} or 10 g-COD L^{-1} d^{-1}, with and without grease trap waste. There was also an increased methane yield from grease trap waste additions with a 4 g-COD L^{-1} d^{-1} loading, but that increase was not observed at a 10 g-COD L^{-1} d^{-1} loading. The VS destruction rates were also increased in the 4 g-COD L^{-1} d^{-1} digesters compared to the 10 g-COD L^{-1} d^{-1} digesters, but grease trap waste addition had no apparent effect. The increase in VS destruction at lower loading rates is due to the increased SRT. The lack of enhancement of VS destruction by grease trap waste suggests the previously observed enhancements of sludge digestibility by FOG (Kabouris et al. 2007; Kabouris et al. 2009) may be unique to sewage sludge co-digestion and not applicable to food waste.

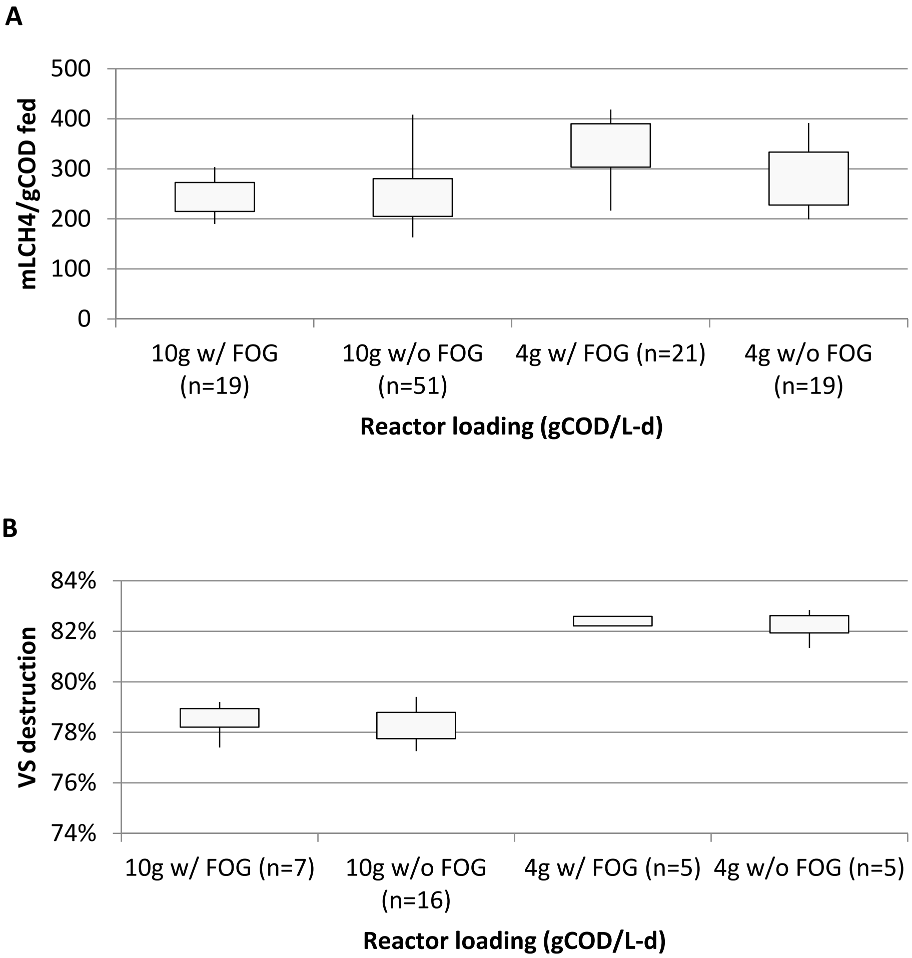


Figure 15. Digester performance at steady loading rates of food waste alone or supplemented with FOG. Boxes represent 25th and 75th percentiles and whiskers represent 5th and 95th percentile. A) Methane yield; B) VS destruction.

5.2.8 Discussion and Conclusions

The average BMP of the food wastes was 390 mL/g COD, which suggests that the wastes were highly degradable by anaerobic digestion. There were no major inhibitory effects apparent, as none of the bottles experienced a lag before the onset of methane production. Many of the wastes tested produced methane yields above 400 mL/g COD which is the theoretical value for full conversion (Tchobanoglous et al. 2003). The grease trap waste produced the highest methane yield with 700 mL/g COD. This supports the readily-degradable nature of this waste, but also suggests that it enhanced digestion of the sewage sludge inoculum. Recent studies have shown enhanced methane yields from the addition of high-fat wastes to sewage sludge (Davidsson et al. 2008; Kabouris et al. 2007; Kabouris et al. 2009; Luostarinen et al. 2009).

The methane yield was quite variable between the wastes, and it was found that there was a correlation with the fat and protein content of the food waste. Several factors may have contributed to this correlation. Lignocellulose and some other types of carbohydrates are poorly degradable, so the fat and protein may have represented a more highly-degradable fraction. The fat-plus-protein content appears to be a useful and practical parameter for screening co-digestion wastes.

Digestion of high-fat wastes can be operationally challenging. Degradation of fats produces long-chain fatty acids, which are potentially-toxic intermediates (Koster and Cramer 1987; Li et al. 2002). Excessive loading of fats has been observed to lead to the inhibition of anaerobic digestion (Hatamoto et al. 2007; Koster and Cramer 1987). Therefore, proper acclimation and adaptation to new high-energy wastes is critical. Mitchell Hall grease trap waste was not uniquely inhibitory since canola oil caused similar inhibition. Therefore, acclimation requirements apply in general. Acclimation was not required at low COD loading rates (4 g-COD L^{-1} d^{-1}). The stability of digesters with high COD loading rates (10 g-COD L^{-1} d^{-1}) was influenced by the presence of grease trap waste. Digesters started with this COD loading rate of food waste alone showed transiently elevated VFA/TALK ratios but subsequent acclimation and stability. This suggests there might be an unstable period during which the digester would be vulnerable to further upset. Digesters started at the high COD loading rate with 10% of COD from grease trap waste did not acclimate and failed. Thus the need for special acclimation procedures depends on the energy loading rate.

Acclimation of the digesters to high energy loading rates and grease trap waste was successful using two different strategies. One strategy involved starting with a feed comprised of 90% food waste and 10% grease trap waste (i.e., on an energy basis) and gradually increasing the energy loading rate from 4 to 10 g-COD L^{-1} d^{-1}. Another strategy involved starting with a feed comprised of food waste only at an energy loading rate of 10 g-COD L^{-1} d^{-1} and gradually increasing the grease trap waste energy percentage from 0 to 10%. Combinations of these strategies can be envisioned and are likely to be successful. These data demonstrate that grease trap wastes are not inherently inhibitory but proper acclimation strategies are necessary.

In addition to acclimation, supplementation with trace metal nutrients and feeding concentrated rather than diluted food waste was necessary. Trace metals analysis revealed that these food wastes were deficient in cobalt and nickel, and possibly molybdenum. These three elements are required as enzymatic cofactors, and are among the trace metals that have been identified as critical to successful anaerobic digestion (Speece 1996). Feeding organic waste at a high VS concentration also proved necessary for stable digester operation. The food wastes were highly degradable, with VS destruction rates greater than 75%. Feeding the waste at VS concentrations typically used anaerobic sludge digestion resulted in digester solids concentrations too low to support stable operation. Digester performance improved when the food waste VS concentrations were kept at greater than 10%.

The SELR (g-COD g-VS^{-1} d^{-1}) was introduced as a new concept and an alternative to the traditional volumetric solids loading rate (g-VS L^{-1} d^{-1}). The SELR is based on the energy balance and metabolic limits of digester microbial communities. It is especially appropriate for new and diverse organic feed stocks being considered for anaerobic digestion. Support for the SELR concept included observed relationships between digester stability and SELR values. While refinement is required, a maximum SELR 0.4 g-COD g-VS^{-1} d^{-1} appears to be justified for stable digester operation for food waste. Further evaluation of this concept in a wide variety of digesters is recommended to explore its validity and utility to other wastes. Evaluation of alternative methods for active biomass quantification (e.g., ATP or prediction from methane production) in digesters is also recommended.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

5.3.1 General Overview

Figure 16 is a process flow diagram for the demonstration system installed and operated at the USAFA WWTP. Two replicate 1230-L (325-gal) digesters with a working capacity of 950 L (250 gal) were continuously mixed (100 revolutions per minute [rpm]), temperature-controlled (37 °C), and included equipment for food waste mixing and pumping as well as pumps for wasting. Biogas from the digesters was combined and routed through 2.3 kg of SulfaTrap R7 mixed metal oxide adsorbent (TDA Research, Wheat Ridge, Colorado) for H_2S removal. The biogas then flowed to a 50-m^3 triple-membrane biogas holder (Base Structures, Bristol, United Kingdom). Biogas was then discharged to the USAFA flare. Near the end of the demonstration in Phase IV biogas stored in the holder was purified using the VSA system described in Appendix F and elsewhere (Jayaraman et al. 2015). The process was modified between Phases III and IV as illustrated in **Figure 16**. The purpose was to eliminate water addition to the food waste/canola oil mixture. Digestate was recycled and mixed with the food waste/canola oil mixture to make it pumpable. Engineering drawings including site plans, process and instrumentation diagrams, and mechanical drawings are included in Appendix G. The engineering drawings depict how the demonstration trailer was originally built for the demonstration. However, several modifications were made based on troubleshooting conducted during Phase I. These modifications along with additional details on the demonstration system and described provided below.

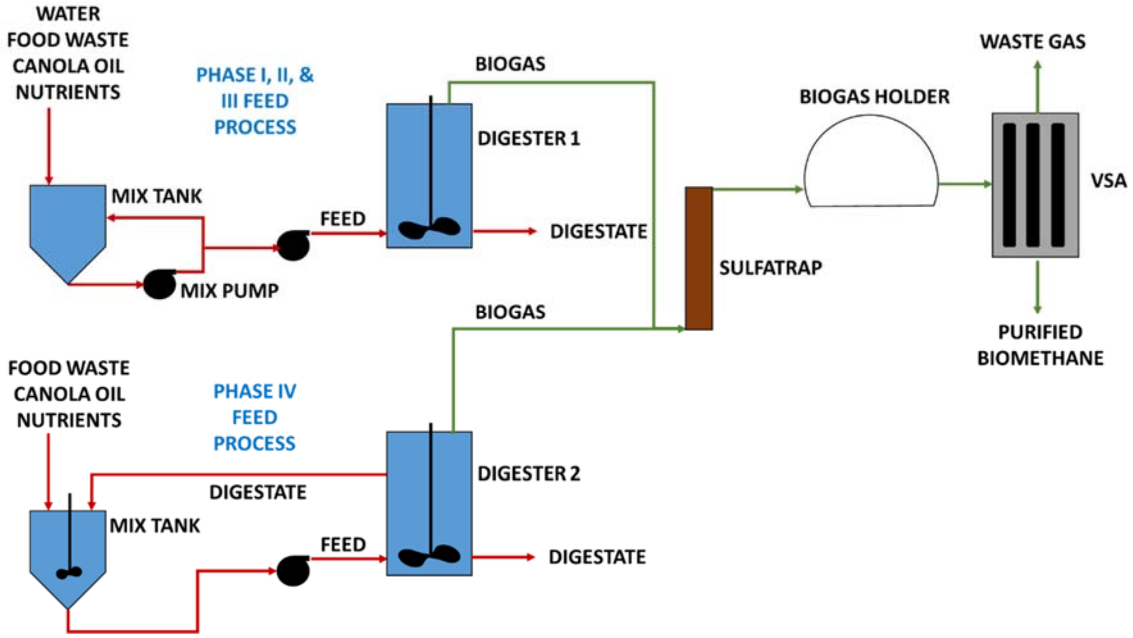

WATER
FOOD WASTE
CANOLA OIL
NUTRIENTS
PHASE I, II, & III FEED PROCESS
BIOGAS
DIGESTER 1
MIX TANK
FEED
DIGESTATE
MIX PUMP
BIOGAS
SULFATRAP
BIOGAS HOLDER
WASTE GAS
VSA
PURIFIED BIOMETHANE
FOOD WASTE
CANOLA OIL
NUTRIENTS
PHASE IV FEED PROCESS
DIGESTER 2
DIGESTATE
MIX TANK
FEED
DIGESTATE

Figure 16. Process flow diagram.

5.3.2 Detailed Description of Demonstration Equipment

An existing test trailer (**Figure 17**) owned by King County, Washington was provided at no cost to the ESTCP demonstration and modified to meet demonstration requirements. This section describes the equipment.

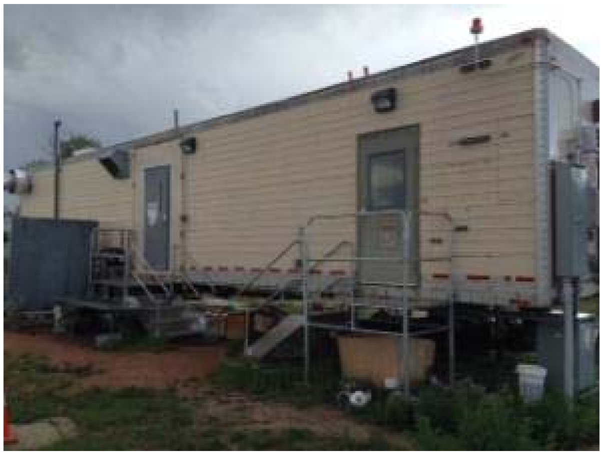


Figure 17. Demonstration trailer.

Digesters

Each digester tank was 90 cm (36 in) in diameter and 200 cm (77 in) tall and constructed of stainless steel (**Figure 18**). Each tank was constructed with a flat bottom and vertical baffles to enhance mixing by top-mounted propeller mixer. Each digester was equipped with an explosion-proof heating system (Chromalox, Pittsburgh, Pennsylvania AEPS-024-220-917, 120 V, 220 W, PCN/Part No. 235213, quantity 8; and AEPS-024-220-917 240 V 220 W, PCN/Part No. 235211, quantity 4) and was insulated. A programmable logic controller was used to control the heaters and maintain a digester fluid temperature of 37 ^{o}C. Digester mixing was accomplished using a top-installed, single impeller mixer (Sharpe Mixers, Seattle, Washington) driven by an explosion-proof 0.5-hp single-phase motor (Baldor VL5005A). The mixer impeller consisted of three blades pitched at thirty degrees with a tip-to-tip diameter of 25 cm (10 in) and was operated at a nominal shaft speed of 100 rpm. The impeller was positioned 25 cm (10 in) from the bottom of the tank. Each digester was equipped with an overflow foam pot which was used to protect the biogas system. The overflow foam pot was 15 cm (6 in) in diameter and approximately 150 cm (60 in) tall and made of clear Polyvinylchloride (PVC). Each digester was equipped with a flame arrestor and rupture disk intended to protect the digester from over pressurization.

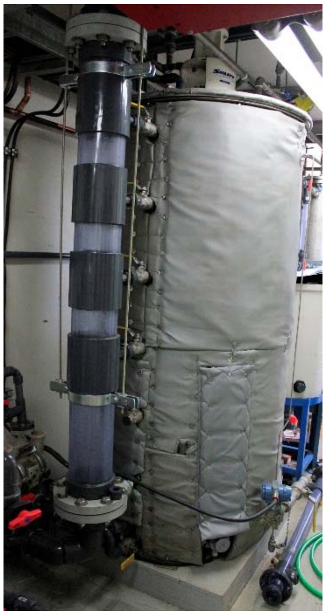


Figure 18. Insulated digester tank and foam pot.

Feed and Waste Systems

During Phases I through III food waste, canola oil were mixed with water and recirculated in a 380-L (100-gal) Nalgene feed tank using a 51-mm (2-in) air-operated diaphragm pump (**Figure 19**). Chicken wire was secured to the lid of the tank to assist in screening debris from the food waste (**Figure 19**). This pump was also used to transfer the mixture to the digesters through Day 16 of Phase II. However the pump was not capable of precisely metering desired quantities of mixture to the digester. On Day 17 a hand-operated diaphragm pump (Wastecorp Pumps, Grand Island, New York, Sludge Sucker Model No. 2FA-H) was for the remainder of Phase II and for Phase III. During Phase IV a 110-L (30-gal) tank and air-powered mixer (Grainger, ¼ hp Dayton Part No. 32V122) with three propeller mixers (Mixer Direct, Louisville, Kentucky, Model PRPL04062) was used to mix food waste with digestate (**Figure 20**). The hand-operated diaphragm pump was used to transfer the mixture back into the digester. Sludge wasting was conducted during all phases using a diaphragm pump (Walden Model No. M2R, Grand Terrace, California). Sludge wasting was conducted prior to feeding and the volume wasted was selected to maintain an average digester volume of 950 L (250 gal).

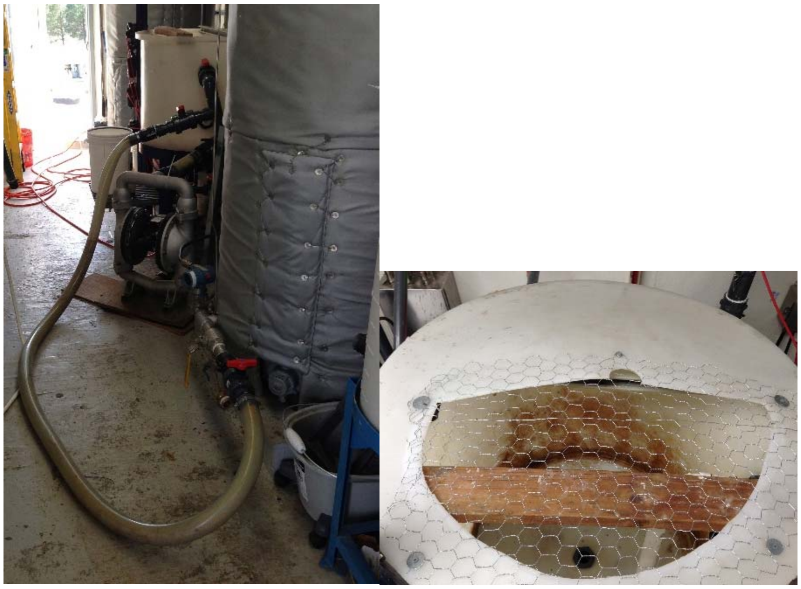


Figure 19. Feed tank, diaphragm pump, transfer hose, and digester with close-up of chicken wire screen on feed tank lid.

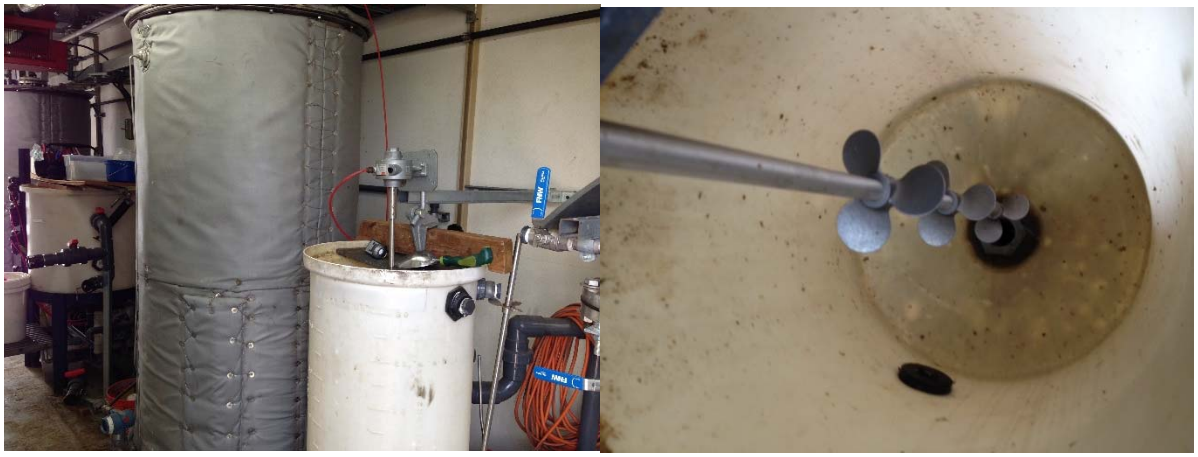


Figure 20. Phase IV feed tank and mixer assembly adjacent to the digester.

Sulfur Sorbent Column

TDA SulfaTrap R7 (2.3 kg) was tested in a clear PVC column measuring 5.1 cm (2 in) in diameter by 91 cm (36 in) in length (**Figure 21**). An identical column packed with gravel was placed upstream of the SulfaTrap column to attempt to drop out biogas condensate prior to the SulfaTrap column.

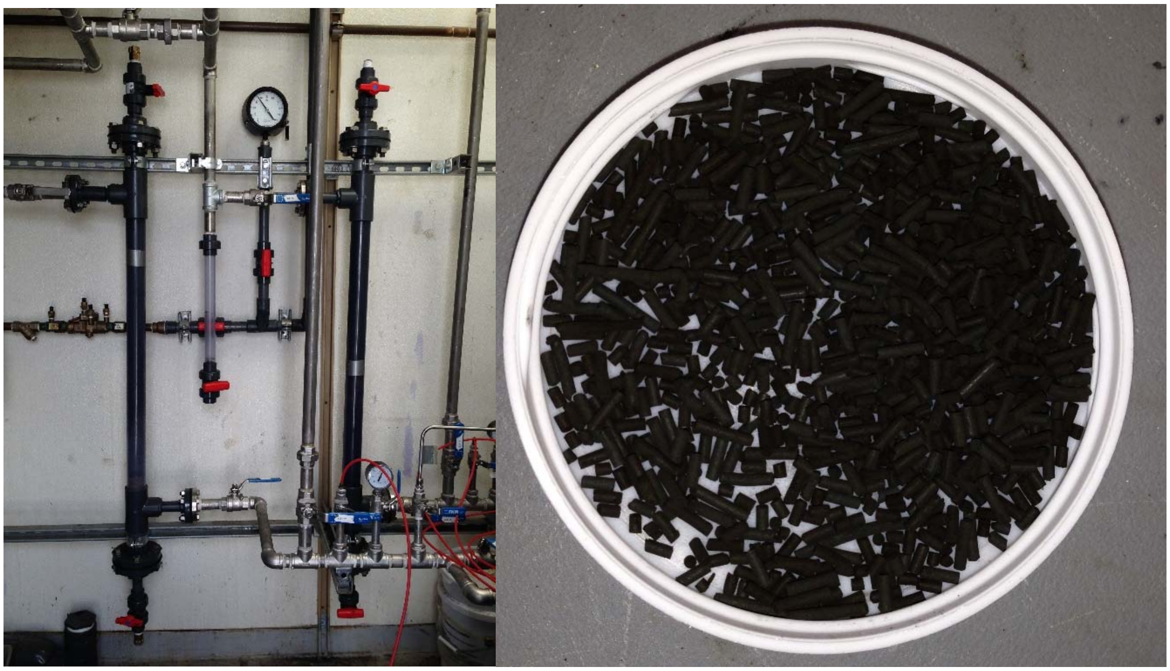


Figure 21. Gravel and SulfaTrap columns in series and photograph of SulfaTrap media.

Gas Storage Vessel

Desulfurized (i.e., sweetened) biogas was stored in a 50-m^3 triple-membrane biogas holder (Base Structures, Bristol, United Kingdom) shown in **Figure 22**. This vessel is designed to maintain a positive pressure on the biogas and prevent potential introduction of air that could form a flammable mixture.

VSA System

The VSA system (**Figure 23**) was fabricated by TDA Research and is described in detail in Appendix F. In general, the VSA system is based on a regenerable mesoporous carbon media modified with surface functional groups to reduce the CO_2 and H_2O concentration in the biogas to pipeline specifications. The adsorption of CO_2 from the biogas stream is carried out at the biogas delivery pressure (about 1.3 atm), while the sorbent is regenerated and CO_2 recovered under vacuum (at about 0.2 atm). The bed is subsequently pressurized with the feed (biogas) gas. The methane loss from the system is reduced by using intermediate pressure equalization steps between the main adsorption and regeneration portions of the cycle. The methane loss with the full vacuum swing cycle is minimal (i.e., less than 10%).

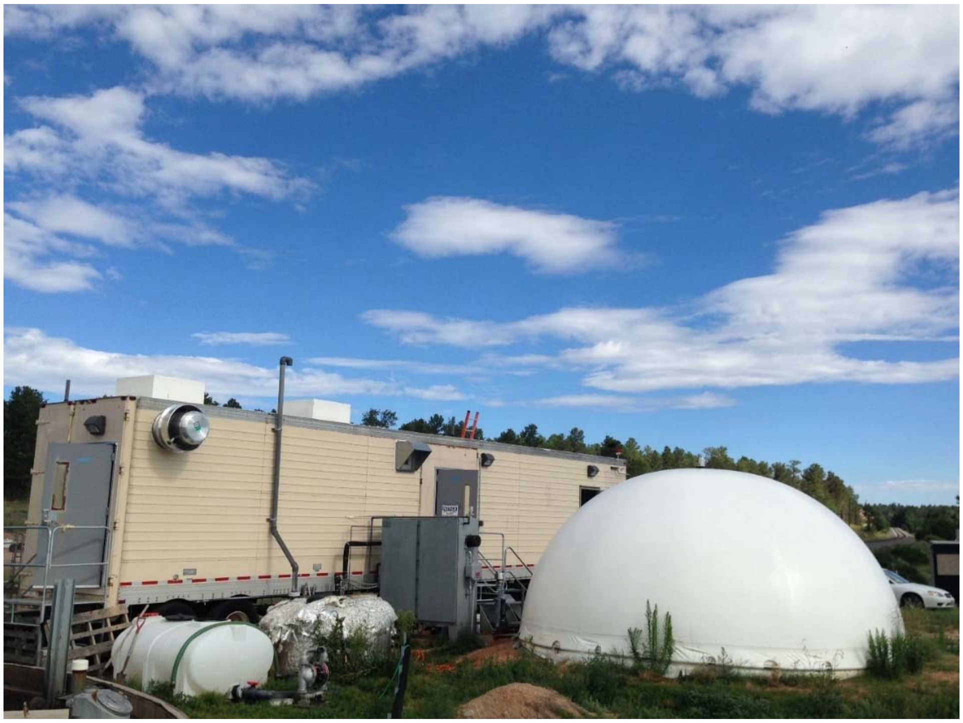


Figure 22. Biogas holder adjacent to the demonstration trailer.

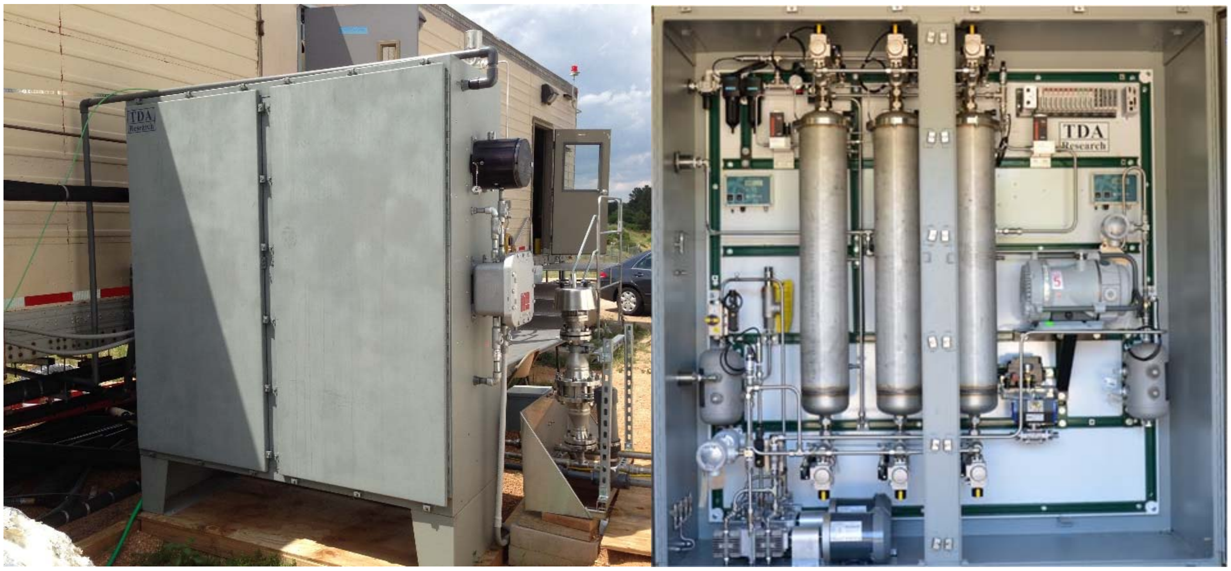

TDA Research
TDA Research

Figure 23. VSA system.

Instrumentation

The demonstration equipment included instrumentation for monitoring temperature, pressure, liquid level, biogas flow rate, and biogas methane concentration.

- A temperature measurement device was installed in an existing thermowell on each digester. Temperature was measured using a 3-wire resistance temperature device (RTD) provided with a 4-20 mA transmitter (Mescon Series No. TH-11U, Frankfort, IL). The RTD and transmitter assembly was factory calibrated for (0 to 200oF (–17 to 94oC) with an accuracy of ± 0.5oF (± 0.3oC).
- Each digester was equipped with a pressure gauge to measure headspace gas pressure. The pressure gauge (Ashcroft, Stratford, Connecticut) selected is a compound style with a range of 30 inches (76 cm) of water column vacuum to 30 inches (76 cm) of water column pressure. The gauge is provided from the factory with an accuracy of +/- 5 % full scale.
- Biogas flow rate was measured using an explosion proof mass flow unit (Fluid Components International, San Marcos, California, Model No. ST75V). The flowmeter was factory calibrated for a gas mixture comprised of 65% methane and 35% carbon dioxide. The calibration range for the flowmeter was 0.05 to 0.5 standard cubic feet per minute (1.4 to 14 L/min). Standard conditions for the flow meter calibration were 70 °F (21 °C) and 1 atmosphere absolute.
- Digester liquid level was measured using a Rosemount (Emerson Electric, St. Louis, Missouri) model 3051C differential pressure transmitter. The transmitter was factory calibrated for 0 to 72 inches (0 to 180 cm) of water column. The water column and the tank diameter were used to determine the liquid volume.
- Methane concentration was measured using a Nova (Niagara Falls, New York) Model 912A-CWX Landfill Gas Analyzer using nondispersive infrared detection and automatic stream switching/sampling valves (**Figure 24**). The instrument was factory calibrated for 0 to 100% methane by volume.
- Process monitoring and control was conducted using a programmable logic controller with power supply, 1.5 MB ethernet processor, six 120VAC 16-point input modules, two 8-point analog input modules, two relay output modules, and five 8-point isolated relay input modules (Allen Bradley, Milwaukee, Wisconsin, Compact Logix 1769-CRL1, ECR, IA16, IF8, OW16, OW8I, PA2, L35E); a Dell Precision T5600 computer with a Rockwell Automation FactoryTalk (9518-HSE250) and RSVIEW (9701-VWSB100AENE) human machine interface; and reporting software for Excel (Sytech [Franklin, Massachusetts] XLReporter Professional, Real/Historical/ODBC – Single).

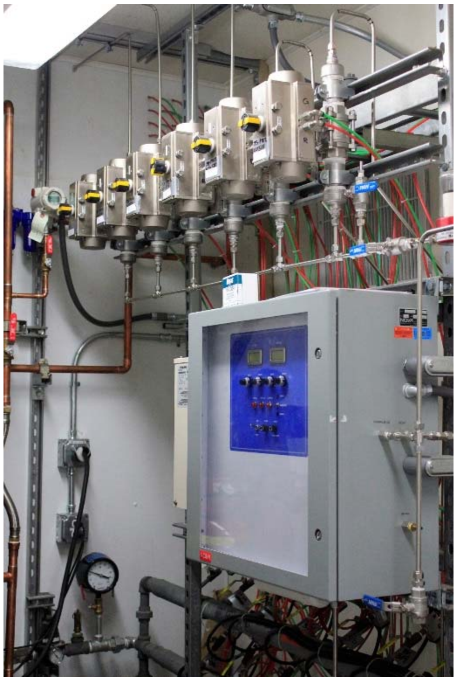


Figure 24. Nova gas analyzer with stream switching valves.

Safety

Because of the flammability of biogas, the trailer was designed for 12 air exchanges per hour and equipment rated for Class 1, Division 1 and Class 1, Division 2 environments as defined by the NEC. The process equipment was physically separated from the control systems in the trailer by a wall. Combustible gas detectors were included in the trailer to monitor concentrations of methane within the atmosphere. Alarm conditions were set at 10% and 15% of the lower explosive limit.

5.4 FIELD TESTING

Food waste was collected from USAFA Mitchell Hall in 19-L (5-gal) buckets on an as-needed basis generally around lunch time and sometimes around breakfast time. The food waste was ground at USAFA using a commercial pulper system prior to landfilling (**Figure 25**).

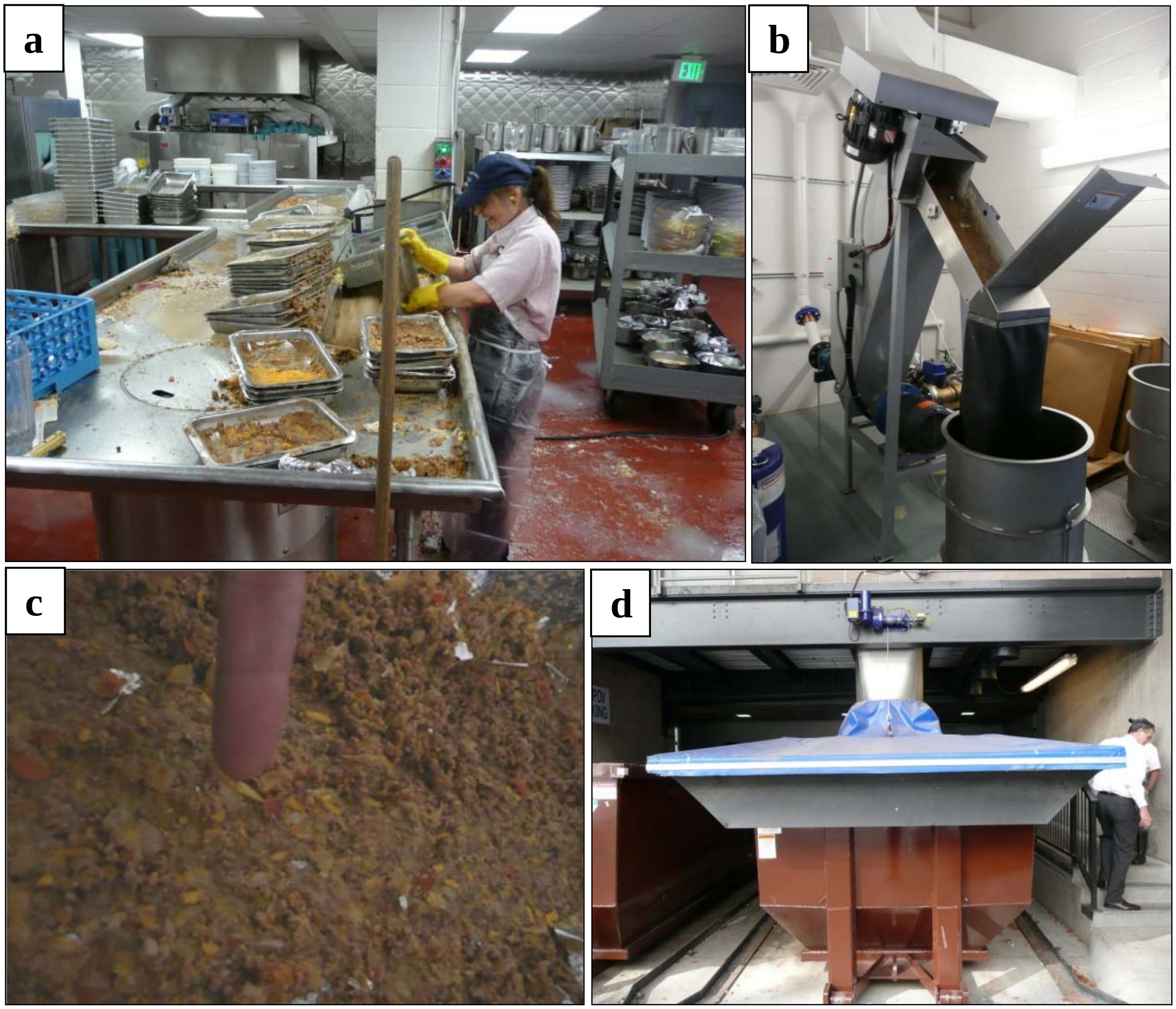


Figure 25. Food waste at Mitchell Hall was manually scraped into recirculating sluice water which was then ground in a pulper/shredder (a). The slurry gravity-drained down one floor into dewatering equipment (b). The dewatered and ground food waste (c) then dropped into a roll off container (d) on the floor below where it was sent to a landfill. Food waste was collected in 5-gallon buckets from the dewatering system (c).

The digesters were seeded with 950 L (250 gal) each of mesophilic anaerobic digester sludge from the USAFA WWTP primary digester. Seeding for Phases I, II, and IV occurred on July 24, 2013; December 20, 2013; and June 6, 2014, respectively. Phase III was a continuation of Phase II and did not involve digester seeding.

Food waste was mixed with canola oil and nutrients prior to being fed to the digester. Canola oil was used as a surrogate for USAFA grease trap waste based on treatability study results (Section 5.2). Canola oil was added so that is comprised about 10% of the food waste/canola oil VS. Nutrients were added at the concentrations shown in **Table 6**. Nutrient dosing was based on treatability study results and related research regarding the potential role of selenium in mitigating ammonium toxicity (Zhang et al. 2010). Measured concentrations of metal nutrients in the digestate are presented in Appendix H. The measured concentrations do not indicate limitations based on previous research (Hawkes et al. 1992; Scherer et al. 1983; Speece 1996; Zhang et al. 2010).

Table 6. Nutrient concentrations.

Element	Compound	Element concentration added to each batch of food waste+canola oil during Phases II and III (mg/kg)	Element concentration added to the digester on Day 0 of Phase IV (mg/L)
Boron	H_3BO_3	11	2.4
Cobalt	$CoCl_2•6H_2O$	2.3	0.50
Molybdenum	$Na_2MoO_4•2H_2O$	6.4	1.4
Nickel	$NiSO_4•6H_2O$	2.6	0.57
Selenium	$Na_2SeO_3•5H_2O$	1.7[a]	0.36

[a] Not added until day 21.

Operation during Phase I had numerous challenges as the system was started up. These challenges included mechanical failures, issues with inert debris in the food waste plugging and jamming piping and equipment, leaks in the gas handling system, limited availability of food waste, and loss of heating. These issues were resolved and the digesters were restarted in Phase II. Digester feeding generally occurred on Monday, Wednesday, and Friday. The feeding process during Phases II and III involved addition of water to the mix tank followed by addition of food waste, canola oil, and a nutrient stock solution to achieve a TS concentration ~10%. The food waste was screened manually to remove non-food debris. The mixture was recirculated for about 10 minutes prior to being fed to the digester. The digesters were drained prior to feeding by a volume equal to the planned feed mixture volume. This approach prevented draining of newly added feed and maintained a constant digester liquid volume. Additional details regarding digester feeding in Phases II and III are included in Appendix I. During Phase IV only one digester was operated because one of the digesters incurred a failure of its mixing shaft seal. Food waste and canola oil were mixed with recycled digestate instead of city water. Sufficient digestate was used to reduce the food waste/canola oil mixture TS to ~10% and then pumped back into the digester. Details on gas biogas treatment methods conducted during Phase IV are presented in the TDA report included in Appendix F.

The four phases of operation are shown graphically in **Figure 26**, which shows the trending of the pH and biogas methane content during the operational phases. **Table 7** shows the relationship between dates of operation and elapsed time for these four phases.

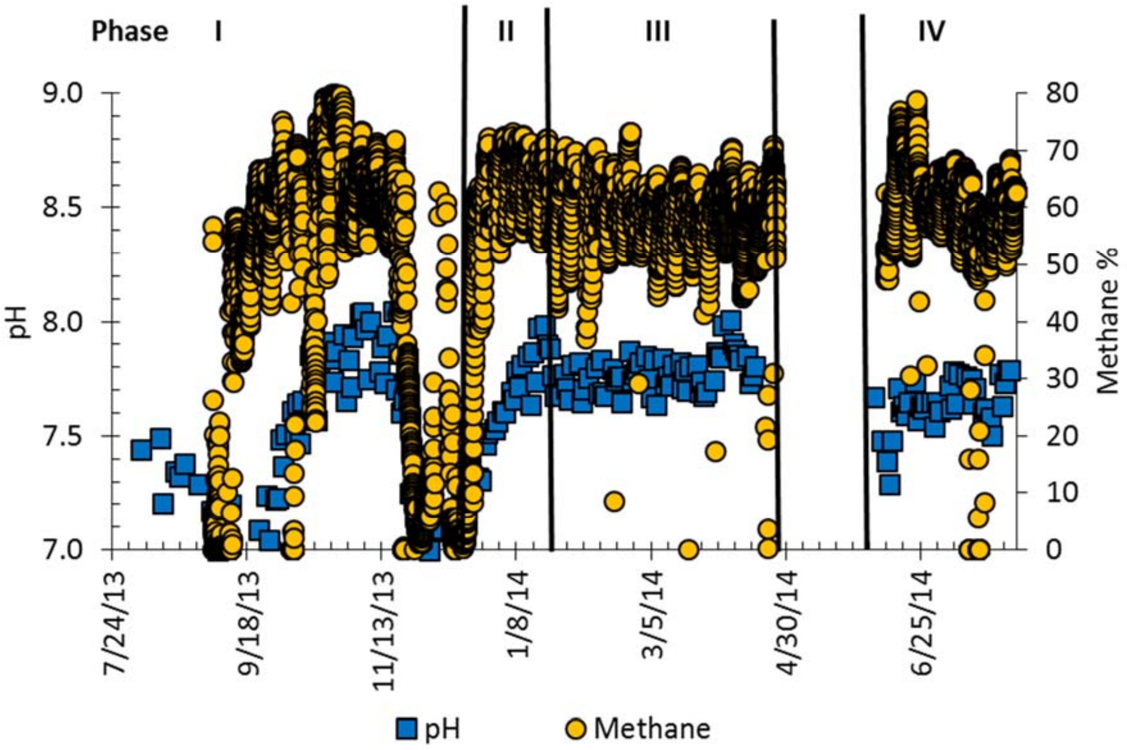


Figure 26. pH and biogas methane concentration trends during the four demonstration phases.

Table 7. Demonstration phases.

Phase	Dates	Elapsed Time (d)
I. Shakedown	7/24/13 to 12/19/13	0 to 148
II. Restart	12/20/13 to 1/21/14	0 to 32
III. Stable Operation	1/22/14 to 4/25/14	33 to 126
IV. Modified Feeding Strategy	6/6/14 to 8/4/14	0 to 59

5.5 SAMPLING AND ANALYTICAL METHODS

System monitoring and sampling involved a combination of on-line instruments and grab samples. On-line instrumentation is described in Section 5.3.2 and Appendix F. In general grab sampling was conducted weekly. Grab samples of food waste were collected from a single bucket. Digester feed samples during Phases II and III were collected from the mix tank after addition of food waste, canola oil, nutrients, and water. During Phase IV samples of food waste/canola oil mixed with digestate were not collected because of hazards associated with H_2S exposure. Rather, undiluted food waste sampling and analysis was used to determine digester loading. Digestate sampling was conducted by opening a valve at the bottom of the digester. Gas sampling for analysese of fixed gases (CH_4, CO_2, N_2, and O_2) and sulfur compounds was conducted using Tedlar bags connected to sample taps on the biogas lines. Sampling for analysis of fixed gases from the VSA was conducted using Tedlar bags and required synchronization with the timing of sorption and desorption cycles because both purified gas and waste gas exited the same sampling port (see Appendix F). Sampling for siloxane analysis was conducted using a methanol-containing impinger (Saeed et al. 2002) provided by ALS Environmental (Simi Valley, California).

Analytical methods are listed in **Table 8.** The analyses were conducted by certified laboratories (ALS Environmental; Kelso, Washington and Simi Valley, California) using standard methods with the following exceptions. VFAs were analyzed using high performance liquid chromatography with a C18 column and UV detection at 210 and 245 nm. COD analysis of food waste and digester feed was conducted according to the Standard Operating Procedure (SOP) included in Appendix J. In summary, food waste samples were weighed, mixed with a known volume of water, and blended in a Vitamix (Cleveland, Ohio) blender until homogenized. Serial dilutions were then conducted until the COD was in the range of the Hach COD test (50 to 1500 mg/L). The standard procedure for the Hach analysis was then followed. COD of the food waste was calculated by multiplying the Hach COD reading by the dilution factor. Sulfur in the spent SulfaTrap media was analyzed by Hazen Research (Golden, Colorado) using a Leco (St. Joseph, Michigan) model S-200 Sulfur Determinator, equipped with the "short path" infrared cell, halide scrubber, and autocleaner.

5.5.1 Calibration of Analytical Equipment

Factory calibrations for on-line instrumentation were used. All calibration procedures for field equipment was carried out in accordance with the manufacturer's instructions. pH probes were calibrated daily with 7.0 and 10.0 buffers. The Hach COD test kit accuracy was checked with an NIST traceable Hach standard (potassium phthalate, 1000 mg/L COD). The Nova gas analyzer accuracy was checked with methane standards (65% and 100%).

5.5.2 Quality Assurance Sampling

Quality assurance sampling included collection of field replicates at a frequency of 5%. Summary of the results from sampling and analysis is included in the Quality Assurance Summary (Appendix K). In addition, multiple lines of evidence and data trends were used to interpret results from this study. As such, the quality of the data for the study are considered good and individual data quality issues were not considered serious with two exceptions. First, propionic acid results were inconsistent and the HPLC chromatograms indicated peak interference with an unidentified compound. Therefore, propionic acid data are considered suspect. Nevertheless, the contract laboratory (ALS Environmental) applied its SOPs to accept or reject data. The accepted data were used in calculation of ratios of VFA/TALK. Second, grab samples of gas from the VSA required synchronization with the sorb/desorb cycles as described above. The sample collected on day 47 of Phase IV were not included in the data analysis because of contamination with desorption gas.

Table 8. Analytical methods.

Analyte	Method	Preservative	Maximum Holding Time
Total Volatile Solids and Total Volatile Suspended Solids	EPA 160.4[a]	4°C	7 d
Total Suspended Solids	SM 2540D[b]	4°C	7 d
Total Fixed Solids	SM 2540G	4°C	7 d
Total Solids	EPA 160.3	4°C	7 d
Volatile Fatty Acids	See text	4°C	8 d
Ammonia	SM 4500NH3-G	4°C H_2SO_4	28 d
COD	Hach Method 8000	NA	NA
Food Waste Fat	AOAC OMA 960.39[c]	4°C	NA
Food Waste Protein	AOAC OMA Method 981.10	4°C	NA
Food Waste Ash	AOAC OMA Method 923.03	4°C	NA
Food Waste Moisture	AOAC OMA Method 925.10	4°C	NA
Food Waste Carbohydrates	Calculated by difference (Subtraction of moisture, fat, protein and ash from total) 21 CFR Part 101.9	4°C	NA
Alkalinity	SM 2320B	4°C	14 d
pH	pH probe	NA	NA
Total Metals (Ag, As, Ba, Cd, Cr, Cu, Fe, Mg, Pb, Zn)	EPA 6010C[d]	4°C, HNO_3	180 d
Total Metals (Co, Mo, Ni, Se)	EPA 6020A	4°C, HNO_3	180 d
Total Metals (Hg)	EPA 7470A	4°C, HNO_3	28 d
Fecal Coliforms	SM 9221E	4°C $Na_2S_2O_3$	6 h
Heterotrophic Plate Count	SM 9215B	4°C	24 h
Total Sulfide	SM 4500-S2-D	$ZnAc_2$ & NaOH	7 d
Total Sulfur	See text	None	NA
Ammonia	SM 4500NH3-D	4°C H_2SO_4	28 d
Hydrogen Sulfide Gas	ASTM D5504-08[e]	None	24 h
Hydrogen Sulfide Gas (Screening)	RAE Systems sorbent tube No. 10-103-20 (50 to 800 ppmv)	NA	NA
Siloxanes	Air Toxics Method TO-14	Methanol	24 h
Fixed Gases (CH_4, CO_2, N_2, O_2)	ASTM D1946	None	24 h

[a] (USEPA 1979)
[b] (Eaton et al. 2005)
[c] (AOAC International 2012)
[d] (USEPA 2013b)
[e] (ASTM International 2013)

5.5.3 Decontamination Procedures

Food waste mixing tanks were cleaned with tap water following use. Sample bottles were new. No other decontamination procedures were required as this was not a hazardous waste project.

5.5.4 Sample Documentation

Sample documentation involved completion of chain of custody forms with a pre-defined sample naming conventions. Sample analytical results were transmitted to CDM Smith electronically as electronic data deliverables (EDDs). The data from the EDDs imported into a master Excel spreadsheet where data analysis was conducted.

5.6 SAMPLING RESULTS

5.6.1 Food Waste and Feed Characteristics

The characteristics of the undiluted food waste, the food waste/canola oil mixture, and the digester feed are shown in **Table 9**. These characteristics are for food waste samples following manual removal of non-food debris that included foil and plastic wrapping, plastic utensils, Styrofoam, bottle caps, popsicle sticks, etc. (**Figure 27**). The debris comprised 0.54±0.69% on a wet mass basis (N=48, median = 0.30%) and the maximum content measured was 3.1%. The debris-free food waste solids contents were similar in phases III and IV and most of the solids were volatile (96±0.8% in Phase III and 94±2.6% in Phase IV). The pulping and dewatering process used at USAFA produced a food waste product that contained greater than 20% TS. The TS and VS were slightly increased by addition of canola oil. The food waste/canola oil mixture was diluted to less than 10% TS during Phase III in contrast to Phase IV where the mixture was not diluted with water prior to mixing with digester sludge and being pumped back into the digester. Thus the effective TS that was fed to the digester in Phase IV was 25±6% compared to 9.2±1.3% during Phase III. The ratio of COD to VS was greater in Phase IV than in Phase III, possibly due to variation in the food waste composition over time and relatively greater fat and protein content during Phase IV. For comparison, the specific COD contents of carbohydrates, protein, and fat have been estimated to be 1.06, 1.36, and 2.88 g-COD/g (Speece 1996; Stallman 2011). The fat, protein, and carbohydrate content of the food waste varied considerably over time as illustrated by the relatively high standard deviations (**Table 9**) and the observed temporal trends (Appendix H, Figure 2).

Table 9. Average Food waste and digester feed characteristics.

Sample	Phase	TS	VS	COD	COD/VS^{c}	Fat	Protein	Carbo-hydrate
		(% by mass)		(mg/L)	(mg/mg)	(% of dry organics)		
Undiluted Food Waste	3	26±2.8	25±2.8	-	-	20±10	38±17	42±21
Undiluted Food Waste	4	22±6.1	21±5.9	320,000±82,000	1.6±0.2	-		
Undiluted Food Waste/Canola Oil Mixture^{a}	3	29±2.6	28±2.7	-	-	28±8.5	32±17	40±19
Undiluted Food Waste/Canola Oil Mixture^{a}	4	25±6.0	24±5.8	390,000±80,000	1.7±0.1	-		
Digester Feed	3	9.2±1.3	8.9±1.3	120,000±29,000	1.2±0.2	-		
Digester Feed^{b}	4	25±6.0	24±5.8	390,000±80,000	1.7±0.1	-		

[a] By calculation

[b] Identical to undiluted food waste/canola oil mixture

[c] Calculated using paired data

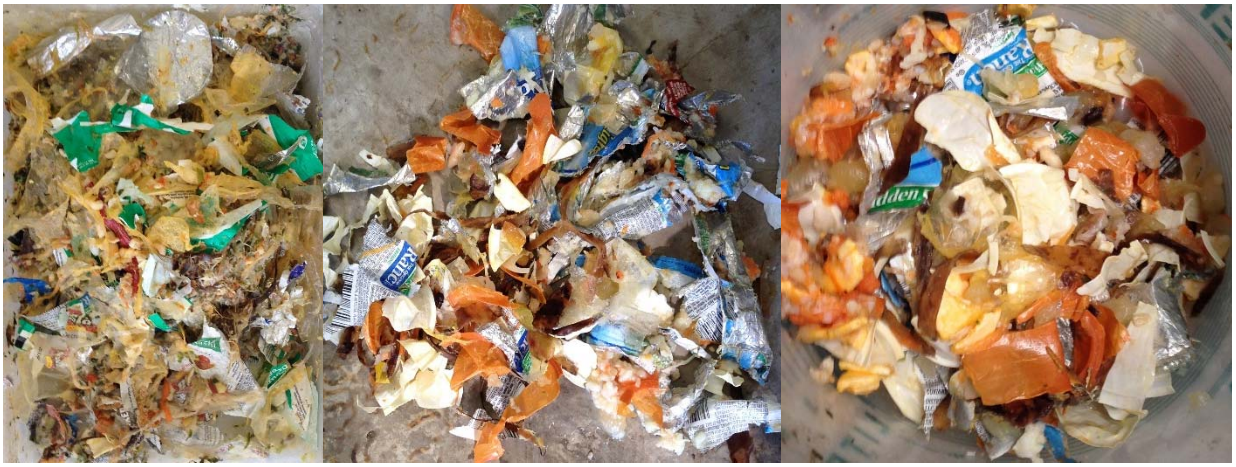


Figure 27. Photographs of typical debris removed from food waste prior to digester feeding.

The average canola oil mass fractions of the total VS added were 9.5±1.4% and 11±2.8% in Phases III and IV, respectively. **Figure 28** shows the temporal variation of this fraction in each phase. The canola oil fraction during Phase II was greater than the intended amount (i.e., 10%) and was reduced around day 30.

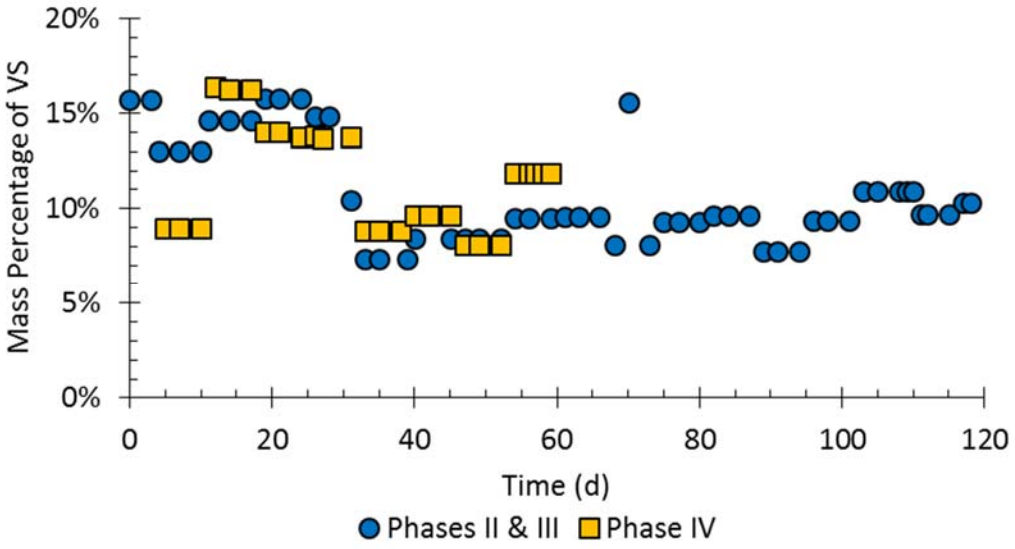


Figure 28. Canola oil VS mass percentage of the total food waste/canola oil mixture fed to the digesters in each phase.

5.6.2 Phases II and III

Hydraulic and Organics Loading

Phase II covered the period from 0 to 32 days when the organic loading rate to the digesters was gradually increased (Phase I covered equipment shakedown and results are not reported). Commensurately the HRT and SRT decreased as illustrated in **Figure 29**. The HRT and SRT were equal because the digesters were completely mixed. The period of stable operation (Phase III) was considered to start on Day 33 based on pH (see **Figure 26**). During Phase III the average SRT was 40±14 d exceeding the goal of 15 d. Thus the "stable" Phase III covered the period of 2 to 3 SRTs. Typically 3 SRTs are required prior to considering a digester at steady state. While this time period was not met, other data reported below indicate the digester conditions and performance were generally stable. Shorter SRTs were not possible because of limitations on loading rates as described below.

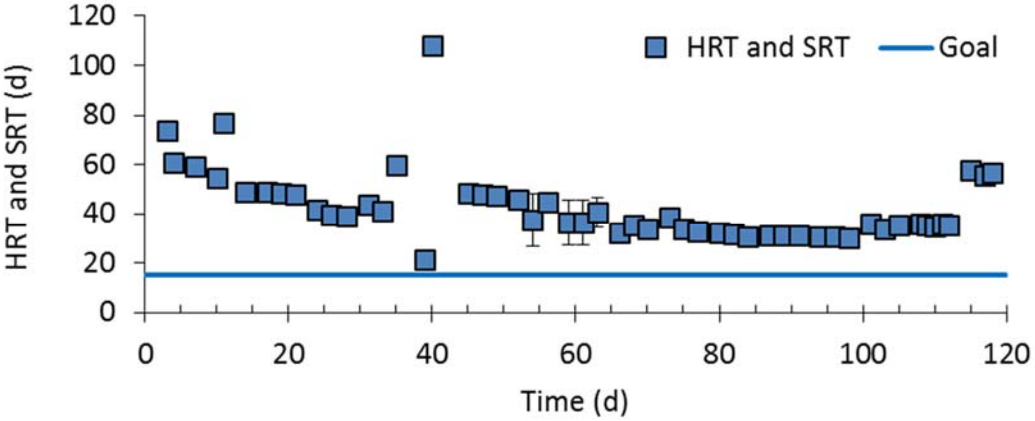


Figure 29. HRT and SRT during phases II and III. The goal is a minimum value for Class B biosolids.

Volumetric organic loading rates based on VS and COD were not met during Phase III (**Figure 30**). Loading rates were increased during Phase II (0 to 32 d). Further attempts to further increase loading rates were not attempted during Phase III because the digesters were thought to be showing indications of stress and potential failure at the time. While pH was in a physiologically suitable range (7.8±0.1, see also **Figure 26**), the digester sludge was changing from a black to brown (**Figure 31**) and the average ratio of VFA/TALK (**Figure 32**) was somewhat high (0.15±0.09 mg-acetate equivalents/mg-$CaCO_3$) though not greater than the goal of 0.2 mg-acetate equivalents/mg-$CaCO_3$ (see Appendix H, Figure 3 for trends of individual VFAs). Food particles and a sheen suggestive of undigested canola oil were observed. However, as discussed below, methane production continued indicating the digesters had not failed in spite of these observations. SELR data (**Figure 30b**) provided a possible explanation as to why the organic loading rate could not be increased further during Phase III. The SELR increased during Phase II and averaged 0.44±0.17 kg-COD kg-VSS^{-1} d^{-1} during Phase III exceeding the goal of 0.26 kg-COD kg-VSS^{-1} d^{-1}. The average SELR was greater than the goal while the volumetric COD loading rate was less than its goal because the digester VSS concentrations were low and decreasing during Phase III (**Figure 33**). The SELR is equal to the volumetric COD loading rate divided by the VSS concentration in the digester. The VSS was quite low (7300±2000 mg/L) relative to typical anaerobic digesters that operate at a VSS concentration of about 15,000 to 30,000 (Tchobanoglous et al. 2003; Water Environment Federation 2010). This low and declining VSS concentration may have limited further increases in the volumetric organic loading rate to the digesters.

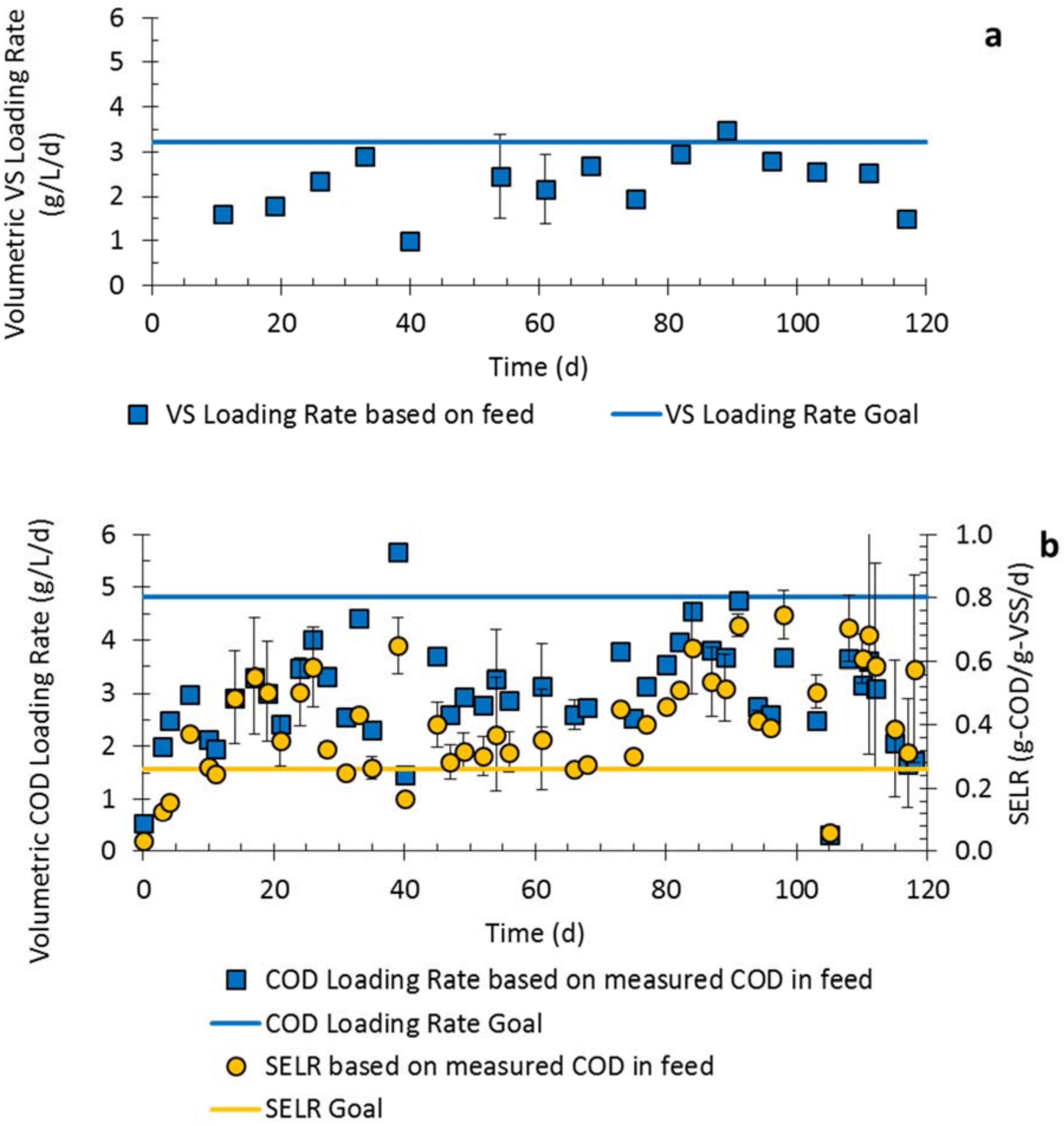
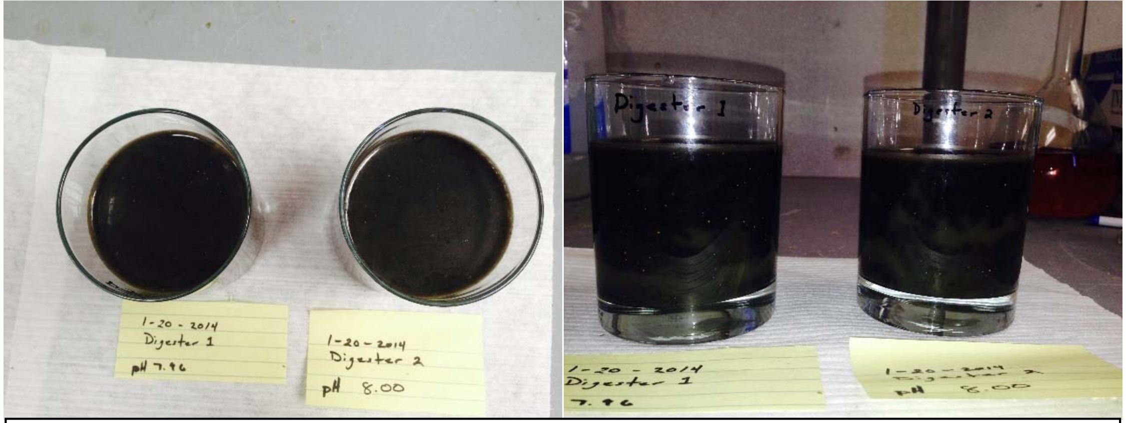
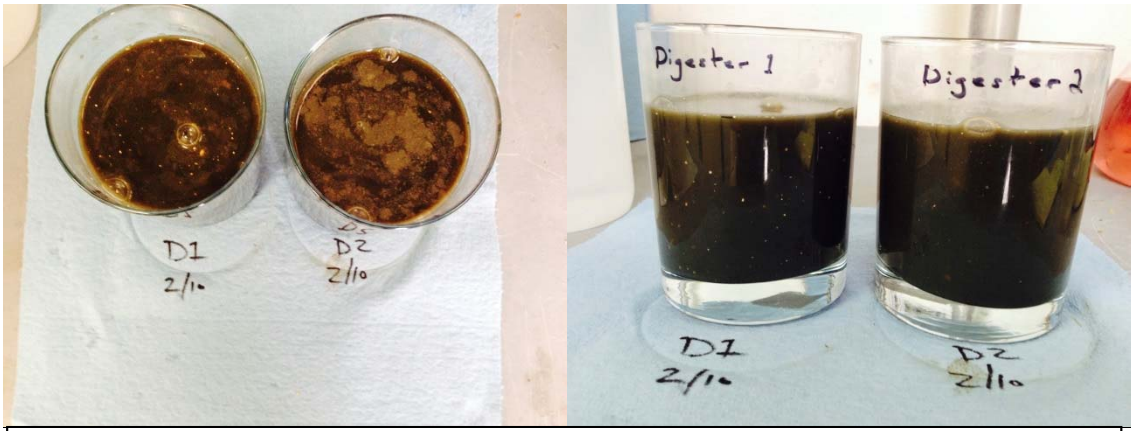


Figure 30. Volumetric VS loading rate (a), and volumetric COD and specific energy loading rates (b) compared to goals.

1/20/14 (Day 31)


1-20-2014
Digester 1
pH 7.96
1-20-2014
Digester 2
pH 8.00
Digester 1
Digester 2
1-20-2014
Digester 1
7.96
1-20-2014
Digester 2
pH 8.00

2/10/14 (Day 52)


D1
2/10
D2
2/10
Digester 1
Digester 2
D1
2/10
D2
2/10

3/11/14 (Day 81)

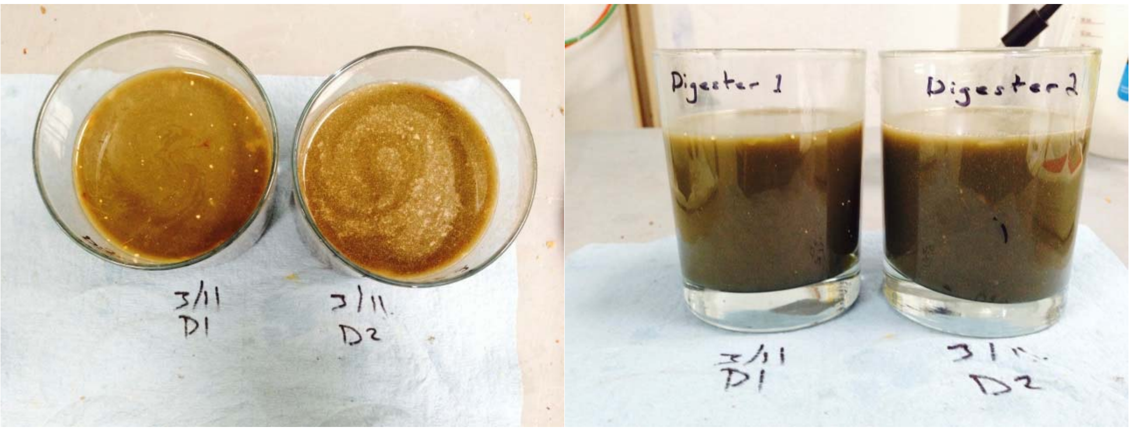

3/11
D1
3/11
D2
Digester 1
Digester 2
3/11
D1
3/11
D2

Figure 31. Photographs of digester sludge during phases II and III.

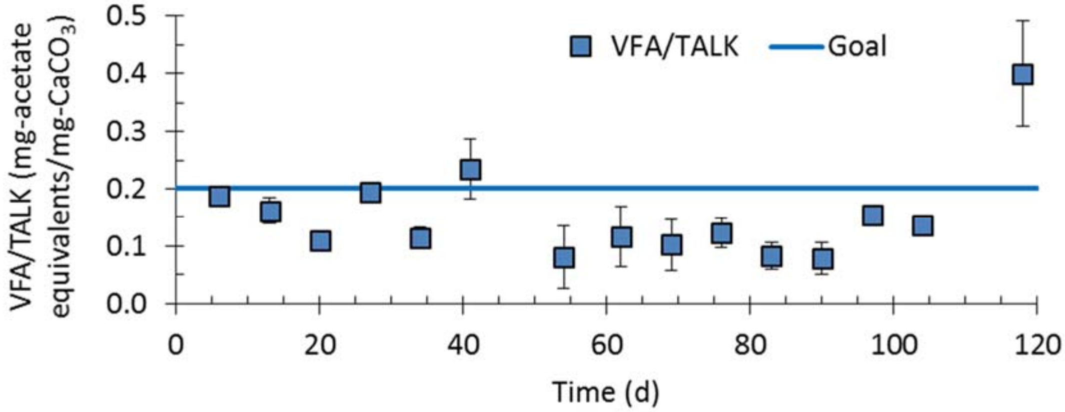


Figure 32. Ratio of VFA/TALK compared to goal during phases II and III.

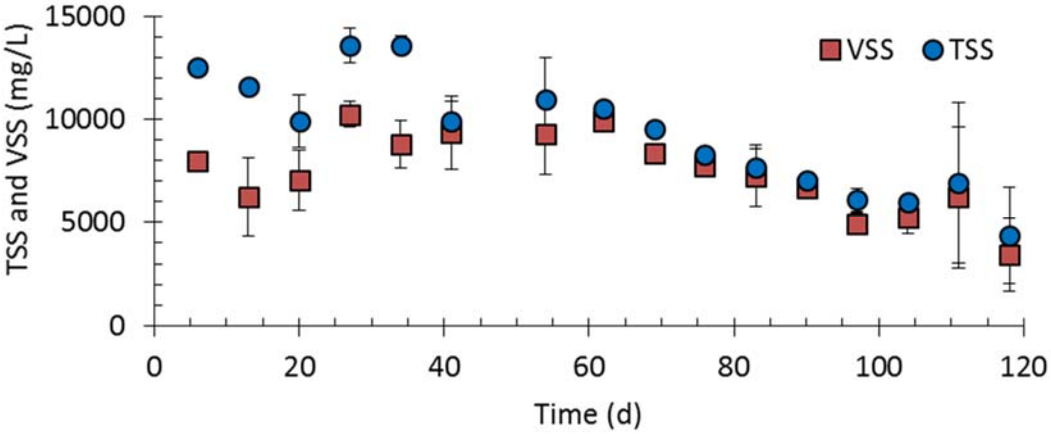


Figure 33. VSS and TSS concentration trends during phases II and III.

Methane Production

Both the biogas flow rate and the methane content in the biogas remained steady during Phase III (**Figure 34**) supporting the conclusion that the digesters were stable and not failing. Typically one of the eariest indicators of anaerobic digestion failure is a sudden drop in biogas production and a decrease in the biogas methane content. Two spikes in biogas flow rate around 10 and 20 d were artifacts attributable to digester foaming and flow meter disturbance. The foaming may have been attributable either to startup conditions or the relatively greater canola oil fraction that was added to the food waste through Day 28 (**Figure 28**). Foaming was not observed thereafter.

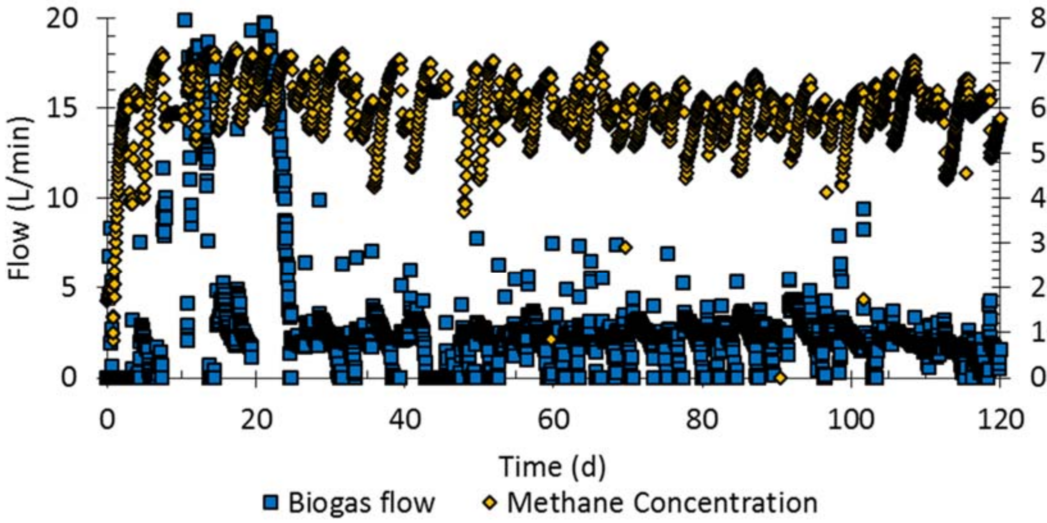


Figure 34. Biogas flow rate and methane concentration during phases II and III.

Cycling of methane concentration and biogas flow rate were attributable to cyclic feeding. **Figure 35** shows a closer look at the data over a 22-d period. Digester feeding was conducted on Monday, Wednesday, and Friday between days 90 and 106 and then daily between days 108 and 114. The mass of food waste fed to the digester on a Friday was 50% greater than that fed on a Monday or Wednesday between days 90 and 106. The reason for this different organic loading is that a Friday feed was intended to provide sufficient organics for 3 days of digestion whereas a Monday or Wednesday feed was intended to provide sufficient organics for 2 days of digestion. For the daily feeding test between days 108 and 112 the organic load was 50% of the previous weeks' Monday and Wednesday loads because the feed was intended to provide sufficient organics for one day of digestion. The Friday feed on day 112 was a normal feed with an organic load threefold greater than the previous daily MTWT feedings. Methane concentration was observed to decrease immediately following each feed and then subsequently increase. The magnitude of the decrease and increase was lowest following a daily feed (i.e., 1X organic load), greatest following a Friday feed (i.e., 3X organic load), and intermediate following a Monday or Wednesday feed between days 90 and 106 (i.e., 2X organic load). The initial decrease in methane concentration was attributed to increased CO_2 generation associated with acidogenesis. For example consider the fermentation of glucose to hydrogen, carbon dioxide, and acetate:

$$C_6H_{12}C_6 + 2H_2O \rightarrow 4H_2 + 2CO_2 + 2C_2H_4O_2 \tag{3}$$

Figure 35 illustrates the rapid incease in acetic acid following feeding on Day 103. The generated CO_2 effectively diluted the methane in the biogas. Methanogenesis was not inhibited, rather it just occurred more slowly than acidogenesis. The subsequent increase in methane concentration was due to consumption of available substrates (acetate and hydrogen) by the methanogens. ADM1 modeling of different feeding strategies (**Figure 36**) supports these observations. The modeled decrease in methane concentration was 18% following MWF feeding versus 8% for daily feeding. The observed methane concentration decreases (**Figure 35**) were 9.6±0.8% for MWF feeding (days 90 to 106) versus 5.0±0.4% for daily feeding (days 108 to 112). While the absolute values of the observed and modeled decreases are different, they illustrate the effect on relative organic loads and feeding frequency on methane concentration cycles. The ADM1 model was calibrated based on earlier laboratory bench-scale studies and was not recalibrated for the pilot-scale demonstration which may explain the differences in methane decreases. See Appendix E for additional details on ADM1 modeling.

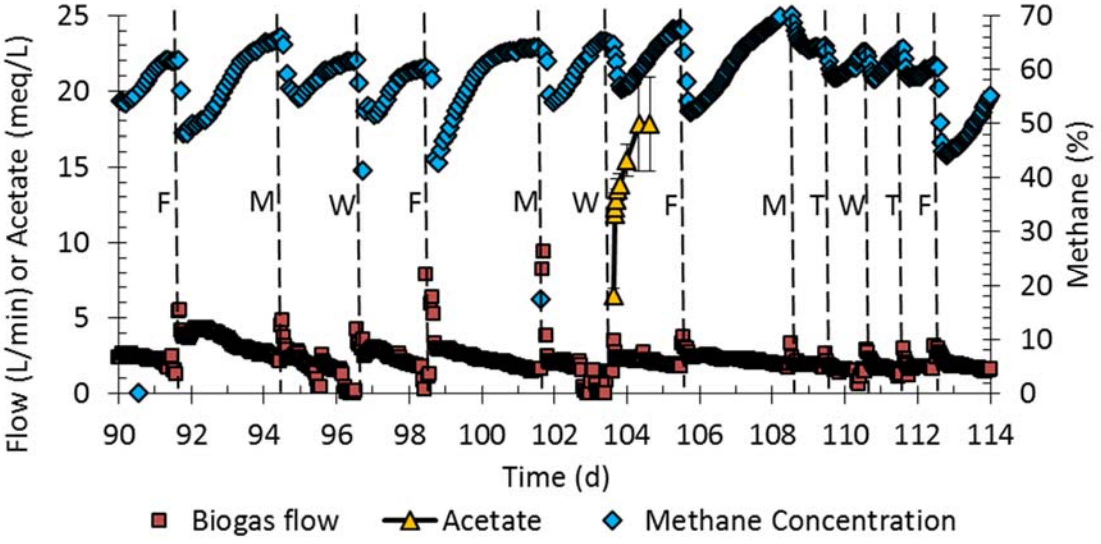


Figure 35. Transient flow rates, methane concentrations, and acetate concentrations in response to feeding (vertical dashed lines) on Monday (M), Wednesday (W), and Friday (F) or daily (MTWTF).

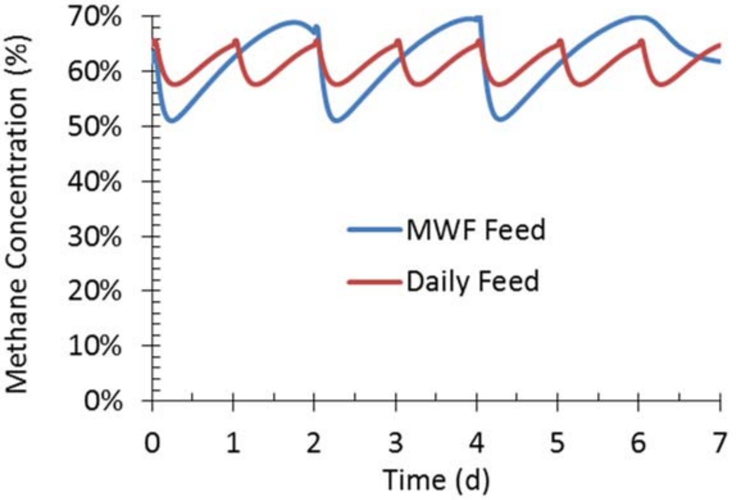


Figure 36. ADM1 model results showing transient methane concentrations in response to daily feeding and MWF feeding.

While methane production was consistent throughout Phase III (**Figure 34**), the production rate of 0.82±0.22 L/L/d was less goal of 2 L/L/d (**Figure 37**). The initially high rate on day 6 was associated with the digester seed. It is likely that methane production was less than the goal because of the lower organic loading rate (COD and VS loading rates) as discussed earlier (**Figure 30**). Methane yields based on loaded COD and VS were 270±75 L/kg-COD and 360±70 L/kg-VS and exceeded the goals of 190 L/kg-COD and 310 L/kg-VS (**Figure 38**). These support the conclusion that low organic loading rates to the digesters rather than inhibition limited the volumetric methane production rate.

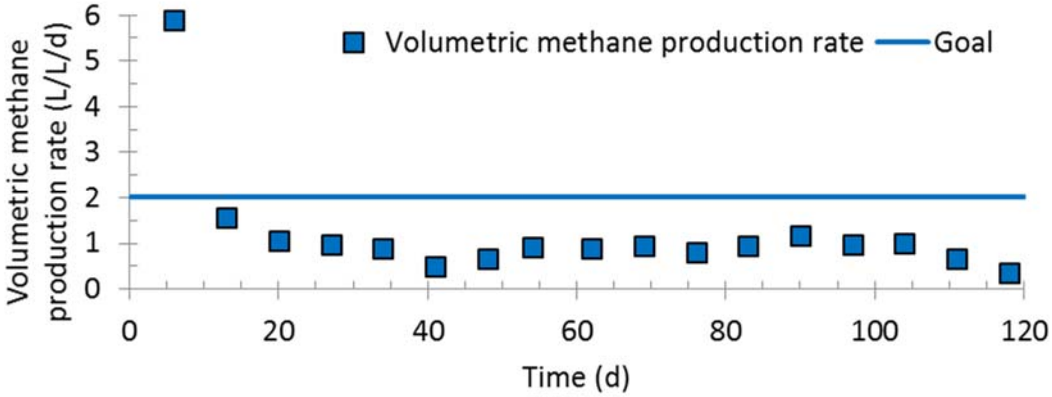


Figure 37. Volumetric methane production rate during phases II and III compared to goal.

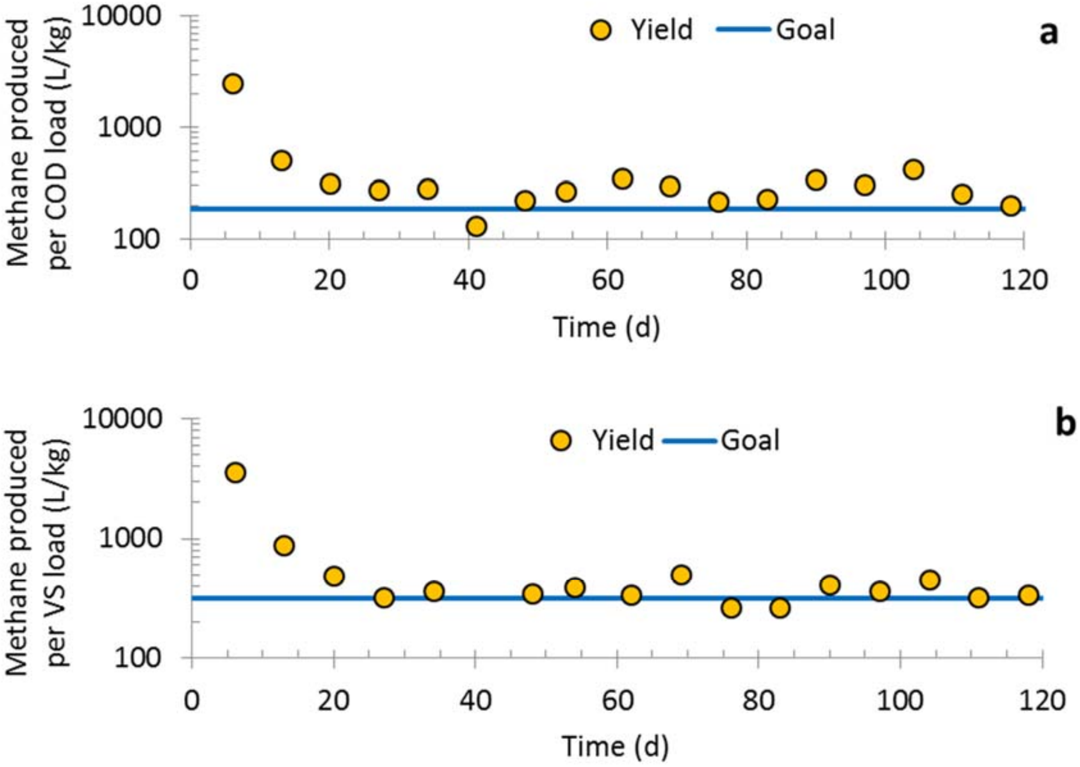


Figure 38. Methane yield per unit loaded COD (a) and VS (b) during phases II and III compared to goals.

A common metric used at WWTP is the methane production per unit of VS destroyed. Wastewater treatment plant anaerobic digesters treating wastewater solids typically produce about 7.5 to 10 ft^3 of methane per lb of VS destroyed (470 to 620 L/kg) (Tchobanoglous et al. 2003; Water Environment Federation 2010). Digester VS measurements were not initiated until day 76 thus limited data from Phase III are available. The data show the methane yield based on VSD was increasing over time (**Figure 39**) and averaged 440±140 L/kg (7.0±2.3 ft^3/lb) with a maximum value of 640 L/kg (10 ft^3/lb). Thus the methane production per unit VSD was within the typical range further suggesting a lack of inhibition.

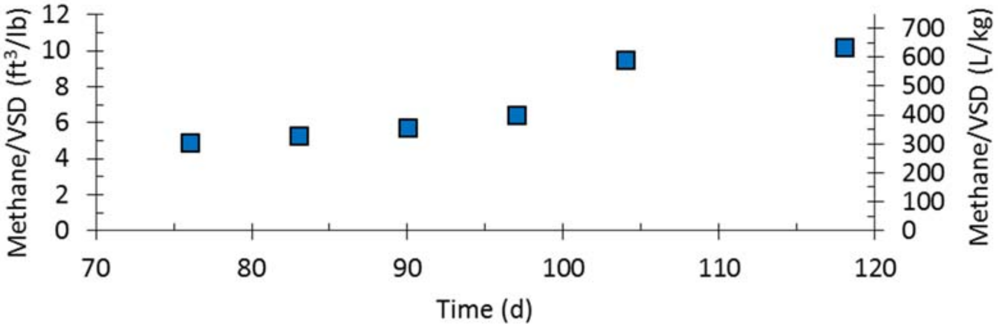


Figure 39. Methane production per unit volatile solids destroyed during phase III.

Energy Conversion

Food waste energy conversion to methane was assessed by calculating the the total COD of the food waste/canola oil mixture fed to the digesters and the methane-COD (377 mL-CH_4/g-COD at standard conditions of 21.4 °C [70 °F] for the biogas flow meter) generated each week (**Figure 40**). No discernable trends were observed indicating digester stability and the average energy conversion was 73±19% which was about the same as the goal of 70%. This energy conversion did not consider parasitic demands (e.g., heating, pumping, and mixing) nor did is consider conversion of methane to electrical power. These aspects are discussed in Sections 6 and 7.

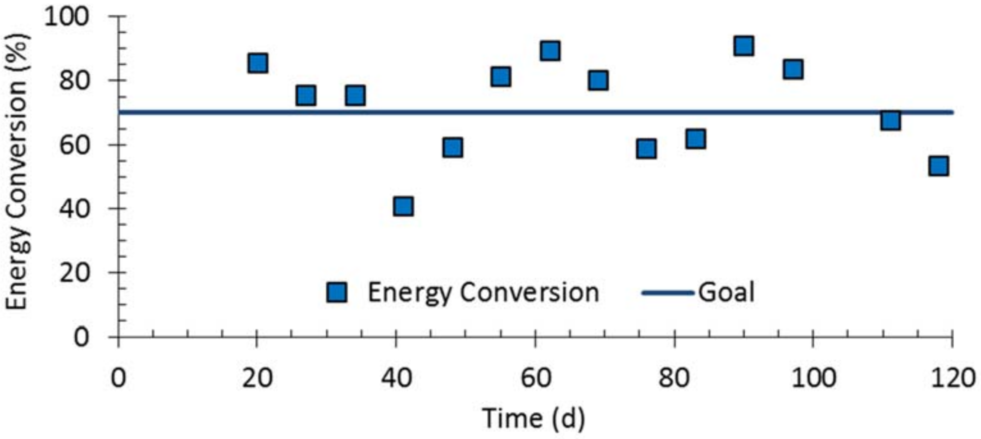


Figure 40. Energy conversion based on COD loading and methane production during phases II and III.

Energy conversion was also evaluated on a specific rate basis. The specific methane production rate was compared to the SELR to assess conversion of food waste energy (i.e., in terms of COD) to methane (**Figure 41**). The total specific methane production rate was less than the SELR (**Figure 41a**) and the slope of the correlation (**Figure 41a** inset) was 71% (intercept forced to 0, $r^2 = 0.41$) which is consistent with the observed energy conversion of 73±19%. Laboratory bench-scale BMP tests with USAFA food waste demonstrated that specific methane production per unit COD loaded was correlated to the protein+fat content (see Section 5.2 and Appendix D). When the SELR was based only on protein+fat (**Figure 41b**) the energy conversion was 100% (intercept forced to 0, $r^2=0.50$). Additionally the temporal variations in the specific methane production rate tracked the protein+fat SELR. These data suggest that methane production from the food waste/canola oil mixture was controlled by the fat+protein content. Additionally, these data indicate that measurement of fat+protein content is a potentially useful predictor of methane yield and production rate. Carbohydrates were apparently not digested as well as protein and fat. One hypothesis is that food waste carbohydrates include cellulosic materials that are relatively recalcitrant to biodegradation compared to protein and fat.

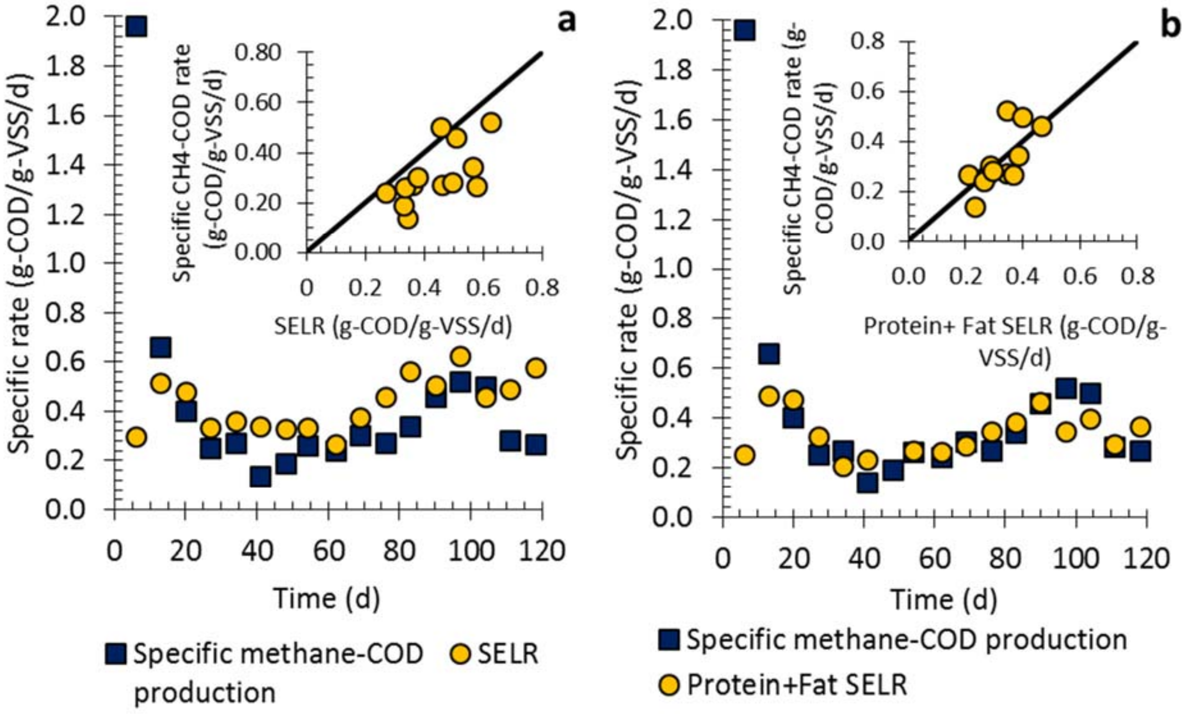


Figure 41. Specific methane-COD production rate compared to total SELR (a) and SELR based on protein+fat content (b). High methane production on Day 6 is attributable to the digester seed. Insets show data from phase III (≥ 33 d) and line of unity.

The energy efficiency of 73±19% calculated above does not take into account parasitic energy losses incurred during conversion of biogas energy into usable power. Conversion efficiencies were calculated to assess the actual performance of the pilot digester and theoretical conversion of biogas to compressed biomethane capable of being used for vehicle fueling. Parasitic losses and net energy performance criteria were calculated for a nominally sized digester (i.e., 1 million gallons) which would be capable of handling 100 tons/day (95,000 kg/d) of food waste based on the above results. Typical pumping flow rates, pump heads, and gas scrubbing compressor energies were estimated or assumed. In summary, the following estimates and assumptions were used to assess parasitic energy demands:

- All motor efficiencies were assumed to be premium, high efficiency motors at 93% efficiency.
- Digester mixing energy: 40-minute tank turnover time, with low head draft tube mixer pump at 0.1 ft of operating head and no static head. Draft tube mixer efficiencies were assumed to be 80%.
- Sludge recirculation heating: 500 gpm pumps with 40 ft of head to pump through the heat exchanger, no static head. Pump efficiency was assumed to be 65%.
- Hot water heating pump: 500 gpm with 25-ft head. Pump efficiencies were assumed to be 80%.
- Digester feed pumps: Positive displacement pumps, providing 22-day SRT, pump discharge pressure of 40 psig. Positive displacement pump efficiency of 50%.
- Gravity discharge from digester. No electrical energy required for plant boilers and plant hot water loop as they are components of larger system.
- Assumed H_2S and CO_2 removal with a water scrubber. No additional energy required for compression as scrubbers operate at 8 to 10 bar, which is less than compressed natural gas pressures.
- Water scrubber water pump assumed at 50 gpm, 6.5 bar pressure.
- Boiler combustion efficiency of 94% as gas is scrubbed of H_2S and CO_2.
- Compressed natural gas pressure of 3600 psig, with isothermal compressors. Isothermal compressors assumed to be 55% efficient and require 25 hp for compressor cooling water pumping and radiator water cooling.

The energy efficiency accounting for parasitic demands was calculated to be 63% which is similar to the goal of ≥50%. Calculations are in included in Appendix L.

Ammonia

Total ammonia concentrations in the digesters during Phase III were high (2900±420 mg-N/L) as were free ammonia concentrations (180±46 mg-N/L). The pH increased because of the alkalinity contributed by the increasing ammonia during Phase II and then stabilized (**Figure 42**). Several studies have suggested that free ammonia is inhibitory at concentrations about 150 mg/L (Ariunbaatar et al. 2015; Braun et al. 1981; McCarty and McKinney 1961). However others have suggested that digester consortia can acclimate to higher concentrations (Yenigun and Demirul 2013). Stable methanogenesis was observed in the digesters between days 33 and 100 at the observed free ammonia concentrations of 160±28 mg-N/L (**Figure 43**). Prior to this time (i.e., during Phase II) acetic acid concentrations increased along with free ammonia; the ratio of VFA/TALK remained relatively contant and the volumetric methane-COD production rate decreased. Phase II from 0 to 33 d was considered to be a period of acclimation. The period from 33 to 100 d was stable based on constant VFA/TALK and contant volumetric methane-COD production rate. The acetic acid concentration reached a maximum of 1600 mg/L on Day 41 and then decreased further suggesting acclimation to the high free ammonia concentration. While stable, the acetic acid concentration was 770±360 mg/L which is considered quite high. Formic acid increased in parallel to acetic acid reaching a maximum concentration of 180 mg/L; clearly discernable trends of other VFAs were not observed (Appendix H, Figure 3). VFA/TALK was 0.12±0.05 mg-acetate equivalents/mg-$CaCO_3$ during the same period. These data suggest stable methanogenesis in the presence of high free ammonia is possible and is associated with atypically high VFA concentrations.

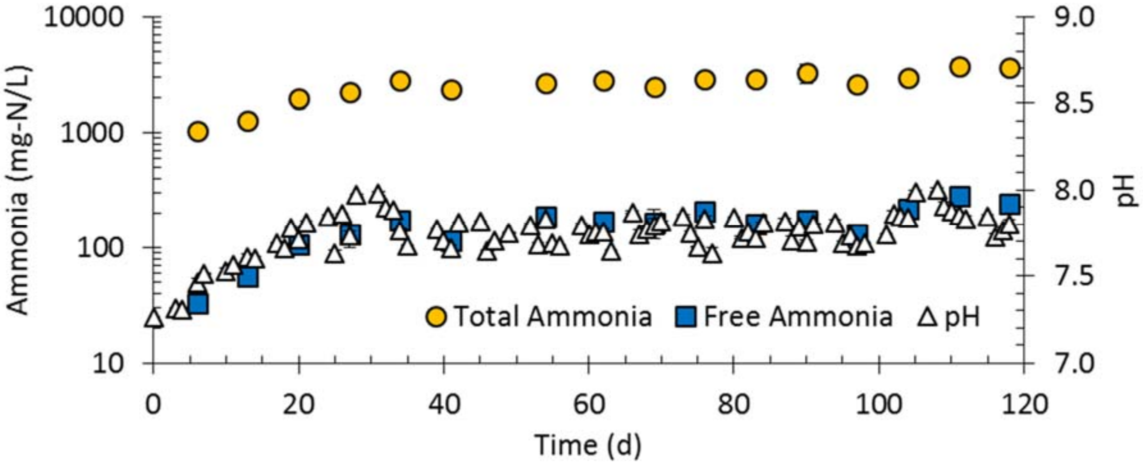


Figure 42. pH and total/free ammonia trends in phases II and III.

After Day 100 a sudden increase in free ammonia was observed reaching a maximum of 280 mg-N/L. This increase was associated with a decreasing trend in methane production rate and a slightly lagging increase in acetic acid and VFA/TALK. The sudden increase in free ammonia may have been attributable to increased protein content in the food waste (Appendix H, Figure 2). The decreasing trend in methane production rate was also associated with a decreased organic loading rate (**Figure 30**) and decreased VSS (**Figure 33**). This transient period post day 100 may have been associated with digester failure or acclimation to a new stable operating state. Neither can be concluded based on the available data. **Figure 44** illustrates that ratio of methane-COD produced to protein+fat COD loaded did not decrease in response to increasing free ammonia. These data support a lack of ammonia inhibition with a caveat – the data at the higher free ammonia concentrations were measured under transient conditions (**Figure 44**). Thus definitive conclusions regarding ammonia inhibition at concentrations greater than 180±46 mg-N/L cannot be made based on the available data.

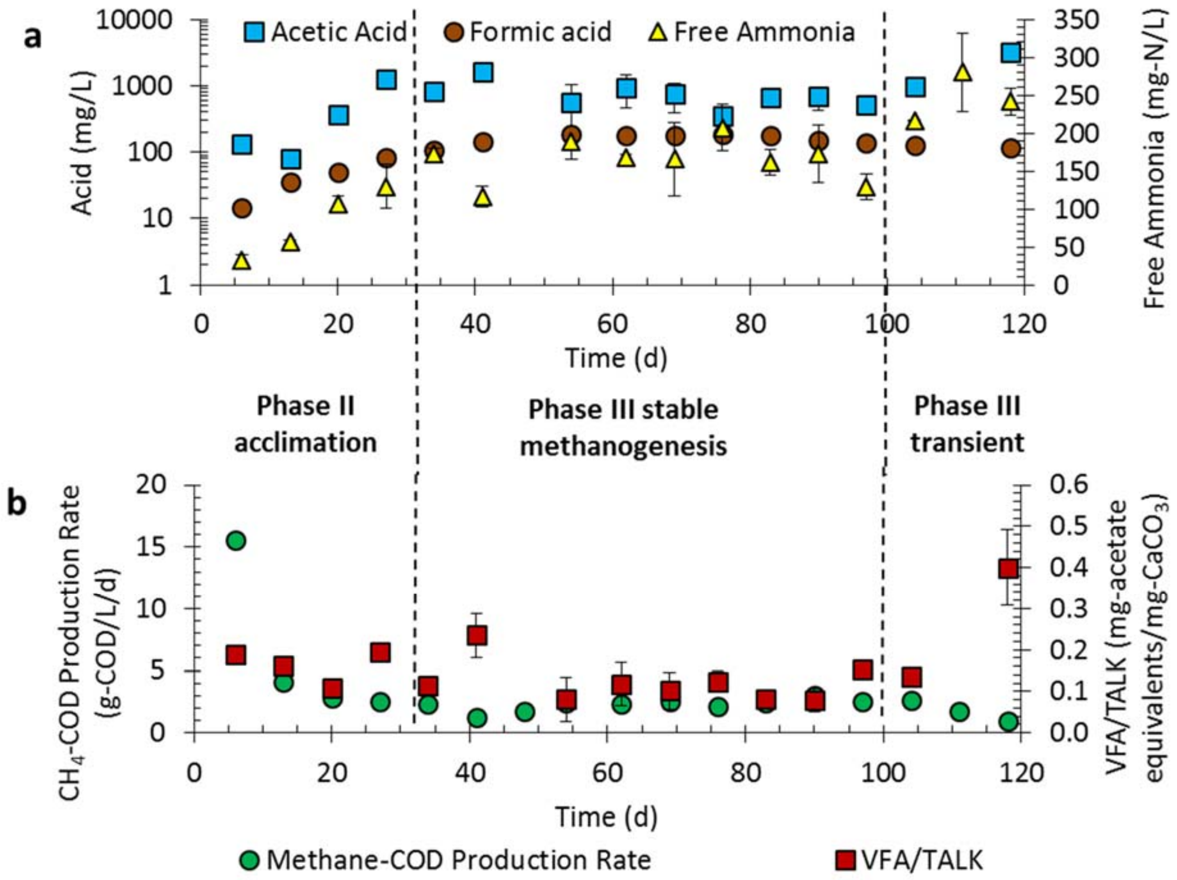


Figure 43. Relationships among free ammonia and acetic acid (a) and specific methane production rate and ratio of VFA/TALK (b).

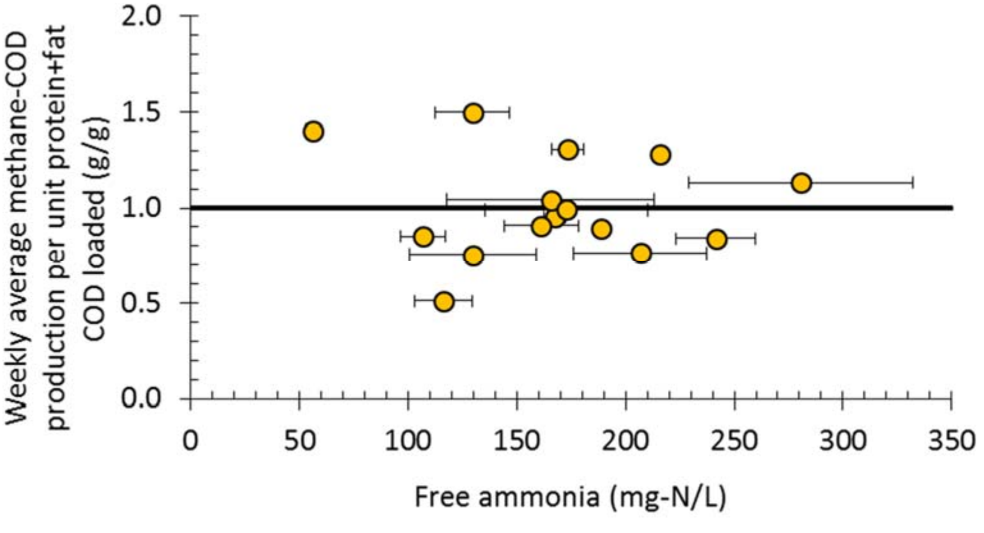


Figure 44. Methane-COD production to protein+fat COD ratio as a function of free ammonia concentration during phases II and III. The solid line is the line of unity.

Solids Destruction

High percentages of TS and VS destruction were observed (**Figure 45**). The average TSD and VSD were 78±3.4% and 81±3.0%, respectively. The observed TSD and VSD were greater than ~55% typically observed for waste activated sludge (Water Environment Federation 2010; Tchobanoglous et al. 2003) and similar to values previous reported for food waste (Gray (Gabb) 2008). The TSD and VSD results were greater than the goals of 60% and 38% respectively. Volatile suspended solids destruction (VSSD) was calculated as an estimate of the reduction of food waste solids to digester sludge that may require subsequent disposal. The VSSD result of 92±2.7% indicates high food waste waste reduction can be achieved by anaerobic digestion.

TSD and VSD were not significantly different from the feed fat+protein content (**Figure 46**; p = 0.42 and 0.19, respectively based on a two-tailed t-test with equal variance). TSD and VSD were significantly different different from the feed VS/TS ratio ($p < 0.001$ in both cases bases on a two-tailed t-test with equal variance). These data suggest that the solids destruction was related to the protein+fat content of the food waste/canola oil mixture and the carbohydrate fraction may have been relatively recalcitrant to anaerobic digestion even at long SRT (40±14 d). Nevertheless, the decreasing trend of TSS and VSS (**Figure 33**) reported above was in part attributable to high solids destruction. For example, the average food waste/canola oil VS was 28±2.7% (**Table 9**) and the final VSS on day 118 was 3500±1800 mg/L (**Figure 33**) indicative of 99% VSSD. This value is greater than the average VSSD of 92±2.7% and slightly greater than the final measured VSSD 96±2.1%. A VSSD of 99% would suggest an effective growth yield (i.e., taking into account cell death) of 1% which is low compared to typical values of 3 to 10% (Water Environment Federation 2010; Tchobanoglous et al. 2003). Therefore additional factors such as increased free ammonia after day 100 (**Figure 43**) may have contributed to decreasing VSS trend in the digester.

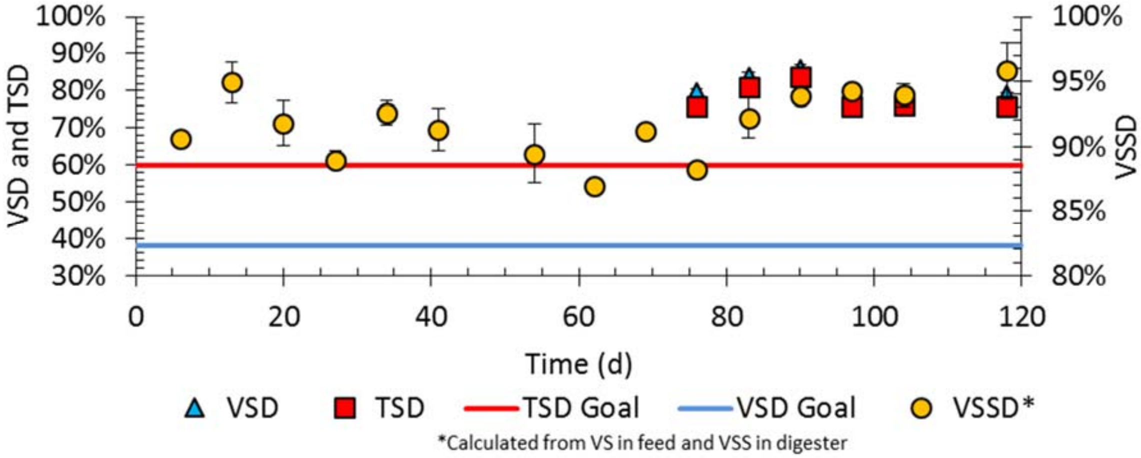


Figure 45. Volatile and total solids destruction compared to goals. Volatile suspended solids destruction (VSSD) is also shown which was calculated from VSS in the digestate and VS in the digester feed.

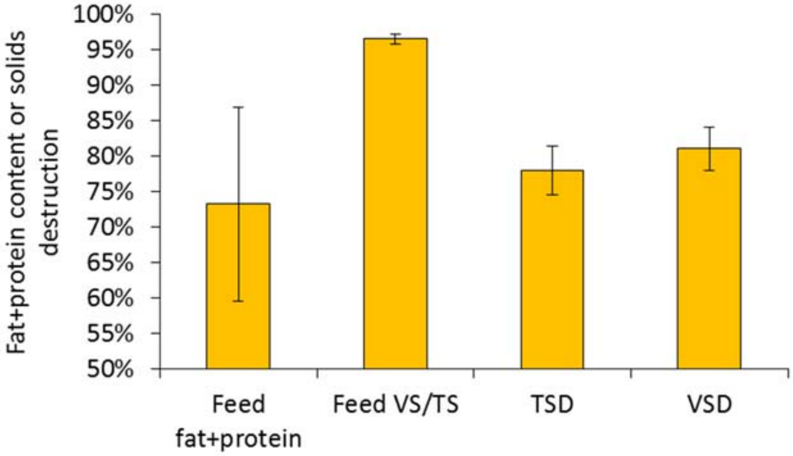


Figure 46. Comparison of digester feed characteritics to observed average total and volatile solids destruction.

ADM1 Modeling Summary

ADM1 modeling was conducted to further explore observed trend in VSS. Modeling was conducted to simulate: 1) washout of inerts introduced with the seed sludge; 2) digestion of VS introduced with the seed sludge; and digestion of food waste/canola oil fed to the digesters. Modeling assumptions, parameters, and supplementary results are presented in Appendix M. **Figure 47** shows model results for the different VSS fractions. The initial VSS of 8 g/L is equal to the initial measured VSS in the digester. Inerts from the digester seed were modeled to washout of the well mixed digester at a rate commensurate with the HRT. The amount of inerts being introduced to the digester with the food waste/canola oil were assumed to be minimal (1%) based on the high VS/TS of the food waste/canola oil mixture. The undigested solids were observed to remain low consistent with the high digestibility of the food waste/canola oil. Microbial growth (i.e., biomass) increased through Phase II (Day 32) and then remained relatively constant during Phase III. The total VSS was modeled to decrease from 8 g/L to about 6 g/L by the end of Phase III. **Figure 48** compares these results to the observed VSS in the replicate digesters. The model appears to have underestimated VSS between Days 33 and 72. Thereafter the model underestimated the observed decline in VSS although considerable scatter was evident. Therefore the model was only partially successful in explaining the observed VSS decline near the end of Phase III. The apparent decline of VSS after ~100 d is unexplained and have been associated with a reacclimation period as described above (**Figure 43**).

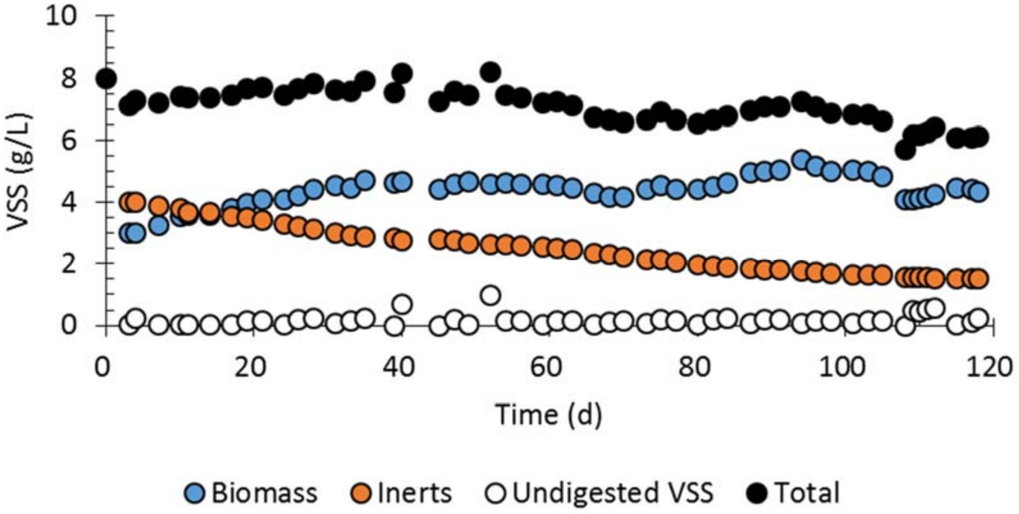


Figure 47. ADM1 model simulation of VSS fractions during phases II and III.

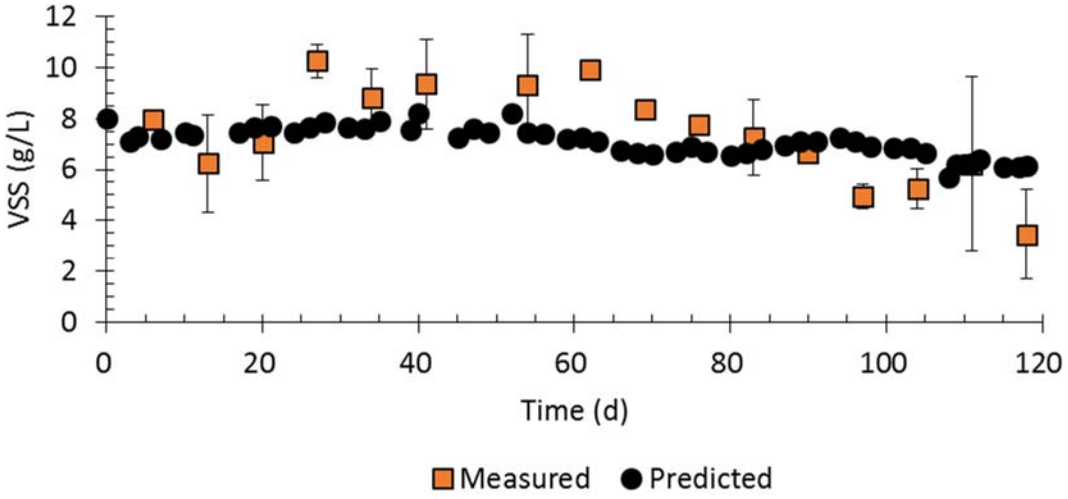


Figure 48. Comparison of ADM1 model results to observed digester VSS.

5.6.3 Phase IV

At the conclusion of Phase III the pilot digesters were drained, the feeding process was modified to eliminate food waste/canola oil dilution with water, and one digester was reseeded to initiate Phase IV. Digestate was used to mix and dilute the food waste/canola oil instead of potable water. Phase IV did not have a startup or acclimation step analogous to Phase II. The SRT and HRT were longer than in Phase III (i.e., 130±91 d versus 40±14 d) because of the more concentrated food waste/canola oil mixture digester feed. The duration of Phase IV was less than one SRT and the digester was not considered to have reached steady state.

The volumetric VS and COD loading rates and the SELR are presented in **Figure 49**. The loading rates were kept relatively constant for the first 20-30 days and the were increased in excess of the goals. The COD and VS loading rates did not parallel each other as well as during Phases II and III (**Figure 30**). The reason may have been challenges with diluting and measuring the COD of the undiluted food waste. Nevertheless, the general trends of organic loading increases through day ~40 followed by decreases were similar. The modified feeding strategy resulted in the volumetric VS and COD loading rates (2.9±0.8 g-VS/L/d [goal = 3.2] and 5.3±1.8 g-COD/L/d [goal = 4.8]) possibly being met during the last 20 days of Phase IV considering data variability. The Phase IV SELR (was similar in Phase IV (0.47±0.30 g-COD/g-VSS/d) to that in Phase III (0.44±0.17 g-COD/g-VSS/d).

The pH transiently decreased and the VFA/TALK ratio transiently increased during the first 10 days of operation (**Figure 50**). Stable operation was observed for the remainder of Phase IV though a second transient pH decrease was observed beginning ~40 d. The organic loading rate was decreased in response to this second pH decrease. pH averaged 7.6±0.1 and remained within the goal of 6.8 to 7.8. VFA/TALK was 0.12±0.09 g-acetate equivalents/g-$CaCO_3$ and less than the goal of 0.20. Biogas flow rates gradually increased and methane concentration remained generally constant (61±6.6%) during Phase IV (**Figure 51**). The methane composition was similar to that for Phase III (59±4.6%). These data suggest the digester was relatively stable during its relatively short period of operation. Thus the modified feeding strategy in Phase IV did not have adverse effects on digester stability.

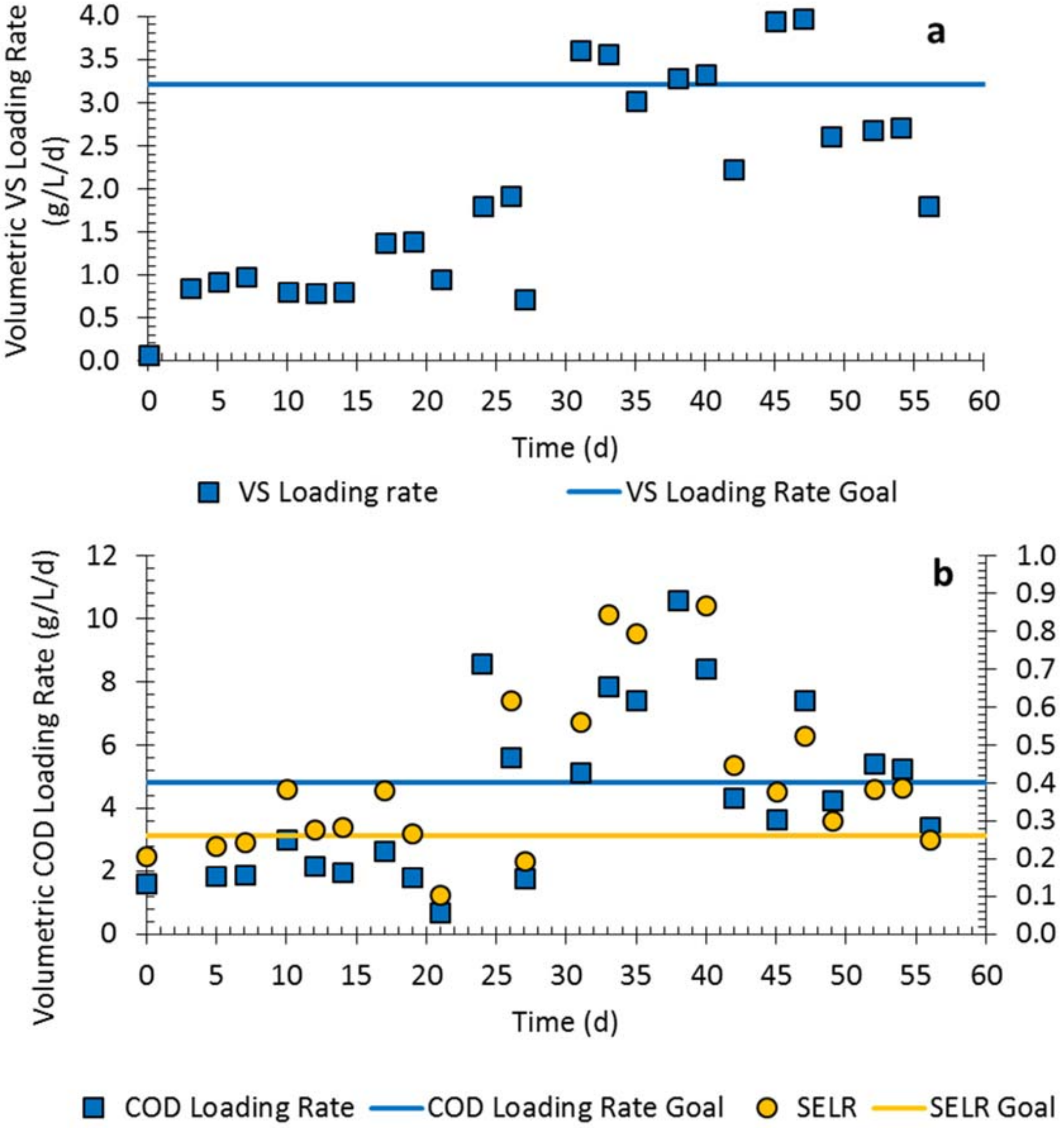


Figure 49. Phase IV volumetric VS (a) and COD loading rates (b) and SELR (b) compared to goals.

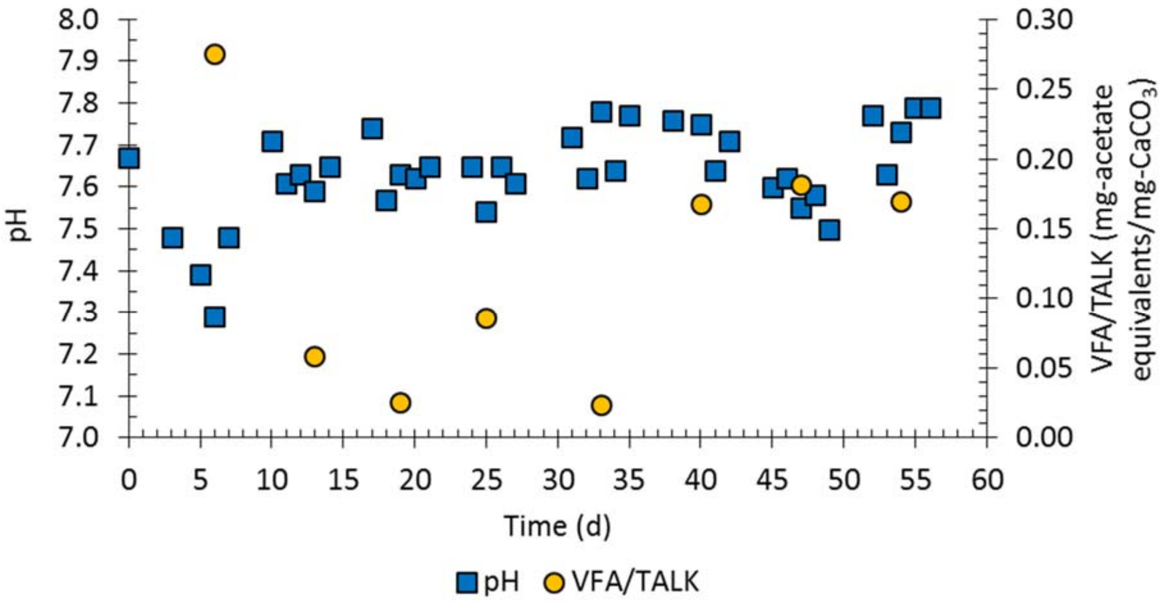


Figure 50. Phase IV trends of pH and VFA/TALK.

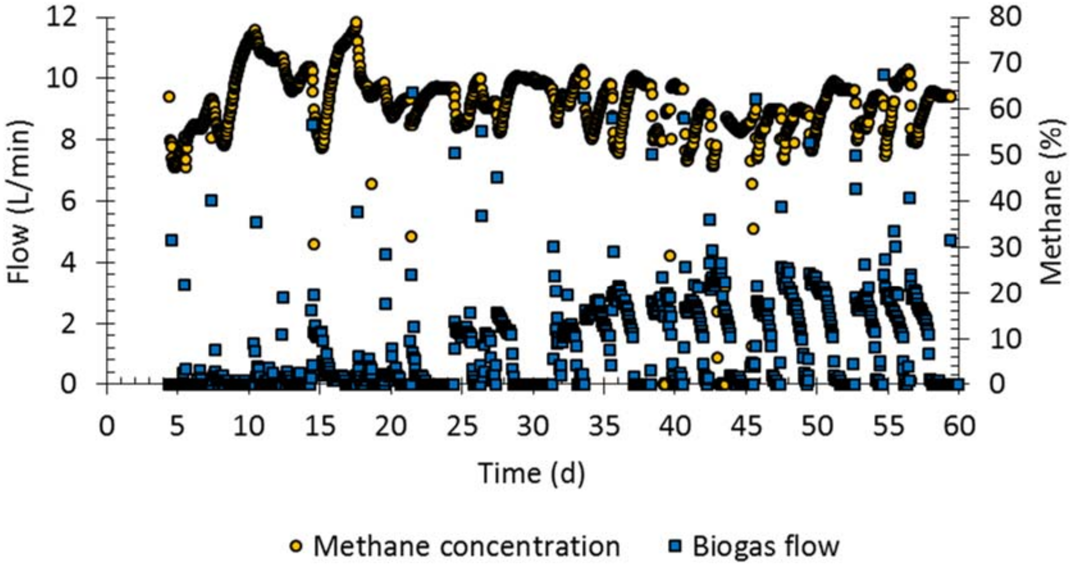


Figure 51. Phase IV trends of biogas flow and methane content.

The modified feeding strategy clearly had the desired effect of increasing TSS and VSS over time (**Figure 52**) in contrast to the decreasing trend observed during Phase III (**Figure 33**). The increased VSS presumably was associated with a greater and more robust microbial population that allowed the volumetric methane production rate goal of 2 L/L/d to be achieved at the end of

Phase IV (**Figure 52**). Digester operation was stopped at this time and thus stability of this methane production rate could not be determined. Nevertheless a clear increasing trend was observed demonstrating the value of the concentrated food waste feeding strategy. The Phase IV methane yields based on VS and COD loading were 490±140 L/kg-VS (compared to the goal of 310 L/kg and the Phase III result of 360±70 L/kg) and 230±150 L/kg-COD (compared to the goal of 190 L/kg and the Phase III result of 270±75 L/kg). Energy conversion (not including parasitic energy demands) increased over time (**Figure 53**) and averaged 62±40%. Methane yields also increased over time (**Figure 54**).

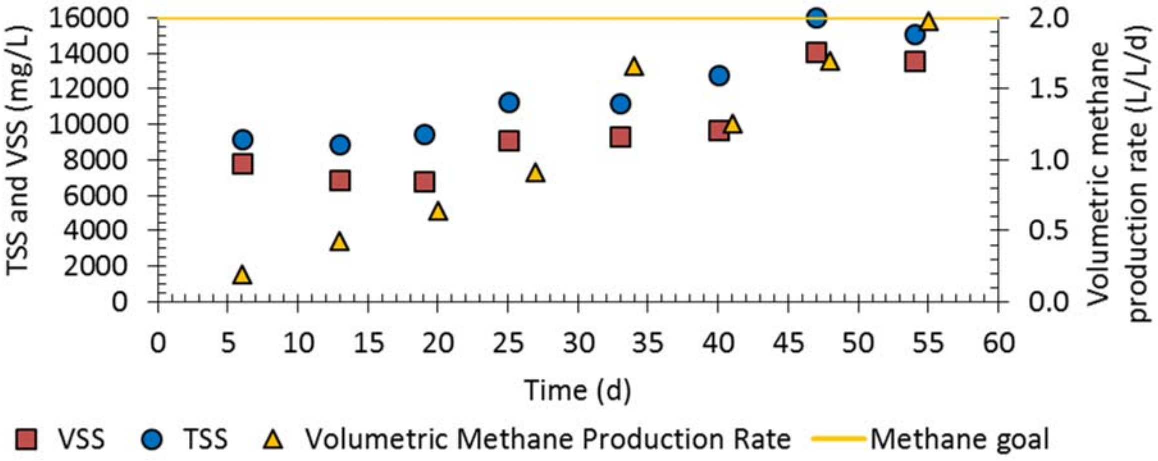


Figure 52. Phase IV trends of solids and volumetric methane production rate compared to goal.

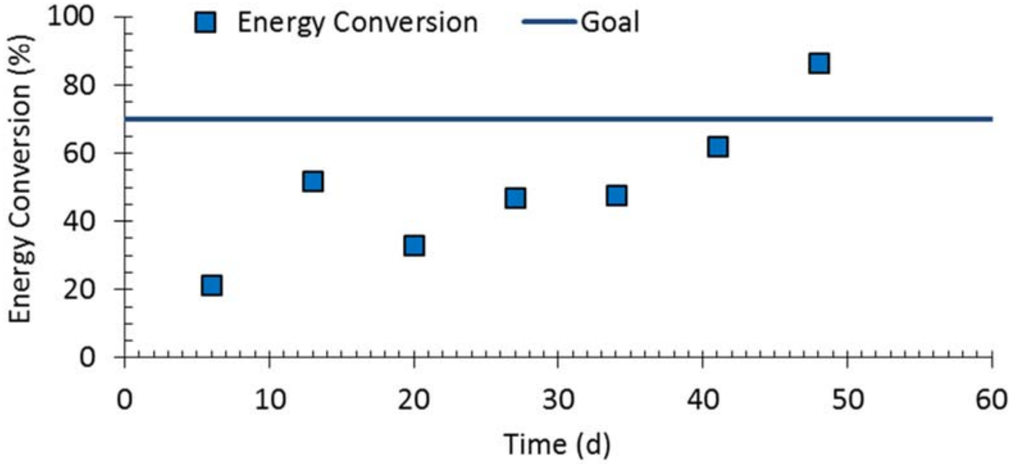


Figure 53. Phase IV energy conversion.

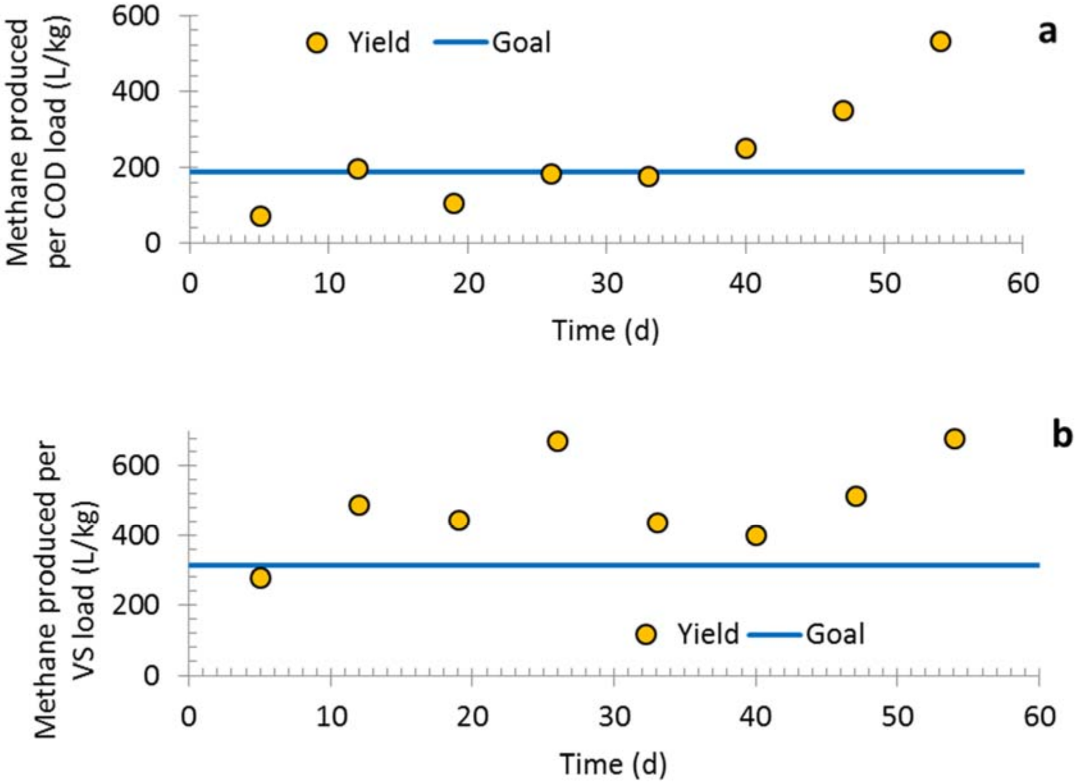


Figure 54. Methane yield per unit loaded COD (a) and VS (b) during Phase IV compared to goals.

Ammonia

Total and free ammonia increased during Phase IV though the maximum concentrations were not as great as in Phase III (**Figure 55**). The maximum free ammonia concentration in Phase IV awas 170 mg-N/L compared to 280 mg-N/L in Phase III. An initially high acetic acid concentration was observed on day 6 of Phase IV which then decreased. It is uncertain whether this high concentration was associated with the digester seed or attributable to the initial feeding of food waste/canola oil and the observed pH and VFA/TALK (**Figure 50**). Thereafter acetic acid concentration may have increased but considerable variability was observed. Average acetic acid concentration during the stable Phase III period (from day 33 to 100) was 770±360 mg/L compared to 250±170 mg/L in Phase IV excluding the initial datum (370±370 mg/L including the initial datum). The average free ammonia concentrations for the same periods were 160±28 mg-N/L for Phase III and 110±14 mg-N/L for Phase IV. Formic acid concentration consistently increased during Phase IV (**Figure 55**) just as in Phase III (Appendix H, Figure 3). No clear evidence of inhibition was observed during Phase IV. The data support the conclusions from Phase III that a free ammonia concentration of 180 mg-N/L was not inhibitory and the food waste/canola oil digestion was associated with elevated VFA concentrations.

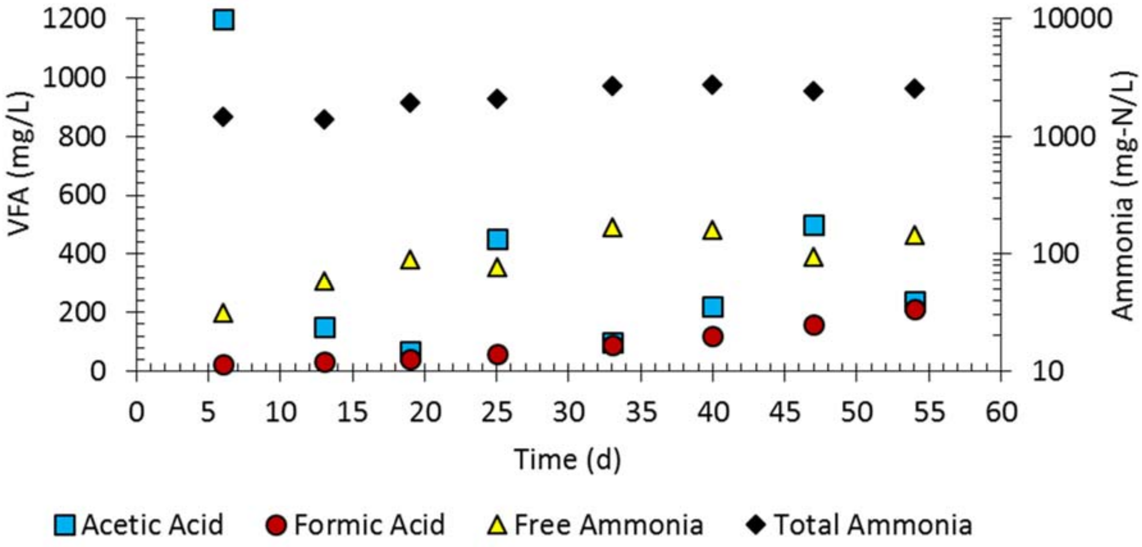


Figure 55. Phase IV trends of acetic and formic acids and free ammonia.

Residuals

The digestates in Phase III and IV were analyzed for various parameters that are related to potential reuse (e.g., as fertilizer or compost amendment) and/or disposal. **Table 10** summarizes the results of testing. The results reported for Phase IV are for single grab sample collected on Day 54 of Phase IV. In addition, Dr. Matt Higgins of Bucknell University conducted dewatering tests on a sludge sample at the end of Phase IV. The sludge was not easily dewatered and the resultant cake solids were 9.5%. The poor dewaterability was attributed to the high ratio of monovalent cations (e.g., ammonium) to divalent cations (e.g., calcium) (see Appendix N).

The follow general conclusions can be made regarding digestate quality:

- COD concentration of the digestate was high in part because of the high VFA concentrations. The VFA concentrations also resulted in the digestate having a strong odor.
- TSS and VSS concentrations were moderate and would likely be greater with prolonged operation at high solids loading in the feed.
- Dewatering the sludge was challenging.
- Ammonia was high indicating good potential as a nutrient source.

- Metals were less than the RCRA toxicity characteristic for designating hazardous waste. However, this regulatory criterion is not necessarily applicable to this sludge if it is regulated under the Clean Water Act. Certain metals (i.e., Co, Mo, Ni, and Se) were present because they were added to the food waste as nutrients. Others may have originated either from the digester seed or the food waste.

Table 10. Digestate analysis results.

Analyte	Units	Result	Regulatory Limit[a]
Total COD	mg/L	30,000	NA
TSS	mg/L	15,000	NA
VSS	mg/L	14,000	NA
Total ammonia	mg-N/L	2,500	NA
Total alkalinity	mg-$CaCO_3$/L	12,000	NA
pH		7.73	NA
HPC	CFU/mL	6.6E+07	NA
Fecal coliforms	MPN/100 mL	4.9E+04	NA
Sulfide	mg/L	71	NA
Arsenic	µg/L	< 100	5,000
Barium	µg/L	25,700	100,000
Cadmium	µg/L	15	1,000
Chromium	µg/L	146	5,000
Cobalt	µg/L	392	NA
Copper	µg/L	3,660	NA
Iron	µg/L	42,300	NA
Lead	µg/L	< 100	5,000
Manganese	µg/L	1,250	NA
Mercury	µg/L	1.52	200
Molybdenum	µg/L	764	NA
Nickel	µg/L	499	NA
Selenium	µg/L	260	NA
Silver	µg/L	24	5,000
Zinc	µg/L	7,140	NA

[a] RCRA toxicity characteristic for hazardous wastes.

5.6.4 Biogas Characterization and Purification

Biogas Characterization

Methane content of the digester biogas was 59±4.6% and 61±6.6% in phases III and IV, respectively. These results are equivalent to the goal of 60%. The biogas also contained H_2S and several organosulfur compounds (**Table 11**). Digester biogas concentrations of H_2S were 2,500±1,100 mg/m^3 (1,800±780 ppm) and 2,000±590 mg/m^3 (1,400±420 ppm) in phases III and IV, respectively. The predominate organosulfur compounds detected in the biogas were methyl mercaptan, n-propyl mercaptan, and dimethyl sulfide which were detected in both phases and at frequencies greater than 10%. Several other organosulfur compounds were detected only in Phase III.

Siloxanes are typically present in anaerobic digester biogas at WWTP and originate from silicones used in personal care products. Siloxanes were not expected to be present in the food waste/canola oil digester biogas but were measured during Phase III nevertheless. **Table 12** indicates low concentrations of three siloxanes were detected in one of two samples. The detections were on Day 59 which was just 19 d more than 1 HRT (40±14 d). On Day 118 they were not detected. Thus the siloxanes were probably associated with the digester seed that was treating waste activated sludge from the USAFA wastewater treatment plant.

Sulfur Removal

During Phase IV SulfaTrap was evaluated for H_2S removal from digester biogas and VSA was evaluated for CO_2 and moisture removal. On Day 14, 2.3 kg of SulfaTrap was installed into the gas purification system and **Figure 56** illustrates the performance with respect to H_2S removal. H_2S concentrations were reduced by 99.9% or more until breakthrough around 50 d. H_2S concentrations prior to breakthrough averaged 0.11±0.14 ppm (0.16 mg/m^3). The sulfur content of the spent SulfaTrap was 3.9% by weight. This is considerably less than the expected loading of >20% (Appendix F). The reason for the lesser performance was moisture condensation on the SulfaTrap media based on visual observation. Moisture condensation affects sulfur loading capacity and mass transfer. Condensation would be prevented in a full-scale application by maintaining biogas at a temperature above its dew point.

Table 11. Biogas reduced sulfur compound concentrations.

Compound	Phase III Digester Biogas Concentration (mg/m^3)						Phase IV Digester Biogas Concentration (mg/m^3)					
	Minimum	Average	Median	Maximum	N	Detection Frequency	Minimum	Average	Median	Maximum	N	Detection Frequency
Hydrogen Sulfide	1,300	2,500	2,600	3,900	6	100%	800	2,000	2,100	2,600	7	100%
Methyl Mercaptan	1.0	7.8	6.6	17	6	100%	0.00	0.34	0.00	2.4	7	14%
n-Propyl Mercaptan	0.00	14	3.9	64	6	67%	0.00	3.8	2.6	14	7	71%
Dimethyl Sulfide	0.00	3.4	0.00	18	6	33%	0.00	0.00	0.00	0.00	7	0%
tert-Butyl Mercaptan	0.00	0.77	0.00	4.6	6	17%	0.00	0.00	0.00	0.00	7	0%
n-Butyl Mercaptan	0.00	0.73	0.00	4.4	6	17%	0.00	0.00	0.00	0.00	7	0%
Ethyl Mercaptan	0.00	0.13	0.00	0.78	6	17%	0.00	0.00	0.00	0.00	7	0%
Thiophene	0.00	0.093	0.00	0.56	6	17%	0.00	0.00	0.00	0.00	7	0%
Carbonyl Sulfide	0.00	0.080	0.00	0.48	6	17%	0.00	0.00	0.00	0.00	7	0%
Isopropyl Mercaptan	0.00	0.053	0.00	0.32	6	17%	0.00	0.00	0.00	0.00	7	0%
Carbon Disulfide	0.00	0.00	0.00	0.00	6	0%	0.00	0.00	0.00	0.00	7	0%
Ethyl Methyl Sulfide	0.00	0.00	0.00	0.00	6	0%	0.00	0.00	0.00	0.00	7	0%
Isobutyl Mercaptan	0.00	0.00	0.00	0.00	6	0%	0.00	0.00	0.00	0.00	7	0%
Diethyl Sulfide	0.00	0.00	0.00	0.00	6	0%	0.00	0.00	0.00	0.00	7	0%
Dimethyl Disulfide	0.00	0.00	0.00	0.00	6	0%	0.00	0.00	0.00	0.00	7	0%
3-Methylthiophene	0.00	0.00	0.00	0.00	6	0%	0.00	0.00	0.00	0.00	7	0%
Tetrahydrothiophene	0.00	0.00	0.00	0.00	6	0%	0.00	0.00	0.00	0.00	7	0%
2,5-Dimethylthiophene	0.00	0.00	0.00	0.00	6	0%	0.00	0.00	0.00	0.00	7	0%
2-Ethylthiophene	0.00	0.00	0.00	0.00	6	0%	0.00	0.00	0.00	0.00	7	0%
Diethyl Disulfide	0.00	0.00	0.00	0.00	6	0%	0.00	0.00	0.00	0.00	7	0%

Table 12. Digester biogas siloxane concentrations.

Compound	Phase III Digester Biogas Concentration (μg/m^3)					
	Minimum	**Average**	**Median**	**Maximum**	**N**	**Detection Frequency**
Decamethylcyclopentasiloxane	0	90	90	180	2	50%
Trimethylsilanol	0	48	48	96	2	50%
Dodecamethylcyclohexasiloxane	0	26	26	52	2	50%
Hexamethyldisiloxane	0	0	0	0	2	0%
Hexamethylcyclotrisiloxane	0	0	0	0	2	0%
Octamethyltrisiloxane	0	0	0	0	2	0%
Octamethylcyclotetrasiloxane	0	0	0	0	2	0%
Decamethyltetrasiloxane	0	0	0	0	2	0%
Dodecamethylpentasiloxane	0	0	0	0	2	0%

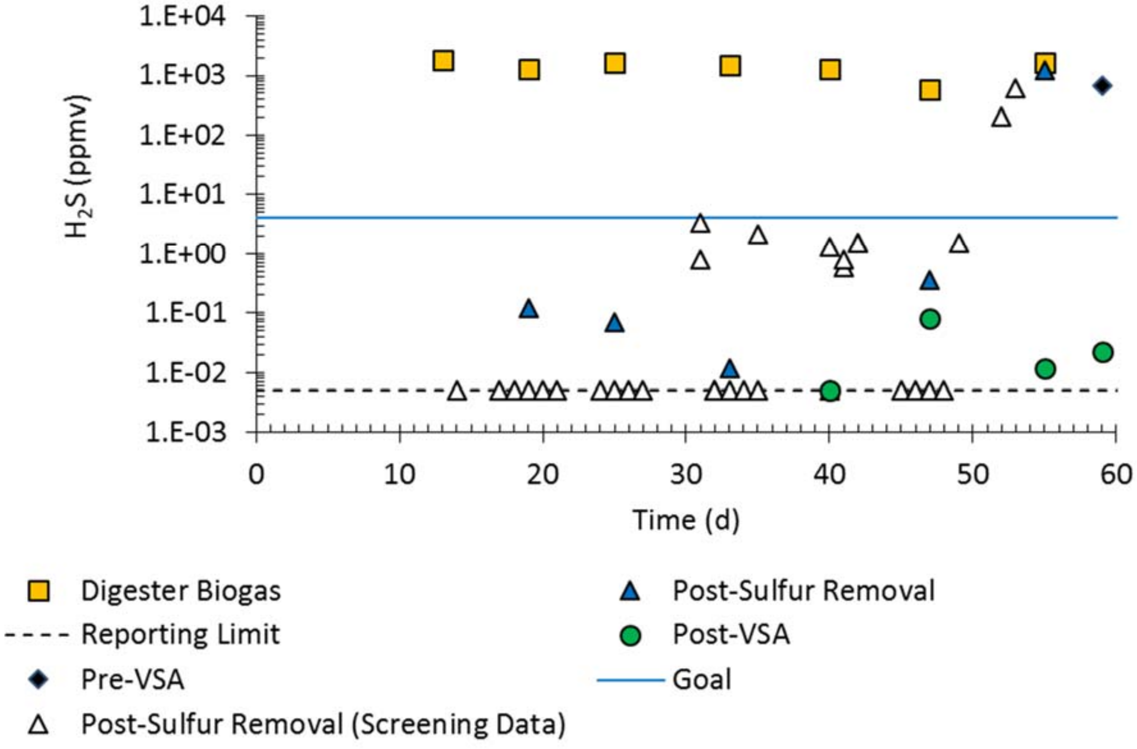


Figure 56. Hydrogen sulfide removal by SulfaTrap installed on Day 14 and VSA operated starting on Day 40. The Pre-VSA sample was collected from the biogas holder to provide a direct measurement of the VSA inlet concentration.

Carbon Dioxane and Moisture Removal

Biogas that has been desulfurized (sweetened) was stored in a biogas holder prior to treatment by the VSA. **Table 13** presents a summary of post-VSA gas composition and characteristics in comparison to natural gas specifications. In general the goals for natural gas quality were met. Nitrogen and oxygen measurements were compromised by accidentally introduced air during grab sampling. This conclusion is supported by the ratio of oxygen to nitrogen was 39±7% which is similar to though slightly higher than that for air (27%). Methane recovery was estimated to be 94±2.9% exceeding the goal of 80%. Detailed information on the VSA testing are included in the TDA report included in Appendix F.

Table 13. Post-VSA gas composition and properties.

Parameter	**Post-VSA**	**Natural gas specification**
H_2S	0.030±0.035 ppmv	< 4 ppmv
CH_4 [a]	98±0.5%	≥ 95%
CO_2 [b]	2.1±0.4%	< 3%
N_2 [c]	3.1±2.0%	< 3%
O_2 [c]	1.2±0.6%	< 0.2%
Moisture content	0.10 g/m^3 (6 lb/MMscf) [d]	< 0.12 g/m^3 (< 7 lb/MMscf)

[a] Result is corrected for air accidentally introduced into the samples during grab sampling. Uncorrected result is 94±2.9%.

[b] On-line infrared analysis indicated CO_2 was less than 1.5%.

[c] Not corrected for sampling artifact.

[d] Equivalent to a dew point of -40 ^{o}C

6.0 PERFORMANCE ASSESSMENT

This section provides a detailed synthesis of the data presented in Section 5 with the Technology Performance Objectives presented in Section 3. Several of the Quantitative and Qualitative Performance Objectives are related and are discussed together below.

6.1 RENEWABLE ENERGY CONVERSION

Renewable energy conversion was evaluated with respect to: 1) energy conversion efficiency, 2) methane yield, 3) methane production rate, and 4) biogas methane content.

The energy conversion efficiency was first evaluated by comparing methane produced by the digester to the food waste and canola oil loaded. The comparison was done on a COD-equivalents basis as an estimate of potential energy content of the digester feed and biogas. The average energy conversion in Phase III was 73±19% (**Figure 40**) and was similar to the goal of ≥70% though not exceeding it. Energy conversion was steadily increasing during Phase IV (**Figure 53**) because the digester operated for 59 d which was less than 1 SRT (130±91 d). Thus the Phase IV energy efficiency of 62±40% is not considered as good of an estimate as that for Phase III. The energy efficiency reported above does not take into account parasitic losses including pumping, digester heating, and conversion of biogas energy into usable power such as compressed natural gas for vehicle fueling. When these losses are taken into account the energy efficiency for Phase III was estimated to be 63% which exceeded the goal of ≥50%.

Methane yields were estimated based on VS and COD loading for Phases III and IV. The methane yields based on VS loading in Phases III and IV were 360±70 L/kg and 490±140 L/kg, respectively. These yields were greater than the goal of 310 L/kg. The methane yields based on COD loading in Phases III and IV were 270±75 L/kg and 230±150 L/kg, respectively. These yields were greater than the goal of 190 L/kg. The yields estimated during Phase III are considered more reliable estimates than during Phase IV because values were relatively stable in Phase III (**Figure 38**) and were increasing during Phase IV (**Figure 54**). The Phase III methane yield calculated as a function of VSD was observed to increase over time (**Figure 39**) and was estimated to be 440±140 L/kg (7.0±2.3 ft^3/lb) with a maximum value of 640 L/kg (10 ft^3/lb). These values are consistent with previously reported yields of 470 to 620 L/kg (7.5 to 10 ft^3/lb) (Tchobanoglous et al. 2003; Water Environment Federation 2010).

The volumetric methane production rate goal of 2 L/L/d was not met in Phase III. During this phase 0.82±22 L/L/d was produced (**Figure 37**) and was limited by the organic loading rate as discussed in Section 6.2 below. Phase IV involved modification of the food waste/canola oil feeding strategy to eliminate water addition and effectively feed a more concentrated food waste/canola oil mixture. This modification resulted in greater VSS concentrations (compare **Figures 33** and **52**) and presumably greater microbial concentrations which in turn allowed greater organic loading rates. The net effect was gradually increasing volumetric methane production rates over the 59-d Phase IV operational period ultimately producing 2.0 L/L/d (**Figure 52**). The average rate was 1.1±0.65 L/L/d. Firm conclusions regarding the long-term ability of the digester to produce ≥ 2 L/L/d methane cannot be made based on the available data because the digester was operated for only 0.45 SRT (59 d). Nevertheless, the consistent trend illustrated in **Figure 52** suggests that meeting or exceeding the goal would have been likely if the digester had been operated longer.

Biogas composition in Phases III and IV were 59±4.6% and 61±6.6%, respectively, and similar to the goal of 60%. The biogas composition cycled due to the cyclic feeding method but was consistent in both phases (**Figures 34 and 51**). Typical methane concentrations in digester biogas range from 59 to 64% (Tchobanoglous et al. 2003; Water Environment Federation 2010).

In addition, the yield and rate of methane production was determined to be correlated to the protein+fat content of the food waste (**Figures 9** and **41**). These observations suggests a useful metric for prediction of methane production from food waste and FOG. They also suggest the carbohydrate fraction of USAFA food waste was relatively recalcitrant. Recalcitrance to biodegradation may have been caused by the carbohydrate fraction being comprised predominately of cellulose (e.g., roughage or fiber) as opposed to starch and simple sugars.

The following conclusions can be made regarding the energy conversion performance objective:

- Energy efficiency of the food waste digestion process met but did not exceed the goals of 70% for food water/canola oil COD conversion to methane. The goal of 50% considering parasitic power losses was exceeded.
- Methane yields based on VS and COD loading were exceeded reflecting the high digestibility of the food waste.
- The protein+fat fraction can be used to predict methane production rate and potentially methane yield.
- The methane content of the biogas was consistent (~60%) though it did cycle in response to cyclic feeding. Continuous feeding would dampen this cycling.

6.2 DIGESTER CAPACITY/STABILITY

Digester capacity and stability was evaluated with respect to: 1) volumetric VS and COD loading rates, 2) specific COD loading rates (SELR), 3) pH, 4) VFAs and the ratio VFA/TALK, 5) ammonia and potential toxicity, and 6) food waste/canola oil composition.

The Phase III volumetric VS (2.4±0.6 g-VS/L/d) and COD (3.0±1.0 g-COD/L/d) loading rates (**Figure 30**) were less than the goals of 3.2 g-VS/L/d and 4.8 g-COD/L/d. Attempts to increase loading further between the start of Phase III on Day 33 and Day 100 were not made because of several observations that suggested digester inhibition and potential for failure. These observations included: 1) high concentrations of VFAs (e.g., acetic acid was as high as 1600 mg/L and averaged 770±360 mg/L [**Figure 43**]), 2) relatively high VFA/TALK ratio (0.12±0.05 mg-acetate equivalents/mg-$CaCO_3$ (**Figure 32**), 3) free ammonia concentrations (160±28 mg-N/L mg-N/L) greater than those previously reported (150 mg/L) to be inhibitory (Ariunbaatar et al. 2015; Braun et al. 1981; McCarty and McKinney 1961), and 4) digestate color changing from black to brown (**Figure 31**). On the other hand pH during Phase III was not inhibitory (7.8±0.1). Inhibition was later determined to not have occurred during this period based on methane yield and biogas methane content (discussed above), stable methane production rates between Days 33 and

100 (**Figure 43**), no observed effect of free ammonia concentrations on conversion of food waste/canola oil fat+protein to methane (**Figure 44**), and consistently high VSD and VSSD (**Figures 45** and **46**). Insufficient nutrients did not explain the observed results since they were supplemented and not observed to be limiting in the pilot demonstration (Appendix H, Figure 1) as they were in the laboratory study (**Figure 11**). If inhibition had occurred for any reason, methane production and yield would have decreased and the VSD and VSSD would have decreased leading to increasing rather than decreasing VSS. The observed decrease in VSS (**Figure 33**) was attributed to high VSSD rather than inhibition. The lack of apparent free ammonia inhibition may be attributable to acclimation (Yenigun and Demirul 2013) or a shift in population from aceticlastic to hydrogenotrophic methanogens. Hydrogenotrophic methanogens have been reported to be less sensitive to free ammonia than aceticlastic methanogens (Wilson et al. 2012; Zhang et al. 2014). Thus acetate oxidation to hydrogen and CO_2 and subsequent hydrogenotrophic methanogenesis (Karakashev et al. 2006) may have been important in the food waste digesters. High VFA concentrations may be characteristic this apparent acclimation. The brown sludge color may have been associated with declining iron concentrations in the digester that started out at 92 mg/L and ended at 12 mg/L (Appendix H, Figure 1). Iron sulfides are typically the cause of the black color in anaerobic digestates.

The laboratory study provided initial evidence that a dilute digester feed could lead to digester instability (**Figure 10**). Previous research has suggested that close associations between syntrophic bacteria and methanogens promotes development of microenvironments that promote more rapid digester startup and stability (McMahon et al. 2004). Based on these results, we hypothesized that dilute VSS concentrations and associated dilute concentrations of syntrophic bacteria and methanogens could lead to instability. The VSS concentration at the end of Phase III was 3,500±1,800 mg/L (**Figure 33**). This low VSS concentration was likely associated with low microbial concentrations which would limit the achievable and sustainable volumetric organic loading rate to the digesters. The SELR was used to evaluate organic loading relative to the low VSS.

As described in Section 5.2, organic loading rates calculated as the VS loading rate per unit of digester volume is a common design and operating parameter for anaerobic digestion of municipal sludge but is not as useful of a parameter for anaerobic digestion of other types of organic wastes which have variable biodegradability and energy content. An alternative metric termed the SELR has been proposed (Evans et al. 2012). The Phase III SELR was 0.44±0.17 g-COD/g-VSS/d (**Figure 30**) which exceeded the goal of 0.26 g-COD/g-VSS/d. Assuming a VSS concentration of 2% in an anaerobic digester treating waste activated sludge and a COD/VS ratio of 1.8 g/g, the SELR goal translates to a volumetric VS loading rate of 2.9 g-VS/L/d (0.18 lb/ft^3/d) which is near the maximum at which anaerobic digesters are typically loaded (Tchobanoglous et al. 2003; Water Environment Federation 2010). The observed value of 0.44±0.17 g-COD/g-VSS/d is 70% greater than the goal suggesting that the organic loading was at risk of exceeded the metabolic capacity of the microorganisms in the digester. However, the capacity was not exceeded based on the observed methane yields and production rates. Furthermore, the specific methane production rate was observed to correlate to the protein+fat SELR (**Figure 41**).

One way to increase the volumetric organic loading rate to the digester is to increase the VSS concentration. Phase IV evaluated this approach where the digester feeding process was modified to eliminate dilution water. Digestate was recycled only to create a pumpable food waste/canola oil slurry. The effective VS of the food waster/canola oil mixture fed to the digesters in Phases III and IV were 8.9±1.3% and 24±5.8%, respectively, an increase of 170%. This process change achieved the desired goal of increasing VSS concentrations in the digester. The VSS concentrations at the end of Phases III and IV were 3,500±1,800 mg/L (**Figure 33**) and 14,000 mg/L (**Figure 52**), respectively even though the starting VSS concentrations were both 7,800 mg/L. With the increase in VSS, the volumetric organic loading rate (**Figure 49**) and methane production rate (**Figure 52**) increased compared to Phase III (**Figures 30** and **37**). The SELR did not increase (0.47±0.30 g-COD/g-VSS/d in Phase IV versus 0.44±0.17 g-COD/g-VSS/d in Phase III) providing additional justification for the SELR concept.

Canola oil was used to simulate USAFA grease trap was and can be inhibitory (**Figure 12**). Yet digester startup strategy can be used to mitigate inhibition (**Figure 13**). A detailed study of these concepts was not conducted during the field demonstration. However the demonstration did provide relevant data. The initial canola oil content was ~15% and then was reduced to ~10% (**Figure 28**). The initially high canola oil content in Phase III may have caused foaming (**Figure 34**). Further testing at this high canola oil content was not conducted in Phase III. But a similar trend of canola oil content was observed in Phase IV where foaming was not observed. The increased VSS and SRT (130±91 d in Phase IV versus 40±14 d in Phase III) may have mitigated digester instability and foaming. The total fat content inclusive of food waste fat and canola oil was 28±8.5% (**Table 9**) suggesting that high fat loading is possible without compromising digester stability. However, acclimation and avoidance of shock loadings is warranted.

The following conclusions can be made regarding the digester capacity/stability performance objective:

- Volumetric organic loading rates for VS and COD were not met on average but were met near the end of Phase IV as a result of the feeding process modification.
- Feeding a concentrated food waste/canola oil mixture (e.g., 24±5.8% VS) in Phase IV resulted in the ability to increase organic loading rates and methane production rates. Feeding this concentrated mixture did lead to a long SRT (130±91 d) but this Phase did not operate sufficiently long (i.e., 0.45 SRT) to obtain steady state data.
- The SELR was a practical parameter that normalized volumetric organic loading rates to food wastes with varying energy contents (i.e., protein, fat, and carbohydrates) and to the VSS and associated microbial content in the digester. A value of 0.4 g-COD/g-VSS/d was is considered to be a reasonable maximum design value that allow stable digester operation.
- Free ammonia concentrations of 160 mg-N/L and potentially greater were not inhibitory.
- Food waste/canola oil digestion was stable even though normal indicators of instability (e.g., high VFA concentrations, high VFA/TALK, brown sludge) were observed.

6.3 WASTE SLUDGE RESIDUALS

Waste sludge residuals was evaluated with respect to: 1) solids destruction, and 2) physical, chemical, and biological characteristics relevant to reuse or disposal.

In addition to energy recovery, solids destruction and minimization of solid waste generation is a goal of food waste digestion. TSD and VSD in Phase III were 78±3.4% and 81±3.0%, respectively, compared to goals of 60% and 38%. Phase IV results are reported in Section 3 however these values are not considered reliable because the Phase IV digester was operated for less than 1 SRT. The Phase III measured values include both suspended and dissolved solids fractions. Therefore they do not represent the amount of sludge (i.e., undissolved solids) destruction. Calculation of sludge destruction was conducted by comparing the VSS of the digestate to the VS of the food waste/canola oil mixture. In doing this calculation the food waste/canola oil solids were assumed to be completely undissolved. The result, defined as the VSSD, was 92±2.7%. The value for TSSD was 91±2.8%. Therefore, the anaerobic digestion process was capable of reducing solid waste generation by 90%.

Biosolids generated by the process are regulated under 40CFR503(b) which provides definitions for two classes of biosolids: Class A and B. Class B is relevant to this demonstration and requires a 15-d SRT and 38% VSD. The SRT for Phase III was 40±14 d. Therefore the digestion process met the requirements for Class B biosolids. These regulation as typically applied to waste activated sludge from a municipal waste water treatment plant. Therefore these regulations may not be directly applicable to food waste digestion. Class A would require digestion at higher temperatures (i.e., thermophilic) and associated pathogen destruction. This was not evaluated but is a possible approach to food waste digestion. Comparisons of mesophilic and thermophilic food waste digestion have been conducted previously (Gray (Gabb) 2008).

Table 10 presented the results of the digestate analysis conducted in Phase IV. Based on these results and the above discussion on solids destruction, the following conclusions can be made regarding residuals from the process:

- The digestate contained high concentrations of ammonia (2,500 mg-N/L) and various metal nutrients indicating it has high potential for use as a liquid fertilizer. The ammonia concentration can be highly variable and will depend on the protein content of the food waste feed. Some of the metals (Co, Mo, Ni, and Se) were added because the food waste was deficient with respect to sustained methanogenesis.
- The solids content was low (1.5%) and these solids were difficult to dewater. These aspects may provide challenges with respect to handling but addition of a source of divalent cations (e.g., lime) may promote better dewaterability.
- Microbial pathogens (i.e., fecal coliforms) were present which may require special handling if used as a liquid fertilizer.

- No hazardous characteristics (e.g., hazardous metals in excess of RCRA toxicity characteristics) were observed that would prohibit disposal. However, sulfide is present as well as VFAs which can create a human health exposure (i.e., H_2S) and an odor issue. These attributes may affect its acceptability as a compost supplement or a liquid fertilizer.

6.4 GAS PURIFICATION

Gas purification was evaluated with respect to: 1) biogas composition, 2) H_2S removal, 3) CO_2 and moisture removal, and 4) potential renewable energy uses.

The biogas contained typical concentrations of methane (59±4.6% in Phase III) and H_2S (2,500±1,100 mg/m^3 [1,800±780 ppmv] in Phase III). The H_2S was removed by more than 99.9% by the SulfaTrap R7 adsorbent but sulfur loading was less than expected (3.9% versus > 20%) because of moisture condensation on the SulfaTrap media. Laboratory studies conducted by TDA with simulated biogas demonstrated sulfur loadings in excess of 20%. (Appendix F). A full-scale system would be designed to prevent moisture condensation.

The VSA system was capable of recovering 94±2.9% methane compared to the goal of 80%. Treated gas met all natural gas specifications with the exception of oxygen and nitrogen content. However, sample contamination with air appears to have compromised sample results. Therefore, the system was likely capable of generating natural gas that could be compressed for vehicle fueling or injection into a natural gas pipeline.

6.5 GHG ACCOUNTING

The food waste digestion/biogas purification process has the potential to offset GHG emissions by: 1) minimizing methane emissions from landfills, and 2) decreasing fossil fuel-derived CO_2 emissions that are generated via electricity production and vehicle use. A comparison of the food waste digestion/biogas purification process to current methods of food waste management (i.e., landfilling and composting) was conducted. Calculations are detailed in Appendix O.

GHG documentation was based on projected emissions from a nominally sized digester (i.e., 1 million gallons). This digester would be capable of handling 100 tons/day (95,000 kg/d) of food waste based on demonstration results. This digester is clearly oversized for most installations but the results from calculations can be scaled to smaller facilities. The calculations assume that the facility operates at a 40-d SRT, produces 270 L of methane per kg COD fed (from study results), and is fed 120,000 mg/L COD (based on study food waste characteristics). Calculations were also based on 94% methane recovery by the VSA process. Power for the process were estimated. Electrical power was assumed to emit 1.34 pounds of CO_2 per kWh electricity consumed (Energy Information Administration 2002).

The calculated greenhouse gas emissions from a food waste digester is –470 tons per year (i.e., a GHG offset). By comparison, previous research demonstrated that the greenhouse gas emissions from landfilling and composting were 0.15 and 0.05 kg CO_2e per kg food waste (Parry 2012). Using the food waste characteristics of this study that would be an equivalent of 530 and 180 tons per year for landfilling and composting, respectively. Thus, food waste disposal in anaerobic digesters represents a significant greenhouse gas savings compared to landfilling and composting.

7.0 COST ASSESSMENT

This study has shown that food waste digestion is technologically viable. The study showed that the anaerobic digestion process reduced food waste solids and the biogas could be purified for use as compressed natural gas. This section of the report examines the economic viability of the process.

7.1 COST MODEL

To assess the economic viability, a simple cost model has been developed. The model utilizes study performance conclusions including solids destruction, methane production, food waste characteristics and SELR as well as published information for per capita food waste generation to estimate the size of a full scale food waste digestion system. This will be done at three different base sizes – net base size of 10,000, 20,000, and 40,000 personnel. Utilization of the methane fuel was evaluated for the following technologies: heat production in boilers, CHP production, biomethane production for pipeline quality natural gas, and biomethane production for vehicle fuel. A White Paper prepared early in this study demonstrated that vehicle fuel can be the most cost-effective use of biomethane generated from food waste digestion (Appendix C).

Costs of the digestion facility and sub-facilities for biogas methane production were estimated based on published information, equipment quotes (adjusted to particular appropriate sizes), and engineering judgment. Supporting calculations are included in Appendix P.

7.1.1 Full Scale Anaerobic Digestion Facilities

Facilities for bases of 10,000, 20,000, and 40,000 personnel were determined. Designs assumed a total solids waste generation rate of 2 kg/capita/day with a food waste fraction of 14.5% of the total municipal solid waste discarded (USEPA 2012). Thus, the per capita food waste generation rate was 0.29 kg/capita/day.

Based on the study results, undiluted food waste has a VS content of 25%. Assuming a feed mixture of FOG and food waste at a volumetric ratio of 1.2:100, which provides about 10% COD from FOG of the total feed COD, then the COD and the VS content of the feed would 353,000 mg/L and 244,000 mg/L, respectively.

Using the calculated feed mixtures and an SELR 0.44 g-COD g-VSS^{-1} d^{-1} as well as the average VSSD 94%, then the estimated reactor volumes were calculated to be 160 m^3, 320 m^3, and 640 m^3 for the 10,000-, 20,000-, and 40,000-personnel bases, respectively. To provide flexibility and partial redundancy the required volumes were assumed to be constructed in two tasks. Biogas production reported as methane for the three base sizes was projected to be 11 m^3/h, 21 m^3/h, and 42 m^3/h from the smallest base to the largest base.

Capital costs for the anaerobic digestion system were calculated using CDM Smith engineering cost curves. These curves were developed from many wastewater treatment plant digesters based on volume of the digestion facility. The costs are full costs including tankage, pumping equipment, boilers, and flares. The costs include contractor markups, mobilization, equipment startup, and demobilization. They do not include engineering services. An additional 25% was added onto the construction costs to cover engineering and construction management services. Anaerobic digester facilities were assumed to be constructed of concrete.

Based on the size of the digesters and the cost curves, the projected costs of the digester system are as follows:

- 10,000 personnel base, $0.5M
- 20,000 personnel base, $0.8M
- 40,000 personnel base, $1.4M

Power draw for digestion equipment was calculated (Appendix P) as follows:

- 10,000 personnel base, 10 kW
- 20,000 personnel base, 12 kW
- 40,000 personnel base, 15 kW

The digester facility is assumed to require sampling and lab analysis once a day with a duration of 3 hours total. In addition, another 1 hour is allocated to maintenance. Analysis are assumed to occur Monday through Friday only.

7.1.2 Gas Utilization Facilities

Methane gas generated from the anaerobic digestion facilities is a beneficial fuel. Most commonly the fuel is used for one of four basic purposes: (1) production of heat, (2) production of heat and power, (3) as a natural gas substitute, or (4) as a vehicle fuel (in the form of compressed natural gas). All alternatives were assumed to include hot water boilers for heat production as the heat is needed to maintain the anaerobic digestion process. However, the heat was assumed to have no value as many locations there is not a demand for heat beyond the anaerobic digestion process. At the methane lower heating value of 36 MJ/m^3 and typical engine efficiencies of 38%, the power production ranges are estimated as follows:

- 10,000 personnel base, 33 kW
- 20,000 personnel base, 67, kW
- 40,000 personnel base, 133 kW

The size of the expected power production is less than typical internal combustion engines. As such, CHP through the traditional engine would likely not be effective. However, the power production aligns with typical microturbines. Therefore, it is assumed that any CHP solution would utilize microturbines. Projected costs for CHP microturbines have been documented (Darrow et al. 2015). Based on this document the expected project costs for a microturbine installation are as follows:

- 10,000 personnel base, \$160,000
- 20,000 personnel base, \$240,000
- 40,000 personnel base, \$480,000

In addition to CHP, the biogas can be scrubbed to natural gas quality. Once scrubbed to natural gas quality, it can be injected into a natural gas line as a natural gas substitute or compressed to high pressures and used as a vehicle fuel. The cost of a vehicle fueling station was based on published data (Smith and Gonzales 2014). Based on this document, the cost of a fast fill filling station is estimated as follows:

- 10,000 personnel base, \$270,000
- 20,000 personnel base, \$510,000
- 40,000 personnel base, \$640,000

Treatment of the raw biogas to natural gas quality require that all contaminants, moisture, sulfur, and CO_2 are removed. **Table 14** presents the different gas purification and utilization systems with the appropriate gas treatment technology. Note that for vehicle fuel, the system was analyzed comparing both the TDA VSA and a water scrubber system.

Table 14 illustrates proposes several different technologies for gas treatment. Where, CO_2 removal is required, a VSA system and a water scrubber system are proposed for the gas treatment systems. The VSA system is described in detail in Appendix F. For treatment systems combined with the VSA system, SulfaTrap is proposed for treatment of H_2S. A gas chiller is required for treatment of gas to a microturbine and for gas treatment after the water scrubber. The VSA System removes moisture as part of the treatment process.

Table 14. Comparison of various gas purification systems.

Utilization	Sulfur Removal	Moisture Removal	CO_2 Removal	Delivery Pressure (kPa gauge)
Combined heat and power using a microturbine	Not required	Gas chiller	Not Required	517
Injection into natural gas pipeline	Iron sponge	VSA	VSA	103
Vehicle fuel –VSA	SulfaTrap	VSA	VSA	24,800
Vehicle fuel – water scrubber	Water scrubber	Gas chiller	Water Scrubber	24,800

As noted in the report in Appendix F, the VSA system produces gas at approximately 134 kPa gauge. The water scrubber is assumed to produce scrubbed gas at 900 kPa. The VSA is assumed to have a methane recovery of 92.6%. Based on communications with Dirkse Milieutechniek (Netherlands), a water scrubber manufacturer, a water scrubber is assumed to have a methane recovery of 97%.

Gas treatment costs for iron sponge treatment, moisture removal, water scrubbers are based on previous project equipment quotations. Equipment quotations are adjusted to this project based on the “rule of six-tenths” (Perry and Chilton 1973; Williams 1947) which is as follows:

$$C_B = C_A \text{ X } (S_B/S_A)^{0.6} \tag{4}$$

Where C_B = the approximate cost of equipment having size S_B

C_A = is the known cost of equipment having corresponding size S_A

Project costs are estimated to be 2 times the equipment cost for construction and installation, plus another 25% for engineering. Thus the costs for the gas treatment options were calculated in Appendix P as follows:

- Moisture removal – Rule of six tenths applied based on flow only
  - 10,000 personnel base, $30,000
  - 20,000 personnel base, $40,000
  - 40,000 personnel base, $70,000
- Iron sponge – Rule of six tenths applied based flow only
  - 10,000 personnel base, $120,000
  - 20,000 personnel base, $170,000
  - 40,000 personnel base, $260,000
- SulfaTrap – Rule of six tenths applied to TDA report in Appendix F
  - 10,000 personnel base, $40,000
  - 20,000 personnel base, $50,000
  - 40,000 personnel base, $80,000
- Water Scrubber – Rule of six tenths applied based flow
  - 10,000 personnel base, $130,000
  - 20,000 personnel base, $190,000
  - 40,000 personnel base, $290,000
- VSA, see Appendix F
  - 10,000 personnel base, $140,000
  - 20,000 personnel base, $210,000
  - 40,000 personnel base, $320,000

- Gas compressors for natural gas line pressure
    - 10,000 personnel base, $130,000
    - 20,000 personnel base, $140,000
    - 40,000 personnel base, $150,000
- Gas compressors for microturbines
    - 10,000 personnel base, $230,000
    - 20,000 personnel base, $240,000
    - 40,000 personnel base, $250,000
- Gas compressors for vehicle fuel – included in vehicle fueling station

Gas treatment systems were assumed to have the following power drawing equipment:

- Moisture removal (based on saturated gas at the flowrates)
    - 10,000 personnel base, 0.5 kW
    - 20,000 personnel base, 0.9 kW
    - 40,000 personnel base, 1.7 kW
- Iron sponge and SulfaTrap, no electrical draw
- Water scrubber
    - Water circulation
        - 10,000 personnel base, 4 kW
        - 20,000 personnel base, 7 kW
        - 40,000 personnel base, 14 kW
    - Gas pressurization, not included as water scrubber paired only with vehicle fuel option that requires pressures in excess of the water scrubber pressure.
    - Tail gas treatment, in a biofilter
        - Assumed at 5 kW for all sizes
- VSA, see Appendix F
    - 10,000 personnel base, 4 kW
    - 20,000 personnel base, 7 kW
    - 40,000 personnel base, 15 kW

- Pressurization to natural gas line pressure, assumes adiabatic compression
  - 10,000 personnel base, 0.3 kW
  - 20,000 personnel base, 0.7 kW
  - 40,000 personnel base, 1.3 kW
- Pressurization for microturbines, assumes adiabatic compression
  - 10,000 personnel base, 1 kW
  - 20,000 personnel base, 2 kW
  - 40,000 personnel base, 4 kW
- Pressurization to vehicle fuel pressures, assumes isothermal compression with water cooled compressors.
  - 10,000 personnel base, 5 kW
  - 20,000 personnel base, 10 kW
  - 40,000 personnel base, 19 kW

In addition to power costs, the operation of gas treatment will be impacted by chemical/sorbent/media costs as well as O&M costs.

The iron sponge and VSA systems are projected to have a consumable cost. The consumable cost projections for these technologies are as follows:

- Iron sponge, media replacement cost, based on $1.76 per pound of iron sponge media
  - 10,000 personnel base, $7,000
  - 20,000 personnel base, $14,000
  - 40,000 personnel base, $28,000
- VSA, see Appendix F
  - 10,000 personnel base, $2,000
  - 20,000 personnel base, $2,000
  - 40,000 personnel base, $4,000

Projected operating costs for SulfaTrap were estimated in Appendix F at $41.31 per kg of sulfur, this equates to the following costs:

- SulfaTrap, see Appendix F
  - 10,000 personnel base, $17,000
  - 20,000 personnel base, $35,000

  - 40,000 personnel base, $70,000

The projected labor requirements for the gas treatment systems are as follows:

- Moisture removal, labor is assumed to be 1 hr/d
- Iron sponge, typical labor is 1 hr/d, plus media change out of 40 hours for one week of the year
- SulfaTrap, typical labor is 12 hr/replacement with replacement occurring twice per year
- Water scrubber, typical labor of 2 hr/d, plus media cleaning 4 times per year at 40 hours per event
- VSA, quantified in Appendix F at 208 hours per year
- Gas compressors, assumed to be 1 hr/d

7.1.3 Cost Summary

A summary of the capital and the O&M costs for the systems is presented in **Table 15**. Note that this analysis assumes $20/hr for O&M labor and electrical energy costs at $0.10 per kWh.

Table 15. Capital and O&M costs.

Process	Capital			O&M		
	10,000 Base Personnel	20,000 Base Personnel	40,000 Base Personnel	10,000 Base Personnel	20,000 Base Personnel	40,000 Base Personnel
Digestion	$500,000	$800,000	$1,400,000	$30,000	$30,000	$30,000
Microturbine	$420,000	$520,000	$800,000	$20,000	$20,000	$20,000
Injection into natural gas pipeline (VSA)	$310,000	$400,000	$550,000	$40,000	$60,000	$100,000
Vehicle Fuel with VSA	$450,000	$770,000	$1,040,000	$40,000	$60,000	$120,000
Vehicle Fuel with water scrubber	$430,000	$740,000	$1,000,000	$50,000	$50,000	$70,000

7.1.4 Revenue and Cost Offsets

The CHP facility will produce electrical power that can be used to reduce facility power costs. The heat from the CHP system is considered to be utilized for digester heating and not to have value beyond the process. Based on the previously estimated power production, the CHP option will offset the following electricity purchases.

- 10,000 personnel base, 290,000 kWh/yr
- 20,000 personnel base, 590,000 kWh/yr
- 40,000 personnel base, 1,170,000 kWh/yr

Based on the methane produced and assuming a 94% recovery of methane in the gas scrubbing technologies and parasitic gas demands for boiler heating, the total methane produced in terms of GJ is as follows:

- 10,000 personnel base, 2,800 GJ/yr
- 20,000 personnel base, 5,700 GJ/yr
- 40,000 personnel base, 11,400 GJ/yr

In terms of GGE the gas:

- 10,000 personnel base, 25,000 gal/yr
- 20,000 personnel base, 50,000 gal/yr
- 40,000 personnel base, 99,000 gal/yr

The estimated fuel production for USAFA was estimated to be 6,000 to 10,000 GGE/year (see Appendix P).

Assuming average electrical purchase costs of $0.10/kWh, minus 1¢ per kWh for engine maintenance, using the current Henry Hub natural gas price of $2.65 per GJ and current gasoline prices across the United States $2.319 per gallon, the following revenue or cost offsets are available to the alternatives.

As power purchase offsets

- 10,000 personnel base, $30,000/yr
- 20,000 personnel base, $50,000/yr
- 40,000 personnel base, $110,000/yr

As wholesale natural gas

- 10,000 personnel base, $10,000/yr
- 20,000 personnel base, $20,000/yr
- 40,000 personnel base, $30,000/yr

As gasoline

- 10,000 personnel base, $60,000/yr
- 20,000 personnel base, $120,000/yr
- 40,000 personnel base, $230,000/yr

7.2 COST DRIVERS

Non-technical cost drivers included installation population, local costs of food waste disposal alternatives (e.g., landfilling or composting), trucking fees associated with food waste transportation, and the cost of gasoline or diesel fuel. Technical cost drivers included the organic loading rate to the digester, gas purification requirements, and the selected gas purification technology. Finally, the ultimate end use of the biogas or biomethane had a large impact on cost effectiveness of the technology. As discussed in Appendix B, the technology was initially estimated to be cost-effective when the price of gasoline is $4/gallon and the landfill tipping fee is $100/ton. As of the date of this report the price of gasoline is less than $3/gallon but has been in excess of $4/gallon in the past. Landfill tipping fees vary widely across the country and can be expected to increase in the future. As described in Section 7.3 below, the technology was cost-effective under a broader range of scenarios that originally predicted.

7.3 COST ANALYSIS

In Section 7.1 the costs and projected revenues for two different digestion and gas utilization technologies were compared. Based on that evaluation, it appears that scrubbing the biogas to natural gas is not a cost effective technology. Additionally, the comparison of a high pressure water scrubber for gas treatment to VSA suggests they have similar costs. This section of the report evaluates the cost effectiveness of the various technologies.

Based on Section 7.2, the high pressure water scrubber has the capital costs and net revenues presented in **Table 16**.

Table 16. Capital costs and net revenues for different alternatives.

Process	Capital			Net Revenues		
	10,000 Base Personnel	20,000 Base Personnel	40,000 Base Personnel	10,000 Base Personnel	20,000 Base Personnel	40,000 Base Personnel
Digestion and CHP	$920,000	$1,320,000	$2,200,000	($20,000)	$0	$50,000
Digestion and natural gas production	$810,000	$1,200,000	$1,950,000	($60,000)	($70,000)	($110,000)
Digestion plus VSA for vehicle fuel	$950,000	$1,570,000	$2,440,000	($10,000)	$30,000	$70,000
Digestion plus high pressure water scrubber for vehicle fuel	$930,000	$1,540,000	$2,400,000	($20,000)	$40,000	$120,000

Using an analysis period of 20 years and a discount rate of 1.2% (based on the real interest rate of a 20 year note) the above costs can be presented in terms of net present cost and as annualized cost as illustrated in **Table 17**.

Table 17. Net present and annualized costs for different alternatives.

Process	Net Present Cost			Annualized Cost		
	10,000 Base Personnel	20,000 Base Personnel	40,000 Base Personnel	10,000 Base Personnel	20,000 Base Personnel	40,000 Base Personnel
Digestion and CHP	$1,270,000	$1,320,000	$1,320,000	($70,000)	($70,000)	($70,000)
Digestion and injection into natural pipeline	$1,870,000	$2,440,000	$3,900,000	($110,000)	($140,000)	($220,000)
Digestion plus VSA for vehicle fuel	$1,130,000	$1,040,000	$1,200,000	($60,000)	($60,000)	($70,000)
Digestion plus high pressure water scrubber for vehicle fuel	$1,280,000	$830,000	$280,000	($70,000)	($50,000)	($20,000)

Although none of the alternatives show a net revenue over the 20-year planning period when amortized capital costs are considered, the current food waste handling system also have costs associated with them. Considering that the estimated tons processed by the bases over the year is 1,200 ton/yr, 2,300 ton/yr, and 4,600 ton/yr for the 10,000, 20,000, and 40,000 personnel base, the cost of food waste disposal is significant. Based on these yearly estimated food waste production values the net cost for food waste disposal via digestion with CHP for energy recovery is as follows:

- 10,000 personnel base, $58/wet ton
- 20,000 personnel base, $30/wet ton
- 40,000 personnel base, $15/wet ton

Net cost for food waste disposal in an anaerobic digester with biogas captured and scrubbed to natural gas quality for sale to the natural gas utility has the following costs per ton of food waste generated.

- 10,000 personnel base, $92/wet ton
- 20,000 personnel base, $61/wet ton
- 40,000 personnel base, $48/wet ton

For the digestion with methane converted to compressed natural gas for vehicle fuel using SulfaTrap and a VSA, then the annual food waste disposal cost is as follows:

- 10,000 personnel base, \$50/wet ton
- 20,000 personnel base, \$26/wet ton
- 40,000 personnel base, \$15/wet ton

Using the anaerobic digester for food waste processing and scrubbing the gas with a water scrubber prior to compressing for fueling vehicles, results in the following net food waste disposal costs.

- 10,000 personnel base, \$58/wet ton
- 20,000 personnel base, \$22/wet ton
- 40,000 personnel base, \$4/wet ton

In comparison average landfill costs across the United States are about \$50/wet ton (Clean Energy Projects Inc. 2015). In comparison to composting, institutional on-site composting facilities have a net cost of about \$29 per wet ton and commercial composting facilities have a net cost of about \$52 per wet ton (Sparks 1998). Thus, even at the smaller 10,000 personnel base the technology is cost competitive with landfilling and off-site composting (**Figure 57**). For installations serving a population of 20,000, food waste disposal through anaerobic digestion and biogas recovery either as a vehicle fuel or in a CHP facility is cost competitive with institutional on-site composting. At larger bases of around 40,000 personnel, disposal of food waste via anaerobic digestion and biogas purification appears to have economic advantages compared to traditional food waste disposal methods.

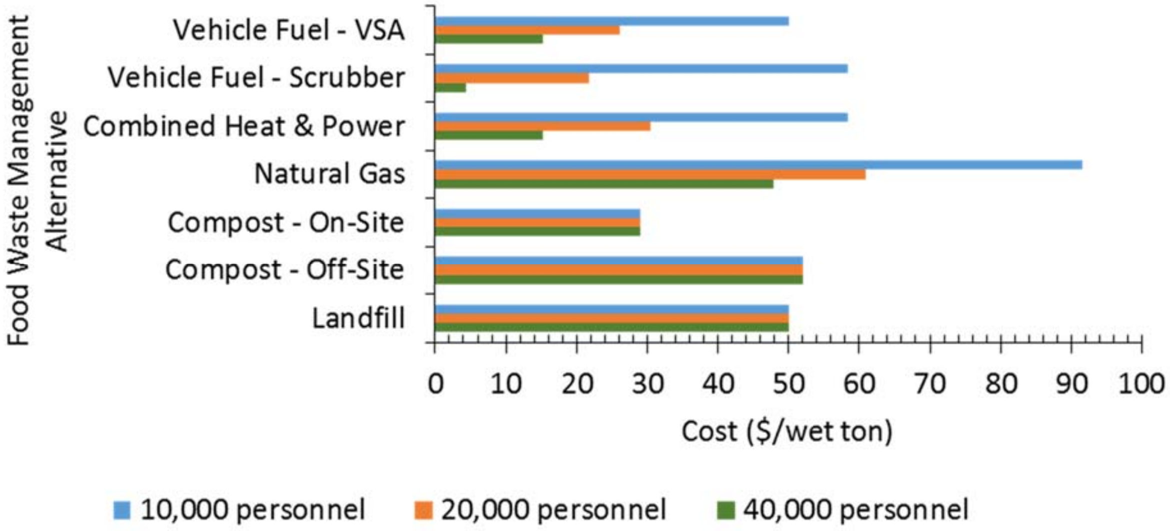


Figure 57. Comparison of food waste management alternatives.

8.0 IMPLEMENTATION ISSUES

The above project showed that anaerobic digestion of food waste at military bases is technologically feasible and can be cost competitive with alternative methods of food waste management depending on the size of the installation. Often anaerobic digestion systems are custom-designed and built. However, in recent years, a number of companies have emerged that specialize in manufacture of on-site anaerobic digestion systems. One important consideration for a military installation is whether they have the staff to operate and maintain what is essentially a wastewater treatment plant. Clearly if the installation already had a wastewater treatment plant on site such as USAFA then the implementation is much easier. Alternatives do exist as described in the Engineering Guidance Document included in Appendix Q. This document is intended to facilitate technology evaluation, selection, and implementation. The alternatives include transport to a local wastewater reclamation facility that has the capability of accepting food waste and FOG.

This study attempted to cover all the costs associated with food waste digestion, but it is likely that some costs may not be included. Investigations that may be required to quantify some of the hidden costs include the following. For vehicle fuel options, the cost of converting the vehicles to run on compressed natural gas is not included. An approximate cost to convert a vehicle from gasoline to compressed natural gas is \$6,000 to \$8,000. This is based on the range of costs of newly purchased vehicles with either a gasoline or a compressed natural gas engine. A second cost not incorporated into the analysis is the disposal of the digestate. The expected digestage volume is estimated to be less than 5% of the estimated wastewater that would be generated by similarly sized plants. As such, it may be possible to route the digestate through the facility sewer system. However, due to the likely strength of the digestate the local sewer authority may restrict the discharge or impose a fee for disposal. Consultation with the local sewer agency would be required prior to discharging the digestate in the sewer.

This study was conducted at a time when gasoline prices are low compared to historically. In the recent past gasoline prices exceeded \$4 per gallon. At these prices the value of the technology would be greater. Additionally, the study assumed an aggregate rate of electricity at \$0.10 per kWh. Electricity prices vary greatly across the country. Further, electricity pricing in some areas and for larger customers can be more complicated. Finally, the treatment system would generate more power than the system uses. As such, the treatment system may require a power purchase agreement as well as additional relays and switches to protect the grid. The electric utility may not provide \$0.10 per kWh in a power purchase agreement. Another factor affecting technology cost-effectiveness is local landfill tipping fees. Greater landfill tipping fees will result in the technology being more cost effective.

Design of the facilities would need to be in compliance with all building codes and in compliance with the National Fire Protection Association (NFPA) and the NEC. There currently is not a NFPA code that pertains to mono-food waste digestion facilities. However, guidance could be provided in NFPA 820 for WWTPs.

The technology would have a net reduction of greenhouse gas emissions compared to landfilling and composting (Parry 2014). This technology may be able to be used to help DOD facilities move in compliance with EO 13514 that calls for agencies to set percentage reduction targets for greenhouse gas emissions for fiscal year 2010. Specifically, the order addresses reducing fossil fuel use in vehicles.

Table 18 presents the design criteria that can be used to size equipment and facilities for an independent food waste handling system. It should be noted that **Table 18** does not include the influent characteristics of the food waste. These characteristics should be assessed based on actual food waste data from the plant. The researchers recognize that the food waste generated at the Air Force Academy and used as the basis for this study may be different than at other facilities. Further, the processing applied at the Air Force Academy, specifically the grinder and pulper, may not exist at all facilities. As a result, the facility will need to work with potential vendors of food waste pulping and grinding systems. These vendors are likely to process the food waste differently, which may have impacts on the food waste concentration and other characteristics. Additional engineering design guidance is provided in the companion Engineering Guidance Report (Vandenburgh and Evans 2016). Food waste characteristics will affect digester performance but COD and SELR were determined to be a useful parameters for evaluating food waste suitability. In addition, Experience with co-digestion of food waste also suggests a minimum COD of 20,000 mg/L with the optimum > 50,000 mg/L (Hare 2016). The minimum VS/TS value is 65% with the optimum being > 85%. Also refer to Appendix C for information relevant to desired waste stream characteristics.

Table 18. Design criteria.

Parameter	Suggested Design Value	Comments
Methane Production (VS basis)	400 L CH_4/kg VS loaded	Use design value to predict methane production from digester. Use for sizing gas utilization equipment and determining potential revenues and offsets from biogas utilization
Methane Production (COD basis)	250 CH_4/kg COD loaded	Use design value to predict methane production from digester. Use for sizing gas utilization equipment and determining potential revenues and offsets from biogas utilization
Specific COD loading rate (SELR)	0.44 g-COD/g-VSS/day	Use design value for sizing the anaerobic digestion facilities.
pH	7.8	Design value for understanding operational pH in digester
TS Reduction	78%	Use design value for projecting solids to be disposed after process
VSS Reduction	92%	Use in combination with SELR to size anaerobic digestion facilities
Biogas CH_4 Content	60%	Use in combination with methane production to determine size of required digester gas piping and other digester gas conveyance system, flares, etc.
Biogas H_2S Content	2,900 mg/m^3	Use to size hydrogen sulfide removal systems

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APPENDICES

Appendix A: Points of Contact

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone E-mail	Role in Project
Andrea Leeson, Ph.D.	ESTCP 4800 Mark Center Drive, Suite 17D08 Alexandria, VA 22350-3605	(571) 372-6398 Andrea.Leeson.civ@mail.mil	ESTCP Program Manager
Lauren Fillmore	Water Environment Research Foundation 635 Slaters Lane, Suite G-110 Alexandria, VA 22314	(571) 384-2107 lfillmore@werf.org	WERF Senior Program Director
Patrick Evans, Ph.D.	CDM Smith 14432 SE Eastgate Way, Suite 100 Bellevue, WA 98007	(206) 351-0228 evanspj@cdmsmith.com	Principal Investigator
H. David Stensel, Ph.D.	The University of Washington 303 More Hall, Box 352700 Seattle, WA 98195-2700	(206) 543-9358 stensel@uw.edu	Co-Principal Investigator (ADM1 modeling, anaerobic digestion)
Ambal Jayaraman, Ph.D.	TDA Research, Inc. 12345 W 52nd Avenue Wheat Ridge, CO 80033	(303) 940-5391 ajayaraman@tda.com	Co-Principal Investigator (biogas purification)

Appendix B: Economics Analysis White Paper

CDM

Memorandum

To: *Dr. Andrea Leeson*

From: *Dr. David Parry, Dr. Patrick Evans and Cale McPherson*

Date: *January 31, 2010*

Subject: *Economics White Paper for ER-200933, Renewable Energy Production from DoD Installation Solid Waste by Anaerobic Digestion*

This white paper provides a preliminary expression of the projected economic benefit for the anaerobic digestion of DoD installation solid waste. Projections made within are based on the best available data for construction, operation and maintenance (O&M) costs, as well the expected performance of the proposed technology. The economic analysis has been completed using the National Institute of Standards and Technology (NIST) Building Life-Cycle Cost (BLCC) Program for MILCON Analysis: ECIP Project.[1] This methodology and white paper were requested by the SERDP/ESTCP Program Office in during the Fall, 2010 In-Progress Review.

Base-Case and Proposed Technology Definition

The ECIP Life-Cycle Cost analysis tool requires user inputs that define the capital and O&M costs and savings for the alternative/technology of interest. Costs and savings are based on a comparison with a base-case or do-nothing alternative. For this economic analysis it was assumed that food waste and other digestible organics would be diverted from disposal in a landfill (the base-case) to an organic waste anaerobic digestion system with energy recovery (the proposed technology). To provide a consistent basis of comparison, a population of 50,000 individuals was assumed. Per capita waste generation was estimated at 0.6 pounds of wet waste per day as reported by an EPA study published in 2008.[2] Additional alternative specific assumptions are described below.

Base-Case: Landfilling

Landfilling of organic waste was the assumed base-case as it is the most common disposal method currently employed within the United States. According to the 2008 EPA study, 31.7 million tons of food waste is disposed of each year in the United States. Over 97 percent of the waste is disposed of without recovery, and 87 percent of the waste ends up in a landfill.

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[1] Federal Energy Management Program: Information Resources, 2010

[2] U.S. EPA, 2008

The average cost for disposal at a landfill in the United States is $43.99 per wet ton, with a range between $15 and $120 per wet ton.[3]

Based on these assumptions, the disposal of food waste from 50,000 individuals would cost an average of $241,000 per year with a range of $82,000 to $657,000.

Proposed Technology: Anaerobic Digestion
The initial definition and cost estimate for the anaerobic digestion and energy recovery system is based on a source separated organic stream, a Greenfield site for installation, complete mix digesters, biogas recovery to generate a renewable compressed natural gas (rCNG) vehicle fuel, and national averages for construction, O&M, power and vehicle fuel costs. Major pieces of infrastructure and equipment included:

- Complete Mix Anaerobic Digesters (tanks, piping, mixing equipment, etc.)
- Hot Water Boilers for digester heating
- Processing and Dewatering Equipment
- Biomethane Treatment to bring the biogas to natural gas quality
- rCNG Fueling Infrastructure to compress the biomethane and dispense it as a vehicle fuel equivalent in quality to CNG, but renewable in nature

Additional process specific assumptions are provided in Table 1 with references given in the attached calculations sheet.

Table 1
Process Assumptions for Life-cycle Cost Analysis

Process Characteristic	***Value***	***Units***
Source Food Waste Solids Content	30	%
Source Food Waste Volatile Solids: Total Solids Ratio	0.86	lbs VS/lbs TS
Digester Solids Residence Time (SRT)	20	days
Digester Feed Solids Content (Loading)	10	%
Digester Volatile Solids Loading Rate	0.27	lbs VS ft^{-3} day^{-1}
Volatile Solids Destruction	80	%
Biogas Yield	22	ft^3/lb VS destroyed
Biomethane Treatment Efficiency	95	%
Produced Biosolids Solids Content	25	%

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[3] Waste Business Journal, 2010

Capital and O&M costs for the equipment and infrastructure were based off of recent construction costs and estimates performed by CDM for installations around the United States and Canada including: St. Joseph, MS; Edmonton, AB; Deer Island, MA; Seattle, WA; Des Moines, IA and Dallas, TX. Unit capital costs were compared to industry reports where possible to confirm the accuracy of estimations.[4] [5]

The capital costs for the digestion and energy recovery system are summarized in Table 2. Each line item represents the installed cost inclusive of overhead, insurance, bonding and escalations.

Table 2
Capital Costs for Anaerobic Digestion and Energy Recovery System

Item	***Capital Cost***
Anaerobic Digester	$ 1,290,000
Dewatering & Processing Equipment	$ 281,000
Biogas Boiler	$ 38,300
Biomethane Treatment System	$ 1,240,000
Vehicle Fueling System	$ 1,240,000
Subtotal	$ 4,089,300
Design	$ 818,000
Total	**$ 4,907,300**

Recurring costs of the proposed technology include power, routine and non-routine maintenance on major equipment, labor, and chemicals. Recurring savings include avoided landfill tipping fees, avoided trucking fees, avoided vehicle fuel costs from the generation of the rCNG vehicle fuel, and avoided soil amendment costs from using the digested and dewatered product for land application. A summary of these recurring costs and savings is provided in Table 3.

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[4] AgStar U.S. EPA, Jan. 2010
[5] Greer, 2007

Table 3
Recurring Costs and Savings for Anaerobic Digestion and Energy Recovery System

Item	***Cost (Savings)***
Cost	
Power Costs	$ 85,200
Anaerobic Digestion O&M	$ 64,700
Processing and Dewatering O&M	$ 37,100
Biomethane System O&M	$ 45,000
Vehicle Fueling O&M	$ 52,900
Savings	
Avoided Tipping Fees	$ (151,000)
Avoided Trucking Fees	$ (34,300)
Avoided Vehicle Fuel	$ (645,000)
Avoided Soil Amendment	$ -
Total	**$ (545,400)**

The values provided in Table 2 are based on the following assumptions:

- Power Costs: Based on national average power costs and includes power demand for all equipment.[6]

- Anaerobic Digestion O&M: Includes routine and non-routine maintenance and labor for digestion system and is based on 5 percent of the digester capital construction cost. Cost is exclusive of power costs, which are carried separately.

- Processing and Dewatering: Costs include polymer and labor demand for the processing and dewatering equipment. Cost is exclusive of power costs, which are carried separately.

- Biomethane System O&M: Includes routine and non-routine maintenance for the biomethane treatment system. Cost is based on a similar system installed at the South Treatment Plant in Renton, WA.[7] Cost is exclusive of power costs, which are carried separately.

- Vehicle Fueling O&M: Includes routine and non-routine maintenance for the vehicle fueling infrastructure (gas dryers, compressor, dispensers, control panels). Cost is based on CDM experience and reported O&M from manufacturers

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[6] U.S. Energy Information Administration, 2005
[7] Nelson, 2008

- Avoided Tipping Fees: Based on the national average for tipping fee of $43.99 per wet ton.[8] The savings is realized from diverting the food waste from the landfill to the digestion system.

- Avoided Trucking Fees: Based on an estimated trucking/hauling cost of $10 per wet ton. The savings is realized from diverting the food waste from the landfill to the digestion system.

- Avoided Vehicle Fuel: Based on the national average cost for unleaded gasoline of $2.78 averaged of the previous 12-months.[9]

- Avoided Soil Amendment: No value assumed in the initial analysis as monetizing the value of the biosolids can be difficult and is uncommon. Instead, it is assumed that all biosolids generated are sent to the landfill and are subject to standard tipping and trucking fees.

Life-Cycle Cost Analysis

Based on the above assumptions and estimates an initial baseline ECIP Life-Cycle Cost estimate was performed to determine the simple payback period, and the savings to investment ratio (SIR) for a 10-year and 20-year project life-cycles when the technology is installed under "national average" conditions. National average conditions were defined as the average cost for key economic inputs such as construction, power, tipping fee and fuel costs. However, because national average costs are only applicable to a small subset of the U.S. market and because they only capture a snapshot of current market rates, sensitivity analyses were performed to evaluate the simple payback and SIR based on changing conditions. The following is a summary of all analyses performed:

- Baseline: National average costs for power, vehicle fuel and tipping fees

- Tipping Fee Sensitivity: Tipping fee varied between $20 and $150 per wet ton

- Cost of Electricity Sensitivity: Power costs varied between $0.05 and $0.25/kWh

- Cost of Vehicle Fuel: Vehicle fuel costs varied between $2.00 and $6.50/gallon

- Digester Feed Concentration: Feed concentration to the digester varied between 5 and 30 percent.

- Biosolids Value: Biosolids value varied between $0 and $15.00 per dry ton.

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[8] Waste Business Journal, 2010
[9] U.S. Energy Information Administration, 2011

Copies of the ECIP report summaries are provided in the appendix of this memorandum for reference.

Baseline Analysis

The initial baseline alternative used national average costs for construction, O&M costs including power rates, vehicle fuel costs and tipping fees as well as the process assumptions detailed in Table 1. A summary table for baseline analysis is provided in Table 3.

Table 3
Baseline Life-Cycle Cost Analysis

Simple Payback, yrs	***SIR, 10 yrs***	***SIR, 20 yrs***
9.06	1.04	1.89

According to DoD Instruction Number 4170.11 the above project installed under "national average" conditions would meet the minimum requirements for funding. The minimum DoD requirements are a simple payback of less than 10 years and a savings to investment ratio (SIR) of 1.25.[10] For the 20-year project life-cycle, the SIR is 1.89.

Tipping Fee Sensitivity

In recognition that tipping fees vary considerably across the United States, a sensitivity analysis was conducted to explore how tipping fees ranging from $20 to $150 per wet ton would influence the life-cycle cost metrics. While this range is outside of the current range in the United States, it was selected to encompass the near term range with an expectation that tipping fees will increase in the future. Current tipping fees have been increasing at approximately 6 percent per year as the cost of construction and operation of landfills has increased.[11] This sensitivity is presented graphically in Figure 1.

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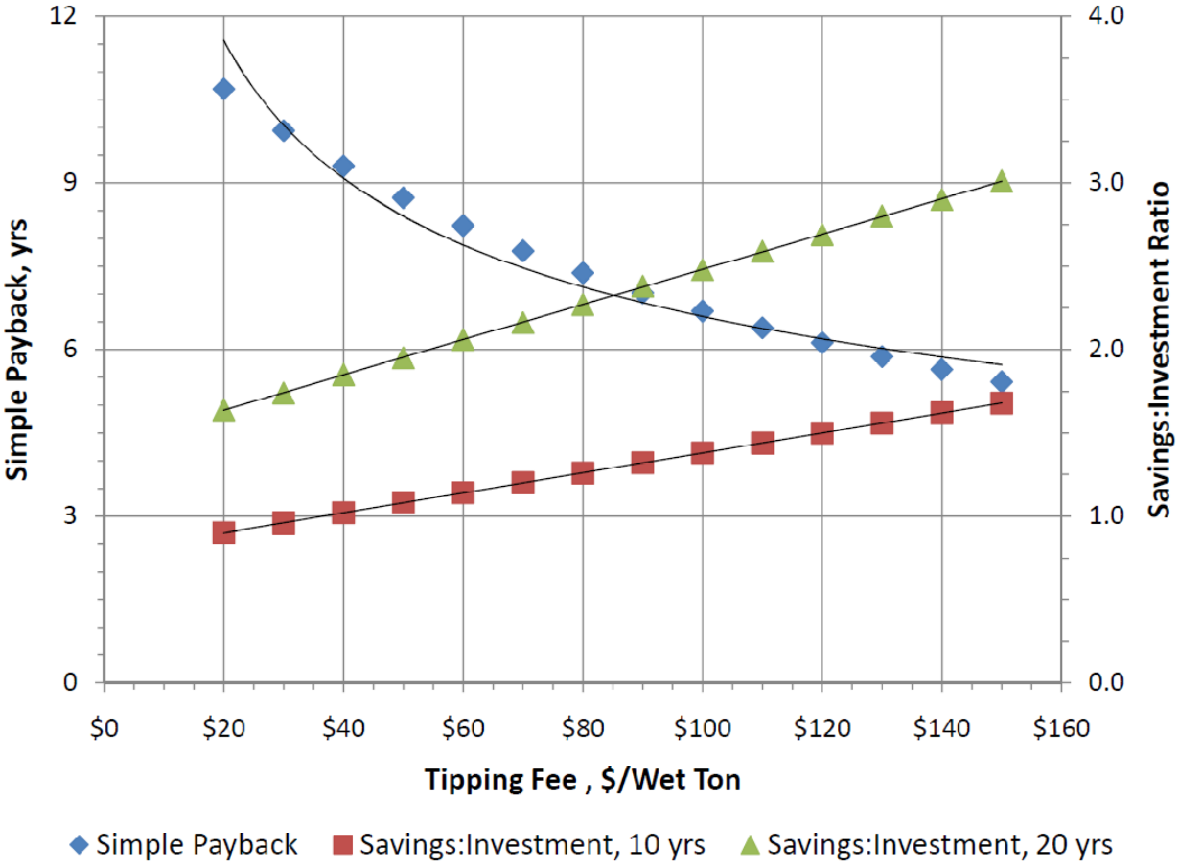
[10] U.S. Department of Defense, 2009

[11] U.S. Landfill Tipping Fees Reach New Record, Despite Economic Downturn, 2010

Figure 1
Tipping Fee Sensitivity Analysis

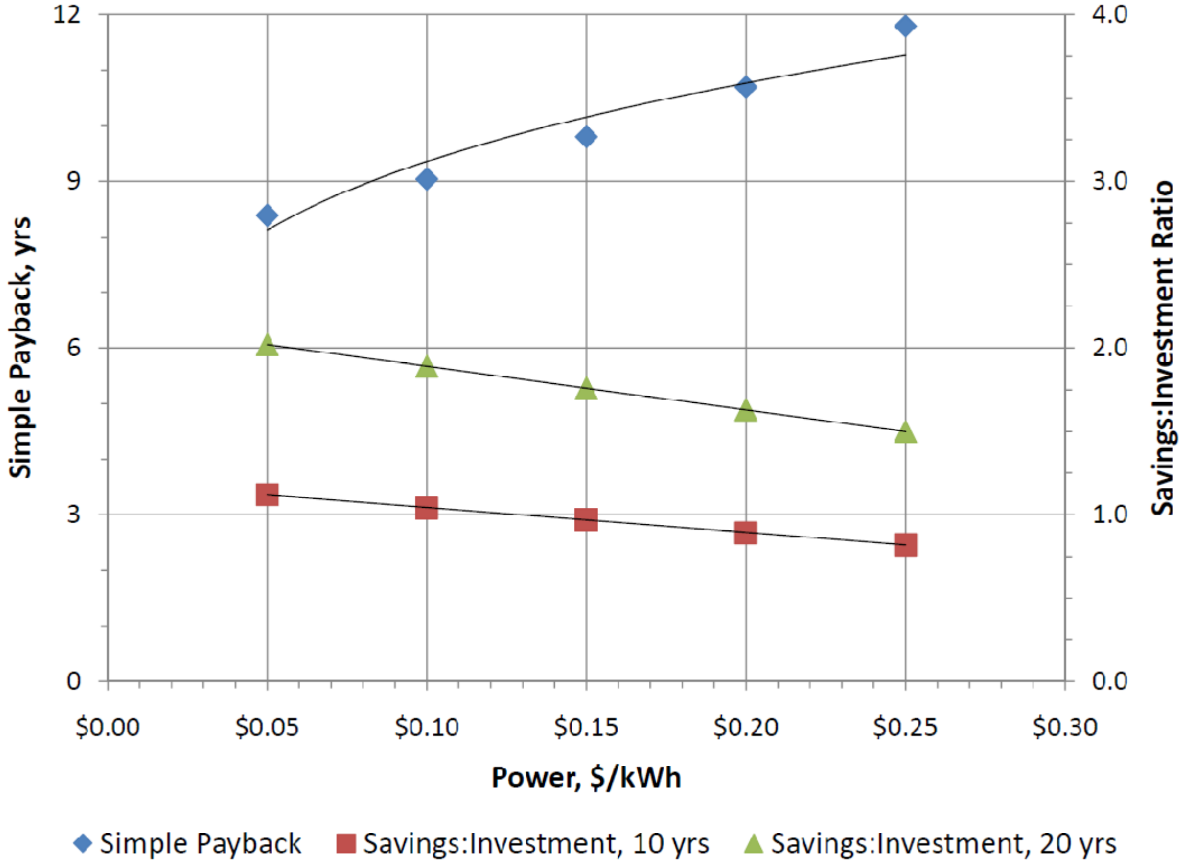


As can be noted in Figure 1, the economic metrics of the proposed technology are greatly influenced by the tipping fee associated with the waste disposal. As tipping fees increase, the simple payback reduces and the SIRs increase sharply. A minimum tipping fee of approximately $40 per wet ton is required to have a simple payback of less than 10 years. The SIR remains above 1.25 for the entire range of tipping fees for the 20-year life-cycle. For the 10-year life-cycle, a minimum tipping fee of $80 per wet ton is required to have an SIR greater than 1.25.

Cost of Electricity Sensitivity

In recognition that power costs vary considerably across the United States, a sensitivity analysis was conducted to explore how power costs ranging from $0.05 to $0.25/kWh would influence life-cycle cost metrics. This sensitivity is presented graphically in Figure 2.

Figure 2
Cost of Electricity Sensitivity Analysis

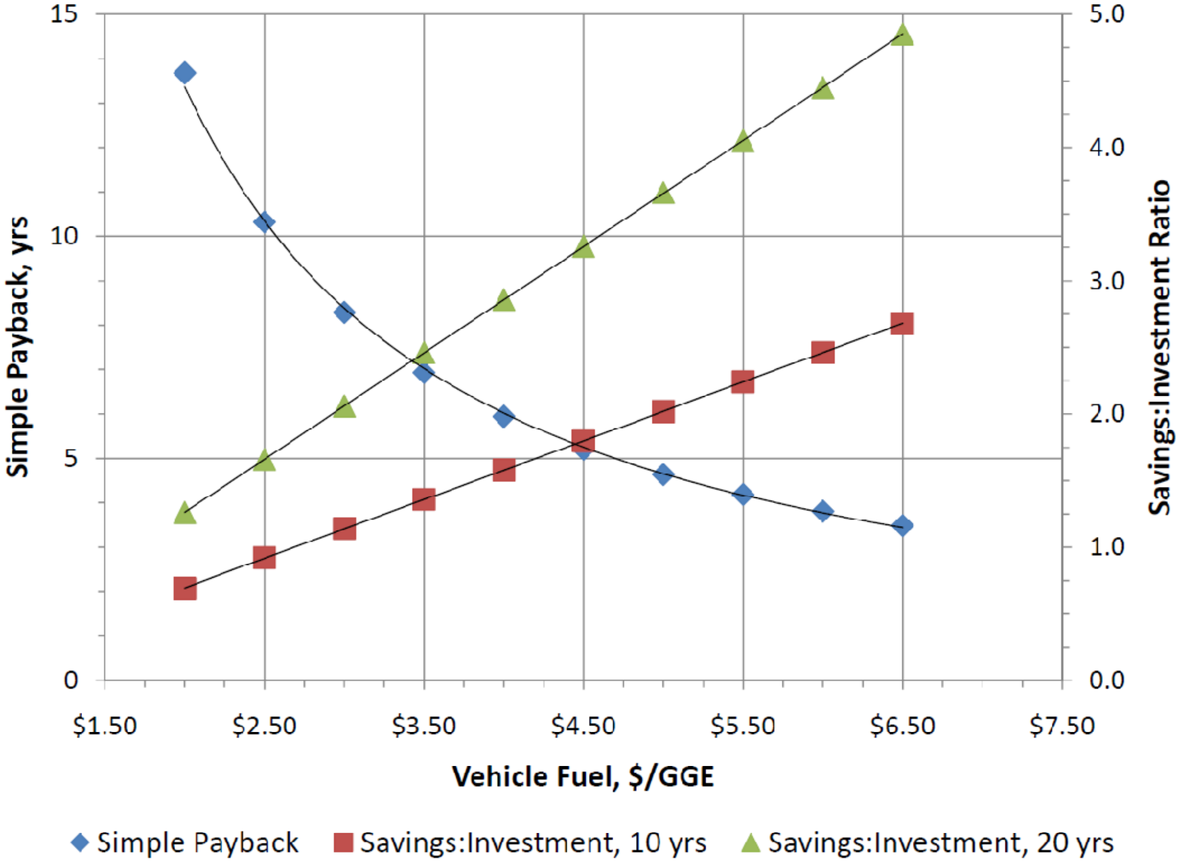


The sensitivity depicted in Figure 2 suggests that the economic metrics of the proposed technology are mildly influenced by the cost of power. As the cost of power increases, the simple payback period increases and the SIRs decrease. The reason for this is that there is a relatively significant power demand associated with the conversion of biogas to vehicle fuel. As power costs increase, the associated O&M costs increase and reduce the overall benefit of this project. In absence of other variables, the cost of power would need to remain below $0.10/kWh for the proposed technology to meet the minimum standards for DoD installations. In excess of this rate, additional variables would need to be considered to determine the viability of the technology.

Cost Vehicle Fuel Sensitivity

In recognition that the cost of vehicle fuel is volatile and that it varies across the United States, a sensitivity analysis was conducted to explore how the cost of fuel ranging from $2.00 to $6.50 per gallon would influence the life-cycle cost metrics. This sensitivity is presented graphically in Figure 3.

Figure 3
Cost of Vehicle Fuel Sensitivity Analysis

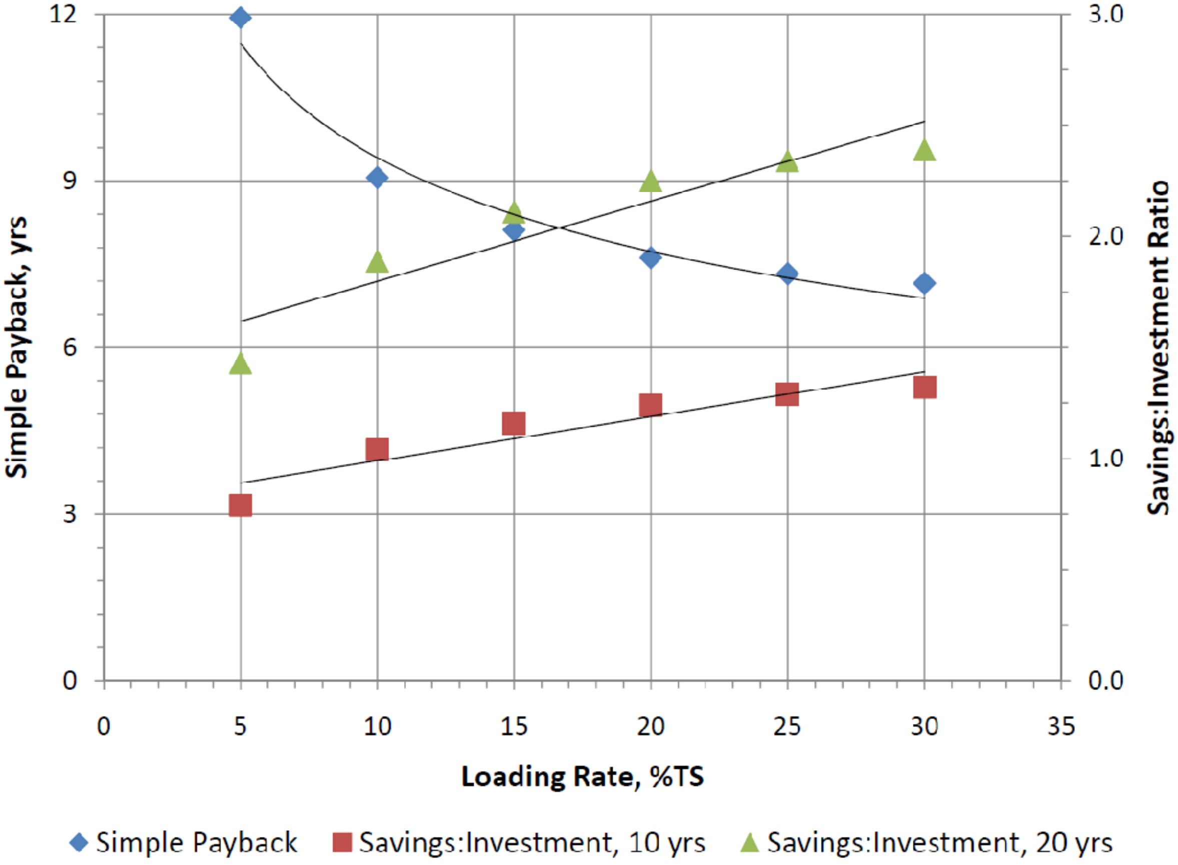


The sensitivity depicted in Figure 3 suggests that the economic metrics of the proposed technology are influenced significantly by the cost of vehicle fuel. As fuel prices increase, the simple payback period decreases and the SIRs increase. The simple payback reduces to less than 10 years and the SIR exceed 1.25 on a 20-year project life-cycle when vehicle fuel costs exceed $2.50 per gallon. This sensitivity suggests that the cost of vehicle fuel has one of the largest impacts on the economic viability of the proposed technology and thus should be considered carefully when evaluating the technology for implementation.

Digester Feed Concentration Sensitivity

The digester feed concentration and solids retention time (SRT) determines the required digester volume, which is directly related to the capital cost of the system. This sensitivity analysis explores how the feed concentration, and by extension the digester volume and capital costs, influence the economic metrics of the life-cycle analysis. For this sensitivity the assumed feed concentration was varied between 5 and 30 percent solids. This sensitivity is presented graphically in Figure 4.

Figure 4
Digester Loading Rate Sensitivity Analysis

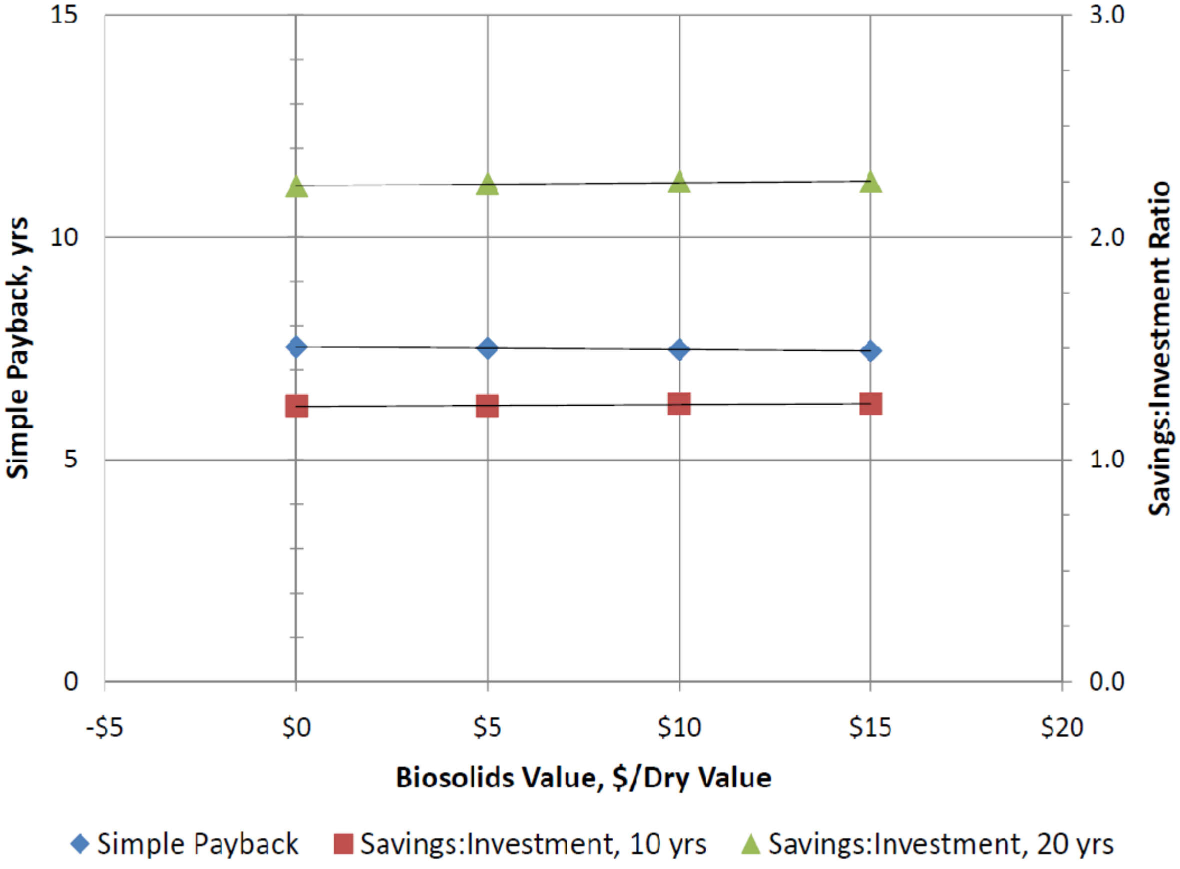


The sensitivity depicted in Figure 4 suggests that the economic metrics of the proposed technology are mildly influenced by the digester feed concentration, but that the influence is diminished as the feed concentration increases above 10 percent solids. At around 10 percent solids, the simple payback period reduces to less than 10 years and the SIRs are in excess of 1.25. Above 10 percent solids the metrics continue to improve, but at a reduced rate. The reason for this is that the digester costs represent a fraction of the overall project costs. Even as these costs are minimized by increasing the feed concentration, the other costs remain constant and keep the economic metrics relatively stable. Overall, it appears that assuming other national average conditions, a digester feed concentration of 10 percent or greater is sufficient to ensure that the project meets the established minimum DoD standards.

Biosolids Value Sensitivity

For the initial analysis it was assumed that any biosolids generated during the digestion process would be disposed of at a landfill and would be subject to the same trucking and tipping fees associated with food waste disposal. This sensitivity analysis explores how the economic metrics are influenced if the biosolids are not disposed of, but are used as a soil amendment. The sensitivity explores biosolids values between $0 and $15 per dry ton. The $0 value would represent a condition where the biosolids are given away (thus avoiding the landfill and trucking fees) and the $15 value would represent a condition in which the price point for the biosolids is set modestly. This sensitivity is presented graphically in Figure 5.

Figure 5
Cost of Vehicle Fuel Sensitivity Analysis



The sensitivity depicted in Figure 5 suggests that the economic metrics of the proposed technology are not influenced significantly by the price point of the biosolids product. However, the ability to give away or sell the biosolids does have a significant impact on the economic metrics. Recall that the initial analysis, which assumed a disposal fee for the biosolids, had a simple payback of 9.06 years and SIRs of 1.04 and 1.89 for the 10 and 20-year life-cycles respectively. By finding a beneficial use for the product, the simple payback was reduced to approximately 7 years, with SIRs of 1.25 and 2.25 for the 10-year and 20-year life-cycles respectively.

Conclusions

Based on this preliminary economic evaluation, it is expected that the proposed technology would meet the established minimum DoD standards for financing under national average conditions for construction, O&M, tipping fee, fuel and power costs. Additionally, as tipping fees and fuel costs increase, the economic viability of technology improves significantly approaching simple payback periods of less than 5 years and SIRs greater than 3.0.

When evaluating minimum conditions for installation, it is suggested that a minimum tipping fee of $40 per wet ton and or minimum fuel cost of $2.50 per gallon be present at the installation to ensure conformance with the minimum DoD standards. Other project variables such as the cost of power, the digester feed concentration, and the value of the biosolids product are also important considerations, but are not as influential.

Completion of the demonstration at the US Air Force Academy is required to validate many of the assumptions listed in Table 1 of this memorandum. However, treatability testing conducted to date has indicated that the assumptions are reasonable for USAFA food waste.

Works Cited

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[11] U.S. Department of Defense. (2009). *Instruction 4170.11 - Installation Energy Management.* Department of Defense.

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Appendix

ESTCP ER-0933 Renewable Energy Production from DoD Installation Solid Wastes by Anaerobic Digestion

1.0 Purpose/Objective

This calculation sheet was developed to estimate the capital and operational costs of a greenfield installation system capable of digesting foodwaste and capturing the biogas for use as vehicle fuel. Outputs from this sheet were used in the BLCC Milcon:ECIP Life-Cycle Cost analysis tool to estimate the simple payback and savings to investment ratios for 10-year and 20-year project lifecycles

2.0 Procedure

The calculation sheet systematically estimates capital and operational costs based on standard operational, construction and O&M parameters. Each individual input for the ECIP analysis is calculated separately.

3.0 References/Data Sources

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4.0 Variable Definitions

Variable	***Definition***	***Source***
$\text{Biogas}_{\text{available}}$	Amount of biogas available for conversion to biomethane, expressed in kW	Calculation Based
$\text{Biogas}_{\text{generated}}$	Volumetric flow rate of biogas generated during digestion	Calculation Based
$\text{Biogas}_{\text{heating}}$	Amount of biogas required to provide digester heating, expressed in kW	Calculation Based
$\text{Biogas}_{\text{LHV}}$	Low heating value of biogas	CDM Lab Analysis; East Bay MUD, 2008
$\text{Biogas}_{\text{power}}$	Equivalent power of biogas generated based on flow rate and heat content	Calculation Based
$\text{Biogas}_{\text{yield}}$	Biogas yield per pound of volatile solids destroyed	CDM Lab Analysis; East Bay MUD, 2008
$\text{Biomethane}_{\text{available}}$	Amount of biomethane available for conversion to rCNG, expressed in kW	Calculation Based
$\text{Biomethane}_{\text{Capital}}$	The capital cost for the biomethane treatment system	Calculation Based
$\text{Biomethane}_{\text{Cost}}$	The unit cost for the biomethane treatment	Nelson, 2008
$\text{Biomethane}_{\text{efficiency}}$	Efficiency of biomethane system at converting fuel to biomethane (i.e. methane capture	Nelson, 2008
$\text{Biomethane}_{\text{Labor}}$	The unit cost for labor and materials to operate	Nelson, 2008
$\text{Biomethane}_{\text{Power}}$	The calculated power demand for the biomethane system	Calculation Based

Biosolids$_{DryLoad}$	Mass load of biosolids generated per day, not including water	Calculation Based
Biosolids$_{TS}$	Assumed solids content of dewatered biosolids	Earle, 2005
Biosolids$_{Value}$	Value of the biosolids product as a soil ammendemnt	CDM Experience
Biosolids$_{WetLoad}$	Mass load of biosolids generated per day, including water	Calculation Based
Boiler$_{Capital}$	The capital cost for the boiler	Calculation Based
Boiler$_{Cost}$	The unit cost for a hot water boiler	CDM Experience
Boiler$_{efficiency}$	Efficiency of boiler at converting fuel to thermal energy	Industry Standard
Boiler$_{size}$	Estimated size of boiler required to meet digester heat demand	Calculation Based
Construction$_{Cost}$	The total construction cost for entire system including all overhead, insurance, escalationes, etc.	Calculation Based
Density	Density of food waste and water	Industry Standard
Design$_{Cost}$	The design cost for the entire system	Calculation Based
Dewatering$_{Capital}$	The capital cost for the dewatering system	Calculation Based
Dewatering$_{Cost}$	The unit cost for dewatering equipment	Earle, 2005
Dewatering$_{Power}$	The calculated power demand for the dewatering system	Calculation Based
Digestate$_{TS}$	Calculated concentration of digested solids within the digester	Calculation Based
Digestate$_{WetLoad}$	Mass load of digested solids generated per day, including water	Calculation Based
Digester$_{activevolume}$	Active volume of digester	Calculation Based
Digester$_{Capital}$	The capital cost for the digester	Calculation Based
Digester$_{conevolume}$	Cone volume of digester	Calculation Based
Digester$_{Cost}$	The unit cost for a digester	AgStar US EPA, Jan. 2010; Greer 2007
Digester$_{heat}$	Heat demand of the digester including heatlosses and heating up of influent feed	Calculation Based
Digester$_{loading}$	Energetic loading to digester in terms of mass of VS per unit volume per day	Calculation Based
Digester$_{SRT}$	Solids rentention time in digester	Industry Standard

5.0 Calculations

DEFINITIONS

$people := 1$

$therm := 10^5 BTU$

$polymer := 1$

$VS := 1$

$biosolids := 1$

$wet := 1$

$TS := 1$

$dollars := 1$

$dry := 1$

$waste := 1$

$kW_{fuel} := 1kW$

$digestate := 1$

$digester := 1$

$GGE := gal$

System Sizing - ASSUMPTIONS

$population := 50000 \cdot people$

$$waste_{pcpd} := 0.6 \frac{lb \cdot wet \cdot waste}{people \cdot day}$$

$$Density := 8.34 \frac{lb}{gal}$$

$$FW_{TS} := .30 \frac{lb \cdot TS}{lb \cdot waste}$$

$$FW_{VS} := 0.86 \frac{lb \cdot VS}{lb \cdot TS}$$

$Digester_{SRT} := 20day$

$$Influent_{TS} := 0.10 \frac{lb \cdot TS}{lb \cdot waste}$$

System Sizing - CALCULATIONS

First, calculate the total load per day of waste generated

$FW_{WetLoad} := population \cdot waste_{pcpd}$

$$FW_{WetLoad} = 30000 \cdot \frac{lb \cdot wet \cdot waste}{day}$$

$FW_{DryLoad} := population \cdot waste_{pcpd} \cdot FW_{TS}$

$$FW_{DryLoad} = 9000 \cdot \frac{lb}{day}$$

Second, calculate the load to the digester after the food waste is diluted down

$$Digester_{WetLoad} := \frac{FW_{DryLoad}}{Influent_{TS}}$$

$$Digester_{WetLoad} = 90000 \bullet \frac{lb \bullet wet \bullet waste}{day}$$

Third, confirm the amount of dilution water required to thin out the feed

$$Dilution_{Flow} := \frac{Digester_{WetLoad} - FW_{WetLoad}}{Density}$$

$$Dilution_{Flow} = 7194 \bullet \frac{gal}{day}$$

Fourth, calculate the active volume in the digester based on the desired SRT.

$$Digester_{activevolume} := \frac{Digester_{WetLoad}}{Density} \bullet Digester_{SRT}$$

$$Digester_{activevolume} = 215827 \bullet gal$$

Fifth, calculate the additional volume in the digester for the cone space

$$Digester_{conevolume} := Digester_{activevolume} \bullet 20\%$$

$$Digester_{conevolume} = 43165 \bullet gal$$

The digester volume is the sum of the active and cone volumes

$$Digester_{volume} := Digester_{activevolume} + Digester_{conevolume}$$

$$Digester_{volume} = 258993 \bullet gal$$

Check the digester loading rate on an energy basis to ensure that it meets expected loading rates

$$Digester_{loading} := \frac{FW_{DryLoad} \bullet FW_{VS}}{Digester_{activevolume}}$$

$$Digester_{loading} = 0.27 \bullet \frac{lb \bullet VS}{ft^3 \bullet day}$$

Digester Heating Requirements - ASSUMPTIONS

$SF_{heatloss} := 1.3$

$Temp_{Digester} := 98\Delta°F$

$Temp_{FW} := 55\Delta°F$

$Temp_{Dilution} := 90\Delta°F$

Digester Heating Requirements - Calculations

First, calculate the thermal energy in the feed (food waste + dilution water)

$$Heat_{Feed} := Temp_{FW} \cdot FW_{WetLoad} + Temp_{Dilution} \cdot Dilution_{Flow} \cdot Density$$

$$Heat_{Feed} = 7050000 \cdot \frac{lb \cdot \Delta°F}{day}$$

Second, calculate the thermal energy required in the digester

$$Heat_{Digester} := Temp_{Digester} \cdot FW_{WetLoad} + Temp_{Digester} \cdot Dilution_{Flow} \cdot Density$$

$$Heat_{Digester} = 8820000 \cdot \frac{lb \cdot \Delta°F}{day}$$

The heat demand is the difference between the thermal energies times a specific heat requirement and efficiency. The heat demand calculated here will be used to estimate the biogas available for utilization

$$Digester_{heat} := \left(Heat_{Digester} - Heat_{Feed}\right) \cdot \frac{1BTU}{lb \cdot \Delta°F} \cdot SF_{heatloss}$$

$$Digester_{heat} = 95875 \cdot \frac{BTU}{hr}$$

$$Digester_{heat} = 28 \cdot kW$$

The boiler is sized assuming no heat recovery from the recycle flow and follows the same principles as above.

$$Boiler_{size} := Digester_{WetLoad} \cdot \left(1 \frac{BTU}{lb \cdot \Delta°F}\right) \cdot \left(Temp_{Digester} - Temp_{FW}\right) \cdot SF_{heatloss}$$

$$Boiler_{size} = 61 \cdot kW$$

Biogas Generation - ASSUMPTIONS

$VS_{Destruction} := 80\%$

$Biogas_{yield} := 22 \frac{ft^3}{lb \cdot dry \cdot VS}$

$Biogas_{LHV} := 580 \frac{BTU}{ft^3}$

Biogas Generation - CALCULATIONS

First, calculate the amount of volatile solids destroyed in the digester

$VSD := population \cdot waste_{pcpd} \cdot FW_{TS} \cdot FW_{VS} \cdot VS_{Destruction}$

$VSD = 6192 \cdot \frac{lb \cdot dry \cdot VS}{day}$

Second, calculate biogas produced using a unit production/yield

$Biogas_{generated} := Biogas_{yield} \cdot VSD$

$Biogas_{generated} = 136224 \cdot \frac{ft^3}{day}$

Third, calculate the raw power of the biogas fuel based on the biogas heating value

$Biogas_{power} := Biogas_{generated} \cdot Biogas_{LHV}$

$Biogas_{power} = 965 \cdot kW_{fuel}$

Biogas Utilization - ASSUMPTIONS

$Boiler_{efficiency} := 83\%$

$Biomethane_{efficiency} := 95\%$

$rCNG_{LHV} := 114000 \frac{BTU}{GGE}$

Biogas Utilization - CALCULATIONS

First, calculate the amount of biogas used for heat.

$$\text{Biogas}_{\text{heating}} := \frac{\text{Digester}_{\text{heat}}}{\text{Boiler}_{\text{efficiency}}}$$

$$\text{Biogas}_{\text{heating}} = 34 \cdot \text{kW}_{\text{fuel}}$$

The biogas available for other uses is the gas produced less that which is used for heating

$$\text{Biogas}_{\text{available}} := \text{Biogas}_{\text{power}} - \text{Biogas}_{\text{heating}}$$

$$\text{Biogas}_{\text{available}} = 931 \cdot \text{kW}_{\text{fuel}}$$

Calculate the volume of biomethane (250 psig) that can be generated from the available biogas based on the system efficiency

$$\text{Biomethane}_{\text{available}} := \text{Biogas}_{\text{available}} \cdot \text{Biomethane}_{\text{efficiency}}$$

$$\text{Biomethane}_{\text{available}} = 884 \cdot \text{kW}_{\text{fuel}}$$

Calculate to volume of rCNG (4,500 psig) that can be generated from the avaialable biomethane

$$\text{rCNG}_{\text{available}} := \text{Biomethane}_{\text{available}}$$

$$\text{rCNG}_{\text{available}} = 884 \cdot \text{kW}_{\text{fuel}}$$

$$\text{rCNG}_{\text{GGE}} := \frac{\text{rCNG}_{\text{available}}}{\text{rCNG}_{\text{LHV}}}$$

$$\text{rCNG}_{\text{GGE}} = 635 \cdot \frac{\text{GGE}}{\text{day}}$$

Biosolids Generated - ASSUMPTIONS

$$\text{Biosolids}_{\text{TS}} := 0.25 \frac{\text{lb} \cdot \text{TS}}{\text{lb} \cdot \text{biosolids}}$$

Biosolids Generated - CALCULATIONS

First, calculate the solids content of the digestate based on the VS destroyed, assuming a conservation of mass within the digester.

$$\text{Digestate}_{\text{TS}} := \text{Influent}_{\text{TS}} \bullet \left[1 - \left(\text{FW}_{\text{VS}}\right)\left(\text{VS}_{\text{Destruction}}\right)\right]$$

$$\text{Digestate}_{\text{TS}} = 0.031 \bullet \frac{\text{lb} \bullet \text{TS}}{\text{lb} \bullet \text{digestate}}$$

First, calculate the mass load dry solids leaving the digester based on the amount of solids destroyed.

$$\text{Biosolids}_{\text{DryLoad}} := \text{FW}_{\text{WetLoad}} \bullet \text{FW}_{\text{TS}} - \text{VSD}$$

$$\text{Biosolids}_{\text{DryLoad}} = 2808 \bullet \frac{\text{lb} \bullet \text{dry} \bullet \text{TS}}{\text{day}}$$

Second, calculate the volumetric load of solids leaving the digester on a wet basis based on the digestate solids concentration and the density of solids

$$\text{Digestate}_{\text{WetLoad}} := \frac{\text{Biosolids}_{\text{DryLoad}}}{\text{Digestate}_{\text{TS}}}$$

$$\text{Digestate}_{\text{WetLoad}} = 90000 \bullet \frac{\text{lb} \bullet \text{wet} \bullet \text{digestate}}{\text{day}}$$

Third, calculate the volumetric load of dewatered biosolids based on the assumed solids content of the product.

$$\text{Biosolids}_{\text{WetLoad}} := \frac{\text{Biosolids}_{\text{DryLoad}}}{\text{Biosolids}_{\text{TS}}}$$

$$\text{Biosolids}_{\text{WetLoad}} = 11232 \bullet \frac{\text{lb} \bullet \text{wet} \bullet \text{biosolids}}{\text{day}}$$

The difference between the digestate and biosolids wet load is the mass of water expelled each day as pressate. This mass can be converted to a volumetric load of water by the density.

$$\text{Pressate}_{\text{WetLoad}} := \text{Digestate}_{\text{WetLoad}} - \text{Biosolids}_{\text{WetLoad}}$$

$$\text{Pressate}_{\text{WetLoad}} = 78768 \bullet \frac{\text{lb}}{\text{day}}$$

$$\text{Pressate}_{\text{Flow}} := \frac{\text{Pressate}_{\text{WetLoad}}}{\text{Density}}$$

$$\text{Pressate}_{\text{Flow}} = 9445 \cdot \frac{\text{gal}}{\text{day}}$$

The ammount of water sent to the sewer is the difference between the dilution flow and the pressate flow

$$\text{Sewer}_{\text{Flow}} := \text{Pressate}_{\text{Flow}} - \text{Dilution}_{\text{Flow}}$$

$$\text{Sewer}_{\text{Flow}} = 2250 \cdot \frac{\text{gal}}{\text{day}}$$

O & M - ASSUMPTIONS

$$\text{Power}_{\text{mixing}} := 50 \frac{\text{hp}}{10^6 \text{gal}}$$

$$\text{Power}_{\text{dewatering}} := 14 \frac{\text{kW} \cdot \text{hr}}{\text{ton} \cdot \text{TS}}$$

$$\text{Power}_{\text{biogastreatment}} := 13 \frac{\text{kW} \cdot \text{hr}}{10^6 \text{BTU}}$$

$$\text{Power}_{\text{rCNG}} := 1.75 \frac{\text{kW} \cdot \text{hr}}{\text{GGE}}$$

$$\text{Polymer}_{\text{dewatering}} := 15 \frac{\text{lb} \cdot \text{polymer}}{\text{ton} \cdot \text{TS}}$$

$$\text{Polymer}_{\text{cost}} := 3 \frac{\text{dollars}}{\text{lb} \cdot \text{polymer}}$$

O & M - CALCULATIONS

Calculate the power demand for the digester

$$\text{Digestion}_{\text{Power}} := \text{Power}_{\text{mixing}} \cdot \text{Digester}_{\text{volume}}$$

$$\text{Digestion}_{\text{Power}} = 10 \cdot \text{kW}$$

Calculate the power demand for the dewatering equipment

$$\text{Dewatering}_{\text{Power}} := \text{Power}_{\text{dewatering}} \cdot \text{Biosolids}_{\text{DryLoad}}$$

$$\text{Dewatering}_{\text{Power}} = 0.82 \cdot \text{kW}$$

Calculate the power demand for the biomethane gas purification system

$$\text{Biomethane}_{\text{Power}} := \text{Power}_{\text{biogastreatment}} \bullet \text{Biomethane}_{\text{available}}$$

$$\text{Biomethane}_{\text{Power}} = 39 \bullet \text{kW}$$

Calculate the power demand for the rCNG compression/fueling system

$$\text{rCNG}_{\text{Power}} := \text{Power}_{\text{rCNG}} \bullet \text{rCNG}_{\text{GGE}}$$

$$\text{rCNG}_{\text{Power}} = 46 \bullet \text{kW}$$

Calculate the total power demand as the sum of all the power demands

$$\text{Total}_{\text{Power}} := \text{Digestion}_{\text{Power}} + \text{Dewatering}_{\text{Power}} + \text{Biomethane}_{\text{Power}} + \text{rCNG}_{\text{Power}}$$

$$\text{Total}_{\text{Power}} = 96 \bullet \text{kW}$$

SENSITIVITY INPUTS

$$\text{Digester}_{\text{Cost}} := 5\,\frac{\text{dollars}}{\text{gal}}$$

$$\text{Dewatering}_{\text{Cost}} := 200000\,\frac{\text{dollars}}{\left(\frac{\text{dry} \bullet \text{ton}}{\text{day}}\right)}$$

$$\text{Boiler}_{\text{Cost}} := 220000\,\frac{\text{dollars}}{36\text{bhp}}$$

$$\text{Power}_{\text{Cost}} := 0.1012\,\frac{\text{dollars}}{\text{kW} \bullet \text{hr}}$$

$$\text{Biomethane}_{\text{Cost}} := 1400\,\frac{\text{dollars}}{\text{kW}_{\text{fuel}}}$$

$$\text{Biomethane}_{\text{Labor}} := 0.17\,\frac{\text{dollars}}{\text{therm}}$$

$$\text{rCNG}_{\text{Cost}} := 1400\,\frac{\text{dollars}}{\text{kW}_{\text{fuel}}}$$

$$\text{rCNG}_{\text{Labor}} := 0.20\,\frac{\text{dollars}}{\text{therm}}$$

$$\mathrm{rCNG}_{\mathrm{Value}} := 2.78\,\frac{\mathrm{dollars}}{\mathrm{GGE}} \bullet -1$$

$$\mathrm{TippingFee}_{\mathrm{Value}} := 43.99\,\frac{\mathrm{dollars}}{\mathrm{ton}} \bullet -1$$

$$\mathrm{Trucking}_{\mathrm{Value}} := 10\,\frac{\mathrm{dollars}}{\mathrm{ton}} \bullet -1$$

$$\mathrm{Biosolids}_{\mathrm{Value}} := 0\,\frac{\mathrm{dollars}}{\mathrm{ton}} \bullet -1$$

SUMMARY/LCC INPUTS

Calculate individual component capital cost

$$\mathrm{Digester}_{\mathrm{Capital}} := \mathrm{Digester}_{\mathrm{Cost}} \bullet \mathrm{Digester}_{\mathrm{volume}}$$

$$\mathrm{Digester}_{\mathrm{Capital}} = 1.29 \times 10^{6} \bullet \mathrm{dollars}$$

$$\mathrm{Dewatering}_{\mathrm{Capital}} := \mathrm{Dewatering}_{\mathrm{Cost}} \bullet \mathrm{Biosolids}_{\mathrm{DryLoad}}$$

$$\mathrm{Dewatering}_{\mathrm{Capital}} = 2.81 \times 10^{5} \bullet \mathrm{dollars}$$

$$\mathrm{Boiler}_{\mathrm{Capital}} := \mathrm{Boiler}_{\mathrm{Cost}} \bullet \mathrm{Boiler}_{\mathrm{size}}$$

$$\mathrm{Boiler}_{\mathrm{Capital}} = 3.83 \times 10^{4} \bullet \mathrm{dollars}$$

$$\mathrm{Biomethane}_{\mathrm{Capital}} := \mathrm{Biomethane}_{\mathrm{Cost}} \bullet \mathrm{Biomethane}_{\mathrm{available}}$$

$$\mathrm{Biomethane}_{\mathrm{Capital}} = 1.24 \times 10^{6} \bullet \mathrm{dollars}$$

$$\mathrm{rCNG}_{\mathrm{Capital}} := \mathrm{rCNG}_{\mathrm{Cost}} \bullet \mathrm{rCNG}_{\mathrm{available}}$$

$$\mathrm{rCNG}_{\mathrm{Capital}} = 1.24 \times 10^{6} \bullet \mathrm{dollars}$$

Total construction costs for LCC input

$$\mathrm{Construction}_{\mathrm{Cost}} := \mathrm{Digester}_{\mathrm{Capital}} + \mathrm{Dewatering}_{\mathrm{Capital}} + \mathrm{Boiler}_{\mathrm{Capital}} + \mathrm{Biomethane}_{\mathrm{Capital}} \ldots + \mathrm{rCNG}_{\mathrm{Capital}}$$

$$\mathrm{Construction}_{\mathrm{Cost}} = 4.09 \times 10^{6} \bullet \mathrm{dollars}$$

Design costs for LCC input

$$\mathrm{Design}_{\mathrm{Cost}} := \mathrm{Construction}_{\mathrm{Cost}} \bullet 20\%$$

$Design_{Cost} = 8.18 \times 10^5 \bullet dollars$

Calculate total costs for power

$OM_{Power} := (Total_{Power}) \bullet Power_{Cost}$

$OM_{Power} = 8.52 \times 10^4 \bullet \frac{dollars}{yr}$

Calculate total energy use for LCC input

$Total_{Electricity} := Total_{Power} \bullet 1yr$

$Total_{Electricity} = 8.42 \times 10^5 \bullet kW \bullet hr$

Calculate the O&M for the individual components

$OM_{Digestion} := Digester_{Capital} \bullet \frac{5\%}{yr}$

$OM_{Digestion} = 6.47 \times 10^4 \bullet \frac{dollars}{yr}$

$OM_{Dewatering} := Polymer_{dewatering} \bullet Biosolids_{DryLoad} \bullet Polymer_{cost} + Dewatering_{Capital} \bullet 5\frac{\%}{yr}$

$OM_{Dewatering} = 3.71 \times 10^4 \bullet \frac{dollars}{yr}$

$OM_{Biomethane} := Biomethane_{Labor} \bullet Biomethane_{available}$

$OM_{Biomethane} = 4.5 \times 10^4 \bullet \frac{dollars}{yr}$

$OM_{rCNG} := rCNG_{Labor} \bullet Biomethane_{available}$

$OM_{rCNG} = 5.29 \times 10^4 \bullet \frac{dollars}{yr}$

$Revenue_{rCNG} := rCNG_{GGE} \bullet rCNG_{Value}$

$Revenue_{rCNG} = -6.45 \times 10^5 \bullet \frac{dollars}{yr}$

$rCNG_{available} = 2.65 \times 10^5 \bullet \frac{therm}{yr}$

$$Revenue_{Tipping} := \left(FW_{WetLoad} - Biosolids_{WetLoad}\right) \bullet TippingFee_{Value}$$

$$Revenue_{Tipping} = -1.51 \times 10^{5} \bullet \frac{dollars}{yr}$$

$$Revenue_{Trucking} := \left(FW_{WetLoad} - Biosolids_{WetLoad}\right) \bullet Trucking_{Value} = -0\,\frac{1}{s}$$

$$Revenue_{Trucking} = -3.43 \times 10^{4} \bullet \frac{dollars}{yr}$$

$$Revenue_{Biosolids} := Biosolids_{Value} \bullet Biosolids_{DryLoad}$$

$$Revenue_{Biosolids} = 0 \times 10^{0} \bullet \frac{dollars}{yr}$$

SIMPLE PAYBACK

$$OM_{Total} := OM_{Power} + OM_{Digestion} + OM_{Dewatering} + OM_{Biomethane} + OM_{rCNG} \cdots$$
$$+ Revenue_{rCNG} + Revenue_{Tipping} + Revenue_{Trucking} + Revenue_{Biosolids}$$

$$OM_{Total} = -5.45 \times 10^{5} \bullet \frac{dollars}{yr}$$

$$Payback_{simple} := \frac{Construction_{Cost} + Design_{Cost}}{OM_{Total} \bullet -1}$$

$$Payback_{simple} = 9 \bullet yr$$

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 16:40:39 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Base Case, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$541,690	
5. Simple Payback Period (in years)	9.06	(total investment/first-year savings)
6. Total Discounted Operational Savings	$9,279,521	
7. Savings to Investment Ratio (SIR)	1.89	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	6.33%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 16:51:25 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $20, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$102,100	Annual	15.099	-$1,541,594
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$102,100			-$1,541,594

4. First year savings	$459,290	
5. Simple Payback Period (in years)	10.69	(total investment/first-year savings)
6. Total Discounted Operational Savings	$8,035,375	
7. Savings to Investment Ratio (SIR)	1.64	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.57%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 16:52:26 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $30, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$67,800	Annual	15.099	-$1,023,703
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$67,800			-$1,023,703

4. First year savings	$493,590	
5. Simple Payback Period (in years)	9.94	(total investment/first-year savings)
6. Total Discounted Operational Savings	$8,553,266	
7. Savings to Investment Ratio (SIR)	1.74	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.90%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 16:53:09 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $40, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$33,500	Annual	15.099	-$505,812
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$33,500			-$505,812

4. First year savings	$527,890	
5. Simple Payback Period (in years)	9.30	(total investment/first-year savings)
6. Total Discounted Operational Savings	$9,071,157	
7. Savings to Investment Ratio (SIR)	1.85	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	6.21%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 16:53:50 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $50, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$800	Annual	15.099	$12,079
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$800			$12,079

4. First year savings	$562,190	
5. Simple Payback Period (in years)	8.73	(total investment/first-year savings)
6. Total Discounted Operational Savings	$9,589,048	
7. Savings to Investment Ratio (SIR)	1.95	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	6.51%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 16:55:40 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $60, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$35,100	Annual	15.099	$529,970
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$35,100			$529,970

4. First year savings	$596,490	
5. Simple Payback Period (in years)	8.23	(total investment/first-year savings)
6. Total Discounted Operational Savings	$10,106,939	
7. Savings to Investment Ratio (SIR)	2.06	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	6.79%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 16:56:30 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $70, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$69,400	Annual	15.099	$1,047,861
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$69,400			$1,047,861

4. First year savings	$630,790	
5. Simple Payback Period (in years)	7.78	(total investment/first-year savings)
6. Total Discounted Operational Savings	$10,624,830	
7. Savings to Investment Ratio (SIR)	2.16	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.06%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 16:56:58 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $80, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$103,700	Annual	15.099	$1,565,752
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$103,700			$1,565,752

4. First year savings	$665,090	
5. Simple Payback Period (in years)	7.38	(total investment/first-year savings)
6. Total Discounted Operational Savings	$11,142,721	
7. Savings to Investment Ratio (SIR)	2.27	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.31%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 16:57:29 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $90, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$138,000	Annual	15.099	$2,083,643
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$138,000			$2,083,643

4. First year savings	$699,390	
5. Simple Payback Period (in years)	7.02	(total investment/first-year savings)
6. Total Discounted Operational Savings	$11,660,612	
7. Savings to Investment Ratio (SIR)	2.38	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.56%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 16:57:45 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $100, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$172,300	Annual	15.099	$2,601,534
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$172,300			$2,601,534

4. First year savings	$733,690	
5. Simple Payback Period (in years)	6.69	(total investment/first-year savings)
6. Total Discounted Operational Savings	$12,178,503	
7. Savings to Investment Ratio (SIR)	2.48	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.79%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 16:58:37 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $110, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$206,600	Annual	15.099	$3,119,425
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$206,600			$3,119,425

4. First year savings	$767,990	
5. Simple Payback Period (in years)	6.39	(total investment/first-year savings)
6. Total Discounted Operational Savings	$12,696,394	
7. Savings to Investment Ratio (SIR)	2.59	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	8.01%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 16:58:56 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $120, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$240,900	Annual	15.099	$3,637,316
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$240,900			$3,637,316

4. First year savings	$802,290	
5. Simple Payback Period (in years)	6.12	(total investment/first-year savings)
6. Total Discounted Operational Savings	$13,214,285	
7. Savings to Investment Ratio (SIR)	2.69	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	8.23%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 16:59:39 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $130, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$275,200	Annual	15.099	$4,155,207
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$275,200			$4,155,207

4. First year savings	$836,590	
5. Simple Payback Period (in years)	5.87	(total investment/first-year savings)
6. Total Discounted Operational Savings	$13,732,176	
7. Savings to Investment Ratio (SIR)	2.80	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	8.44%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:00:07 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $140, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$309,500	Annual	15.099	$4,673,098
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$309,500			$4,673,098

4. First year savings	$870,890	
5. Simple Payback Period (in years)	5.64	(total investment/first-year savings)
6. Total Discounted Operational Savings	$14,250,067	
7. Savings to Investment Ratio (SIR)	2.90	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	8.64%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:00:38 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $150, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$343,800	Annual	15.099	$5,190,989
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$343,800			$5,190,989

4. First year savings	$905,190	
5. Simple Payback Period (in years)	5.42	(total investment/first-year savings)
6. Total Discounted Operational Savings	$14,767,958	
7. Savings to Investment Ratio (SIR)	3.01	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	8.83%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:25:46 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Elec, $0.05, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$14.65356	-2,873.0 MBtu	-$42,100	15.130	-$636,979
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$604,500		$10,229,236
Water Subtotal		0.0 Mgal	$0		$0
Total			$604,500		$10,229,236

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$584,800	
5. Simple Payback Period (in years)	8.39	(total investment/first-year savings)
6. Total Discounted Operational Savings	$9,931,788	
7. Savings to Investment Ratio (SIR)	2.02	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	6.70%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:26:21 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Elec, $0.10, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.30711	-2,873.0 MBtu	-$84,200	15.130	-$1,273,958
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$562,400		$9,592,257
Water Subtotal		0.0 Mgal	$0		$0
Total			$562,400		$9,592,257

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$542,700	
5. Simple Payback Period (in years)	9.04	(total investment/first-year savings)
6. Total Discounted Operational Savings	$9,294,809	
7. Savings to Investment Ratio (SIR)	1.89	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	6.34%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:26:56 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Elec, $0.20, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$43.96067	-2,873.0 MBtu	-$126,300	15.130	-$1,910,937
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$520,300		$8,955,278
Water Subtotal		0.0 Mgal	$0		$0
Total			$520,300		$8,955,278

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$500,600	
5. Simple Payback Period (in years)	9.80	(total investment/first-year savings)
6. Total Discounted Operational Savings	$8,657,830	
7. Savings to Investment Ratio (SIR)	1.76	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.97%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:27:42 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Elec, $0.20, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$58.61423	-2,873.0 MBtu	-$168,400	15.130	-$2,547,916
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$478,200		$8,318,299
Water Subtotal		0.0 Mgal	$0		$0
Total			$478,200		$8,318,299

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$458,500	
5. Simple Payback Period (in years)	10.70	(total investment/first-year savings)
6. Total Discounted Operational Savings	$8,020,851	
7. Savings to Investment Ratio (SIR)	1.63	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.56%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:28:11 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Elec, $0.25, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$73.26778	-2,873.0 MBtu	-$210,500	15.130	-$3,184,895
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$436,100		$7,681,320
Water Subtotal		0.0 Mgal	$0		$0
Total			$436,100		$7,681,320

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$416,400	
5. Simple Payback Period (in years)	11.79	(total investment/first-year savings)
6. Total Discounted Operational Savings	$7,383,872	
7. Savings to Investment Ratio (SIR)	1.50	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.13%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:31:40 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $2.00, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$17.49993	26,500.1 MBtu	$463,750	16.805	$7,793,392
Energy Subtotal		23,627.1 MBtu	$378,540		$6,504,146
Water Subtotal		0.0 Mgal	$0		$0
Total			$378,540		$6,504,146

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$358,840	
5. Simple Payback Period (in years)	13.68	(total investment/first-year savings)
6. Total Discounted Operational Savings	$6,206,698	
7. Savings to Investment Ratio (SIR)	1.26	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	4.22%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:32:37 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $2.50, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$21.89992	26,500.1 MBtu	$580,350	16.805	$9,752,873
Energy Subtotal		23,627.1 MBtu	$495,140		$8,463,627
Water Subtotal		0.0 Mgal	$0		$0
Total			$495,140		$8,463,627

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$475,440	
5. Simple Payback Period (in years)	10.32	(total investment/first-year savings)
6. Total Discounted Operational Savings	$8,166,180	
7. Savings to Investment Ratio (SIR)	1.66	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.66%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:33:02 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $3.00, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$26.29990	26,500.1 MBtu	$696,950	16.805	$11,712,354
Energy Subtotal		23,627.1 MBtu	$611,740		$10,423,109
Water Subtotal		0.0 Mgal	$0		$0
Total			$611,740		$10,423,109

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$592,040	
5. Simple Payback Period (in years)	8.29	(total investment/first-year savings)
6. Total Discounted Operational Savings	$10,125,661	
7. Savings to Investment Ratio (SIR)	2.06	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	6.80%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:33:42 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $3.50, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$30.69988	26,500.1 MBtu	$813,550	16.805	$13,671,836
Energy Subtotal		23,627.1 MBtu	$728,340		$12,382,590
Water Subtotal		0.0 Mgal	$0		$0
Total			$728,340		$12,382,590

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$708,640	
5. Simple Payback Period (in years)	6.93	(total investment/first-year savings)
6. Total Discounted Operational Savings	$12,085,142	
7. Savings to Investment Ratio (SIR)	2.46	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.75%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:34:05 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $4.00, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$35.09987	26,500.1 MBtu	$930,150	16.805	$15,631,317
Energy Subtotal		23,627.1 MBtu	$844,940		$14,342,071
Water Subtotal		0.0 Mgal	$0		$0
Total			$844,940		$14,342,071

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$825,240	
5. Simple Payback Period (in years)	5.95	(total investment/first-year savings)
6. Total Discounted Operational Savings	$14,044,624	
7. Savings to Investment Ratio (SIR)	2.86	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	8.56%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:34:32 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $4.50, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$39.49985	26,500.1 MBtu	$1,046,750	16.805	$17,590,798
Energy Subtotal		23,627.1 MBtu	$961,540		$16,301,553
Water Subtotal		0.0 Mgal	$0		$0
Total			$961,540		$16,301,553

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$941,840	
5. Simple Payback Period (in years)	5.21	(total investment/first-year savings)
6. Total Discounted Operational Savings	$16,004,105	
7. Savings to Investment Ratio (SIR)	3.26	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	9.27%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:35:00 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $5.00, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$43.89983	26,500.1 MBtu	$1,163,350	16.805	$19,550,280
Energy Subtotal		23,627.1 MBtu	$1,078,140		$18,261,034
Water Subtotal		0.0 Mgal	$0		$0
Total			$1,078,140		$18,261,034

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$1,058,440	
5. Simple Payback Period (in years)	4.64	(total investment/first-year savings)
6. Total Discounted Operational Savings	$17,963,586	
7. Savings to Investment Ratio (SIR)	3.66	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	9.90%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:35:28 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $5.50, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$48.19982	26,500.1 MBtu	$1,277,300	16.805	$21,465,227
Energy Subtotal		23,627.1 MBtu	$1,192,090		$20,175,982
Water Subtotal		0.0 Mgal	$0		$0
Total			$1,192,090		$20,175,982

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$1,172,390	
5. Simple Payback Period (in years)	4.19	(total investment/first-year savings)
6. Total Discounted Operational Savings	$19,878,534	
7. Savings to Investment Ratio (SIR)	4.05	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	10.46%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:35:52 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $6.00, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$52.59980	26,500.1 MBtu	$1,393,900	16.805	$23,424,708
Energy Subtotal		23,627.1 MBtu	$1,308,690		$22,135,463
Water Subtotal		0.0 Mgal	$0		$0
Total			$1,308,690		$22,135,463

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$1,288,990	
5. Simple Payback Period (in years)	3.81	(total investment/first-year savings)
6. Total Discounted Operational Savings	$21,838,015	
7. Savings to Investment Ratio (SIR)	4.45	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	10.98%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:36:15 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $6.50, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$56.99979	26,500.1 MBtu	$1,510,500	16.805	$25,384,190
Energy Subtotal		23,627.1 MBtu	$1,425,290		$24,094,944
Water Subtotal		0.0 Mgal	$0		$0
Total			$1,425,290		$24,094,944

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$1,405,590	
5. Simple Payback Period (in years)	3.49	(total investment/first-year savings)
6. Total Discounted Operational Savings	$23,797,497	
7. Savings to Investment Ratio (SIR)	4.85	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	11.46%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:46:09 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Loading 5%, 20yr.xml		

1. Investment

Construction Cost	$5,390,000
SIOH	$0
Design Cost	$1,078,000
Total Cost	$6,468,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$6,468,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$541,690	
5. Simple Payback Period (in years)	11.94	(total investment/first-year savings)
6. Total Discounted Operational Savings	$9,279,521	
7. Savings to Investment Ratio (SIR)	1.43	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	4.88%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:46:48 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Loading 10%, 20yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$541,690	
5. Simple Payback Period (in years)	9.06	(total investment/first-year savings)
6. Total Discounted Operational Savings	$9,279,521	
7. Savings to Investment Ratio (SIR)	1.89	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	6.33%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:47:47 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Loading 15%, 20yr.xml		

1. Investment

Construction Cost	$3,660,000
SIOH	$0
Design Cost	$732,000
Total Cost	$4,392,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,392,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$541,690	
5. Simple Payback Period (in years)	8.11	(total investment/first-year savings)
6. Total Discounted Operational Savings	$9,279,521	
7. Savings to Investment Ratio (SIR)	2.11	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	6.93%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:48:28 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Loading 20%, 20yr.xml		

1. Investment

Construction Cost	$3,440,000
SIOH	$0
Design Cost	$688,000
Total Cost	$4,128,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,128,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$541,690	
5. Simple Payback Period (in years)	7.62	(total investment/first-year savings)
6. Total Discounted Operational Savings	$9,279,521	
7. Savings to Investment Ratio (SIR)	2.25	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.26%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:49:24 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Loading 25%, 20yr.xml		

1. Investment

Construction Cost	$3,310,000
SIOH	$0
Design Cost	$662,000
Total Cost	$3,972,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$3,972,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$541,690	
5. Simple Payback Period (in years)	7.33	(total investment/first-year savings)
6. Total Discounted Operational Savings	$9,279,521	
7. Savings to Investment Ratio (SIR)	2.34	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.46%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:49:53 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Loading 30%, 20yr.xml		

1. Investment

Construction Cost	$3,230,000
SIOH	$0
Design Cost	$646,000
Total Cost	$3,876,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$3,876,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$541,690	
5. Simple Payback Period (in years)	7.16	(total investment/first-year savings)
6. Total Discounted Operational Savings	$9,279,521	
7. Savings to Investment Ratio (SIR)	2.39	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.60%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:58:16 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Biosolids, $0, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$90,800	Annual	15.099	$1,370,977
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$90,800			$1,370,977

4. First year savings	$652,190	
5. Simple Payback Period (in years)	7.53	(total investment/first-year savings)
6. Total Discounted Operational Savings	$10,947,946	
7. Savings to Investment Ratio (SIR)	2.23	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.22%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:58:52 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Biosolids, $5, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$93,360	Annual	15.099	$1,409,630
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$93,360			$1,409,630

4. First year savings	$654,750	
5. Simple Payback Period (in years)	7.50	(total investment/first-year savings)
6. Total Discounted Operational Savings	$10,986,599	
7. Savings to Investment Ratio (SIR)	2.24	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.24%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:59:19 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Biosolids, $10, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$95,920	Annual	15.099	$1,448,283
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$95,920			$1,448,283

4. First year savings	$657,310	
5. Simple Payback Period (in years)	7.47	(total investment/first-year savings)
6. Total Discounted Operational Savings	$11,025,252	
7. Savings to Investment Ratio (SIR)	2.25	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.25%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:59:54 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Biosolids, $15, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$98,480	Annual	15.099	$1,486,936
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$98,480			$1,486,936

4. First year savings	$659,870	
5. Simple Payback Period (in years)	7.44	(total investment/first-year savings)
6. Total Discounted Operational Savings	$11,063,905	
7. Savings to Investment Ratio (SIR)	2.25	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.27%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 16:35:06 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Base Case, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$541,690	
5. Simple Payback Period (in years)	9.06	(total investment/first-year savings)
6. Total Discounted Operational Savings	$5,110,744	
7. Savings to Investment Ratio (SIR)	1.04	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	3.42%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:10:15 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $20, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$102,100	Annual	8.657	-$883,897
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$102,100			-$883,897

4. First year savings	$459,290	
5. Simple Payback Period (in years)	10.69	(total investment/first-year savings)
6. Total Discounted Operational Savings	$4,397,394	
7. Savings to Investment Ratio (SIR)	0.90	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	1.87%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:09:47 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $30, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$67,800	Annual	8.657	-$586,956
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$67,800			-$586,956

4. First year savings	$493,590	
5. Simple Payback Period (in years)	9.94	(total investment/first-year savings)
6. Total Discounted Operational Savings	$4,694,334	
7. Savings to Investment Ratio (SIR)	0.96	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	2.54%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:09:18 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $40, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$33,500	Annual	8.657	-$290,015
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$33,500			-$290,015

4. First year savings	$527,890	
5. Simple Payback Period (in years)	9.30	(total investment/first-year savings)
6. Total Discounted Operational Savings	$4,991,275	
7. Savings to Investment Ratio (SIR)	1.02	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	3.17%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:08:48 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $50, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$800	Annual	8.657	$6,926
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$800			$6,926

4. First year savings	$562,190	
5. Simple Payback Period (in years)	8.73	(total investment/first-year savings)
6. Total Discounted Operational Savings	$5,288,216	
7. Savings to Investment Ratio (SIR)	1.08	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	3.77%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:08:23 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $60, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$35,100	Annual	8.657	$303,867
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$35,100			$303,867

4. First year savings	$596,490	
5. Simple Payback Period (in years)	8.23	(total investment/first-year savings)
6. Total Discounted Operational Savings	$5,585,157	
7. Savings to Investment Ratio (SIR)	1.14	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	4.34%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:07:57 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $70, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$69,400	Annual	8.657	$600,808
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$69,400			$600,808

4. First year savings	$630,790	
5. Simple Payback Period (in years)	7.78	(total investment/first-year savings)
6. Total Discounted Operational Savings	$5,882,098	
7. Savings to Investment Ratio (SIR)	1.20	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	4.88%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:07:19 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $80, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$103,700	Annual	8.657	$897,749
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$103,700			$897,749

4. First year savings	$665,090	
5. Simple Payback Period (in years)	7.38	(total investment/first-year savings)
6. Total Discounted Operational Savings	$6,179,039	
7. Savings to Investment Ratio (SIR)	1.26	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.40%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:06:48 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $90, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$138,000	Annual	8.657	$1,194,690
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$138,000			$1,194,690

4. First year savings	$699,390	
5. Simple Payback Period (in years)	7.02	(total investment/first-year savings)
6. Total Discounted Operational Savings	$6,475,980	
7. Savings to Investment Ratio (SIR)	1.32	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.90%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:06:15 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $100, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$172,300	Annual	8.657	$1,491,631
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$172,300			$1,491,631

4. First year savings	$733,690	
5. Simple Payback Period (in years)	6.69	(total investment/first-year savings)
6. Total Discounted Operational Savings	$6,772,921	
7. Savings to Investment Ratio (SIR)	1.38	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	6.37%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:05:39 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $110, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$206,600	Annual	8.657	$1,788,572
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$206,600			$1,788,572

4. First year savings	$767,990	
5. Simple Payback Period (in years)	6.39	(total investment/first-year savings)
6. Total Discounted Operational Savings	$7,069,862	
7. Savings to Investment Ratio (SIR)	1.44	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	6.83%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:04:22 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $120, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$240,900	Annual	8.657	$2,085,513
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$240,900			$2,085,513

4. First year savings	$802,290	
5. Simple Payback Period (in years)	6.12	(total investment/first-year savings)
6. Total Discounted Operational Savings	$7,366,803	
7. Savings to Investment Ratio (SIR)	1.50	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.27%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:03:50 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $130, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$275,200	Annual	8.657	$2,382,454
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$275,200			$2,382,454

4. First year savings	$836,590	
5. Simple Payback Period (in years)	5.87	(total investment/first-year savings)
6. Total Discounted Operational Savings	$7,663,744	
7. Savings to Investment Ratio (SIR)	1.56	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.69%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:03:14 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $140, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$309,500	Annual	8.657	$2,679,394
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$309,500			$2,679,394

4. First year savings	$870,890	
5. Simple Payback Period (in years)	5.64	(total investment/first-year savings)
6. Total Discounted Operational Savings	$7,960,685	
7. Savings to Investment Ratio (SIR)	1.62	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	8.10%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:02:33 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $150, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$343,800	Annual	8.657	$2,976,335
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$343,800			$2,976,335

4. First year savings	$905,190	
5. Simple Payback Period (in years)	5.42	(total investment/first-year savings)
6. Total Discounted Operational Savings	$8,257,626	
7. Savings to Investment Ratio (SIR)	1.68	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	8.50%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:17:50 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Elec, $0.05, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$14.65356	-2,873.0 MBtu	-$42,100	8.696	-$366,115
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$604,500		$5,656,193
Water Subtotal		0.0 Mgal	$0		$0
Total			$604,500		$5,656,193

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$584,800	
5. Simple Payback Period (in years)	8.39	(total investment/first-year savings)
6. Total Discounted Operational Savings	$5,485,647	
7. Savings to Investment Ratio (SIR)	1.12	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	4.15%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:18:16 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Elec, $0.10, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.30711	-2,873.0 MBtu	-$84,200	8.696	-$732,231
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$562,400		$5,290,077
Water Subtotal		0.0 Mgal	$0		$0
Total			$562,400		$5,290,077

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$542,700	
5. Simple Payback Period (in years)	9.04	(total investment/first-year savings)
6. Total Discounted Operational Savings	$5,119,531	
7. Savings to Investment Ratio (SIR)	1.04	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	3.44%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:21:23 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Elec, $0.15, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$43.96067	-2,873.0 MBtu	-$126,300	8.696	-$1,098,346
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$520,300		$4,923,962
Water Subtotal		0.0 Mgal	$0		$0
Total			$520,300		$4,923,962

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$500,600	
5. Simple Payback Period (in years)	9.80	(total investment/first-year savings)
6. Total Discounted Operational Savings	$4,753,416	
7. Savings to Investment Ratio (SIR)	0.97	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	2.67%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:20:42 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Elec, $0.20, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$58.61423	-2,873.0 MBtu	-$168,400	8.696	-$1,464,461
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$478,200		$4,557,847
Water Subtotal		0.0 Mgal	$0		$0
Total			$478,200		$4,557,847

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$458,500	
5. Simple Payback Period (in years)	10.70	(total investment/first-year savings)
6. Total Discounted Operational Savings	$4,387,301	
7. Savings to Investment Ratio (SIR)	0.89	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	1.85%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:20:14 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Elec, $0.25, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$73.26778	-2,873.0 MBtu	-$210,500	8.696	-$1,830,577
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$436,100		$4,191,731
Water Subtotal		0.0 Mgal	$0		$0
Total			$436,100		$4,191,731

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$416,400	
5. Simple Payback Period (in years)	11.79	(total investment/first-year savings)
6. Total Discounted Operational Savings	$4,021,185	
7. Savings to Investment Ratio (SIR)	0.82	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	0.97%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:43:07 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $2.00, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$17.49993	26,500.1 MBtu	$463,750	9.314	$4,319,278
Energy Subtotal		23,627.1 MBtu	$378,540		$3,578,261
Water Subtotal		0.0 Mgal	$0		$0
Total			$378,540		$3,578,261

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$358,840	
5. Simple Payback Period (in years)	13.68	(total investment/first-year savings)
6. Total Discounted Operational Savings	$3,407,715	
7. Savings to Investment Ratio (SIR)	0.69	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	-0.69%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:42:51 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $2.50, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$21.89992	26,500.1 MBtu	$580,350	9.314	$5,405,268
Energy Subtotal		23,627.1 MBtu	$495,140		$4,664,251
Water Subtotal		0.0 Mgal	$0		$0
Total			$495,140		$4,664,251

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$475,440	
5. Simple Payback Period (in years)	10.32	(total investment/first-year savings)
6. Total Discounted Operational Savings	$4,493,705	
7. Savings to Investment Ratio (SIR)	0.92	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	2.10%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:42:34 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $3.00, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$26.29990	26,500.1 MBtu	$696,950	9.314	$6,491,258
Energy Subtotal		23,627.1 MBtu	$611,740		$5,750,241
Water Subtotal		0.0 Mgal	$0		$0
Total			$611,740		$5,750,241

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$592,040	
5. Simple Payback Period (in years)	8.29	(total investment/first-year savings)
6. Total Discounted Operational Savings	$5,579,695	
7. Savings to Investment Ratio (SIR)	1.14	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	4.33%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:42:20 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $3.50, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$30.69988	26,500.1 MBtu	$813,550	9.314	$7,577,248
Energy Subtotal		23,627.1 MBtu	$728,340		$6,836,231
Water Subtotal		0.0 Mgal	$0		$0
Total			$728,340		$6,836,231

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$708,640	
5. Simple Payback Period (in years)	6.93	(total investment/first-year savings)
6. Total Discounted Operational Savings	$6,665,685	
7. Savings to Investment Ratio (SIR)	1.36	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	6.20%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:41:45 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $4.00, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$35.09987	26,500.1 MBtu	$930,150	9.314	$8,663,238
Energy Subtotal		23,627.1 MBtu	$844,940		$7,922,221
Water Subtotal		0.0 Mgal	$0		$0
Total			$844,940		$7,922,221

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$825,240	
5. Simple Payback Period (in years)	5.95	(total investment/first-year savings)
6. Total Discounted Operational Savings	$7,751,675	
7. Savings to Investment Ratio (SIR)	1.58	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.82%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:42:05 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $4.50, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$39.49985	26,500.1 MBtu	$1,046,750	9.314	$9,749,228
Energy Subtotal		23,627.1 MBtu	$961,540		$9,008,211
Water Subtotal		0.0 Mgal	$0		$0
Total			$961,540		$9,008,211

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$941,840	
5. Simple Payback Period (in years)	5.21	(total investment/first-year savings)
6. Total Discounted Operational Savings	$8,837,665	
7. Savings to Investment Ratio (SIR)	1.80	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	9.24%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date	January 1, 2011	Preparation Date:	Sat Jan 29 17:41:16 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $5.00, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$43.89983	26,500.1 MBtu	$1,163,350	9.314	$10,835,218
Energy Subtotal		23,627.1 MBtu	$1,078,140		$10,094,201
Water Subtotal		0.0 Mgal	$0		$0
Total			$1,078,140		$10,094,201

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$1,058,440	
5. Simple Payback Period (in years)	4.64	(total investment/first-year savings)
6. Total Discounted Operational Savings	$9,923,655	
7. Savings to Investment Ratio (SIR)	2.02	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	10.51%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:41:00 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $5.50, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$48.19982	26,500.1 MBtu	$1,277,300	9.314	$11,896,527
Energy Subtotal		23,627.1 MBtu	$1,192,090		$11,155,509
Water Subtotal		0.0 Mgal	$0		$0
Total			$1,192,090		$11,155,509

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$1,172,390	
5. Simple Payback Period (in years)	4.19	(total investment/first-year savings)
6. Total Discounted Operational Savings	$10,984,963	
7. Savings to Investment Ratio (SIR)	2.24	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	11.64%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:40:38 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $6.00, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$52.59980	26,500.1 MBtu	$1,393,900	9.314	$12,982,517
Energy Subtotal		23,627.1 MBtu	$1,308,690		$12,241,499
Water Subtotal		0.0 Mgal	$0		$0
Total			$1,308,690		$12,241,499

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$1,288,990	
5. Simple Payback Period (in years)	3.81	(total investment/first-year savings)
6. Total Discounted Operational Savings	$12,070,953	
7. Savings to Investment Ratio (SIR)	2.46	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	12.70%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:40:23 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $6.50, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$56.99979	26,500.1 MBtu	$1,510,500	9.314	$14,068,507
Energy Subtotal		23,627.1 MBtu	$1,425,290		$13,327,489
Water Subtotal		0.0 Mgal	$0		$0
Total			$1,425,290		$13,327,489

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$1,405,590	
5. Simple Payback Period (in years)	3.49	(total investment/first-year savings)
6. Total Discounted Operational Savings	$13,156,943	
7. Savings to Investment Ratio (SIR)	2.68	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	13.68%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Mon Jan 31 08:53:36 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Version 1\Loading\Loading 5, 10 yr.xml		

1. Investment

Construction Cost	$5,390,000
SIOH	$0
Design Cost	$1,078,000
Total Cost	$6,468,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$6,468,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$541,690	
5. Simple Payback Period (in years)	11.94	(total investment/first-year savings)
6. Total Discounted Operational Savings	$5,110,744	
7. Savings to Investment Ratio (SIR)	0.79	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	0.60%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:54:56 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Loading 10, 10yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$541,690	
5. Simple Payback Period (in years)	9.06	(total investment/first-year savings)
6. Total Discounted Operational Savings	$5,110,744	
7. Savings to Investment Ratio (SIR)	1.04	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	3.42%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:55:24 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Loading 15, 10yr.xml		

1. Investment

Construction Cost	$3,660,000
SIOH	$0
Design Cost	$732,000
Total Cost	$4,392,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,392,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$541,690	
5. Simple Payback Period (in years)	8.11	(total investment/first-year savings)
6. Total Discounted Operational Savings	$5,110,744	
7. Savings to Investment Ratio (SIR)	1.16	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	4.57%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:55:51 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Loading 20, 10yr.xml		

1. Investment

Construction Cost	$3,440,000
SIOH	$0
Design Cost	$688,000
Total Cost	$4,128,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,128,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$541,690	
5. Simple Payback Period (in years)	7.62	(total investment/first-year savings)
6. Total Discounted Operational Savings	$5,110,744	
7. Savings to Investment Ratio (SIR)	1.24	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.22%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:56:23 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Loading 25, 10yr.xml		

1. Investment

Construction Cost	$3,310,000
SIOH	$0
Design Cost	$662,000
Total Cost	$3,972,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$3,972,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$541,690	
5. Simple Payback Period (in years)	7.33	(total investment/first-year savings)
6. Total Discounted Operational Savings	$5,110,744	
7. Savings to Investment Ratio (SIR)	1.29	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.63%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:51:27 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Loading 30%, 10yr.xml		

1. Investment

Construction Cost	$3,230,000
SIOH	$0
Design Cost	$646,000
Total Cost	$3,876,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$3,876,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$541,690	
5. Simple Payback Period (in years)	7.16	(total investment/first-year savings)
6. Total Discounted Operational Savings	$5,110,744	
7. Savings to Investment Ratio (SIR)	1.32	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.89%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 18:00:32 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Biosolids, $0, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$90,800	Annual	8.657	$786,071
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$90,800			$786,071

4. First year savings	$652,190	
5. Simple Payback Period (in years)	7.53	(total investment/first-year savings)
6. Total Discounted Operational Savings	$6,067,362	
7. Savings to Investment Ratio (SIR)	1.24	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.21%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 18:01:04 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Biosolids, $5, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$93,360	Annual	8.657	$808,234
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$93,360			$808,234

4. First year savings	$654,750	
5. Simple Payback Period (in years)	7.50	(total investment/first-year savings)
6. Total Discounted Operational Savings	$6,089,524	
7. Savings to Investment Ratio (SIR)	1.24	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.25%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 18:01:40 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Biosolids, $10, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$95,920	Annual	8.657	$830,396
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$95,920			$830,396

4. First year savings	$657,310	
5. Simple Payback Period (in years)	7.47	(total investment/first-year savings)
6. Total Discounted Operational Savings	$6,111,687	
7. Savings to Investment Ratio (SIR)	1.25	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.28%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 18:02:13 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Biosolids, $15, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$98,480	Annual	8.657	$852,558
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$98,480			$852,558

4. First year savings	$659,870	
5. Simple Payback Period (in years)	7.44	(total investment/first-year savings)
6. Total Discounted Operational Savings	$6,133,849	
7. Savings to Investment Ratio (SIR)	1.25	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.32%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

Appendix C: DoD Food Waste Generation White Paper

Memorandum

To: *Dr. Andrea Leeson*

From: *Dr. Patrick Evans*

Date: *December 7, 2015*

Subject: *DoD Waste Stream Characterization White Paper for ER-200933, Renewable Energy Production from DoD Installation Solid Waste by Anaerobic Digestion, Revision 3*

A DoD waste characterization analysis was conducted to identify and quantify waste streams generated by the Navy, Marine Corps, Air Force, and Army that are suitable for anaerobic digestion. The analysis consisted of two parts. In part one, data and information from the DoD branches were collected and reviewed to identify total waste generation rates and component-specific generation rates. In part two, the waste component categories were evaluated for their suitability for anaerobic digestion. This white paper was compiled to summarize the results of the DoD waste characterization analysis.

DoD Waste Stream Characterization

The most readily available and reliable data on DoD waste streams is in terms of mass generation rates, e.g., tons/yr. Mass generation rates are typically documented as part of a military base's standard operating procedures for use in billing and conservation measures. Mass generation rates were available from all four combat branches of the DoD.

More specific characterization data identifying separate DoD waste streams by component, e.g., plastics, paper, metals, food waste, etc., is rare and considerably less reliable than the mass generation data. Component specific data is uncommon because DoD wastes are typically comingled and disposed of in heterogeneous mixtures. Component identification in a comingled waste stream is a difficult, messy, and time consuming process that requires hand sorting and/or visual inspection. Due to the substantial manual input required for waste identification, studies characterizing the individual components are expensive and are conducted on an infrequent basis.[1] Further, because there is no uniform directive or requirement within the DoD for the tracking and documentation of individual waste components, it is done inconsistently. None of the branches track total waste generation by component. The Navy and the Marine Corps track recycled materials by component, but because these branches do not estimate capture rates of recyclable materials, the data is insufficient for estimating total component specific generation rates.

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[1] (Tchobanoglous, Theisen, & Vigil, 1993)

A summary of the collected data from the four branches is provided below.

Navy Solid Waste Characterization

The NAVFAC provided Navy installation waste characterization data for the FY 2005 through FY 2009.[2] The data included total waste generation rates, and component specific recycling rates. The total waste generation data for the Navy is provided in Table 1. Per capita generation rates were estimated based on population estimates provided by the DoD Statistical Information Analysis Division (DoD SIAD).[3]

Table 1
Navy Total Waste, 2005 to 2009 (in tons and pounds per capita per day)

	Total Waste Generation					
Year	**2005**	**2006**	**2007**	**2008**	**2009**	**Average**
Population, in thousands	**421**	**396**	**262**	**254**	**252**	**317**
Total MSW - tons	751,646	691,747	611,463	608,811	587,334	650,200
Total MSW – pcpd	9.8	9.6	12.8	13.1	12.8	11.6

The reported waste generation at Navy installations shows relative consistency, ranging from 9.6 to 13.1 pounds per person per day with an average of 11.6.

Recycled material data for the Navy is summarized in Table 2.

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[2] (Hamilton, 2010)

[3] (Department of Defense, 2010)

Table 2
Navy Recycled Materials, 2005 to 2009 (tons, %, and pounds per capita per day)

	Recycled Materials, Tons					
Year	**2005**	**2006**	**2007**	**2008**	**2009**	**Average**
Population, in thousands	**421**	**396**	**262**	**254**	**252**	**317**
Paper and Paperboard	35,068	30,924	28,636	28,257	31,605	30,898
Yard Trimmings	11,263	2,781	4,116	7,232	2,102	5,499
Food Scraps	1,579	2,131	6,976	766	1,806	2,652
Metals	56,611	61,280	57,692	46,932	61,504	56,804
Glass	1,597	1,020	868	736	846	1,013
Wood	24,558	10,754	12,089	20,110	12,478	15,998
Rubber and Leather	-	-	-	-	-	-
Textiles	-	-	-	-	-	-
Misc. Inorganic Wastes	-	-	-	-	-	-
Plastics	1,677	1,413	1,942	1,673	3,244	1,990
Other	25,256	17,169	18,518	34,308	17,579	22,566
Recycled Materials - tons	157,609	127,471	130,837	140,014	131,163	137,419
	Recycled Materials, %					
Year	**2005**	**2006**	**2007**	**2008**	**2009**	**Average**
Paper and Paperboard	22.3%	24.3%	21.9%	20.2%	24.1%	22.5%
Yard Trimmings	7.1%	2.2%	3.1%	5.2%	1.6%	4.0%
Food Scraps	1.0%	1.7%	5.3%	0.5%	1.4%	1.9%
Metals	35.9%	48.1%	44.1%	33.5%	46.9%	41.3%
Glass	1.0%	0.8%	0.7%	0.5%	0.6%	0.7%
Wood	15.6%	8.4%	9.2%	14.4%	9.5%	11.6%
Rubber and Leather	-	-	-	-	-	-
Textiles	-	-	-	-	-	-
Misc. Inorganic Wastes	-	-	-	-	-	-
Plastics	1.1%	1.1%	1.5%	1.2%	2.5%	1.4%
Other	16.0%	13.5%	14.2%	24.5%	13.4%	16.4%
Recycled Materials - %	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
	Recycled Materials, pcpd					
Year	**2005**	**2006**	**2007**	**2008**	**2009**	**Average**
Paper and Paperboard	0.46	0.43	0.60	0.61	0.69	0.56
Yard Trimmings	0.15	0.04	0.09	0.16	0.05	0.09
Food Scraps	0.02	0.03	0.15	0.02	0.04	0.05
Metals	0.74	0.85	1.21	1.01	1.34	1.03
Glass	0.02	0.01	0.02	0.02	0.02	0.02
Wood	0.32	0.15	0.25	0.43	0.27	0.29
Rubber and Leather	-	-	-	-	-	-
Textiles	-	-	-	-	-	-
Misc. Inorganic Wastes	-	-	-	-	-	-
Plastics	0.02	0.02	0.04	0.04	0.07	0.04
Other	0.33	0.24	0.39	0.74	0.38	0.42
Recycled Materials - pcpd	2.1	1.8	2.7	3.0	2.9	2.5

Marine Corps Solid Waste Characterization

The NAVFAC also provided Marine Corps installation waste characterization data for the FY 2006 through FY 2009.[4] Like the data provided for the Navy, this data included total waste generation rates, and component specific recycling rates. The total waste generation data for the Marine Corps is provided in Table 3. Per capita generation rates were estimated based on population estimates provided by the DoD SIAD.[5]

Table 3
Marine Corps Total Waste, 2006 to 2009 (in tons and pounds per capita per day)

	Total Waste Generation				
Year	**2006**	**2007**	**2008**	**2009**	**Average**
Population, in thousands	**218**	**163**	**188**	**199**	**192**
Total MSW - tons	234,969	246,931	235,659	221,101	234,665
Total MSW – pcpd	5.9	8.3	6.9	6.1	6.7

The reported waste generation at Marine Corps installations shows relative consistency, ranging from 5.9 to 8.3 pounds per person per day with an average of 6.7. This generation rate is lower than the rate estimated for the Navy.

Recycled material data for the Marine Corps is summarized in Table 4.

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[4] (Hamilton, 2010)

[5] (Department of Defense, 2010)

Table 4
Marine Corps Recycled Materials, 2005 to 2009 (tons, %, and pounds per capita per day)

	Recycled Materials, Tons				
Year	**2006**	**2007**	**2008**	**2009**	**Average**
Population, in thousands	**218**	**163**	**188**	**199**	**192**
Paper and Paperboard	10,900	9,825	13,422	15,036	12,296
Yard Trimmings	2,293	1,289	1,867	2,124	1,893
Food Scraps	4,518	6,610	5,783	1,800	4,678
Metals	18,930	37,686	23,580	19,394	24,898
Glass	639	558	248	331	444
Wood	14,796	14,520	14,741	22,037	16,524
Rubber and Leather	-	-	-	-	-
Textiles	-	-	-	-	-
Misc. Inorganic Wastes	-	-	-	-	-
Plastics	490	771	422	648	583
Other	2,236	10,294	14,683	7,630	8,711
Recycled Materials - tons	54,804	81,552	74,746	69,001	70,026
	Recycled Materials, %				
Year	**2006**	**2007**	**2008**	**2009**	**Average**
Paper and Paperboard	19.9%	12.0%	18.0%	21.8%	17.6%
Yard Trimmings	4.2%	1.6%	2.5%	3.1%	2.7%
Food Scraps	8.2%	8.1%	7.7%	2.6%	6.7%
Metals	34.5%	46.2%	31.5%	28.1%	35.6%
Glass	1.2%	0.7%	0.3%	0.5%	0.6%
Wood	27.0%	17.8%	19.7%	31.9%	23.6%
Rubber and Leather	-	-	-	-	-
Textiles	-	-	-	-	-
Misc. Inorganic Wastes	-	-	-	-	-
Plastics	0.9%	0.9%	0.6%	0.9%	0.8%
Other	4.1%	12.6%	19.6%	11.1%	12.4%
Recycled Materials - %	100.0%	100.0%	100.0%	100.0%	100.0%
	Recycled Materials, pcpd				
Year	**2006**	**2007**	**2008**	**2009**	**Average**
Paper and Paperboard	0.27	0.33	0.39	0.41	0.35
Yard Trimmings	0.06	0.04	0.05	0.06	0.05
Food Scraps	0.114	0.222	0.169	0.050	0.138
Metals	0.48	1.27	0.69	0.53	0.74
Glass	0.016	0.019	0.007	0.009	0.013
Wood	0.37	0.49	0.43	0.61	0.47
Rubber and Leather	-	-	-	-	-
Textiles	-	-	-	-	-
Misc. Inorganic Wastes	-	-	-	-	-
Plastics	0.01	0.03	0.01	0.02	0.02
Other	0.06	0.35	0.43	0.21	0.26
Recycled Materials - pcpd	1.4	2.7	2.2	1.9	2.1

Air Force Solid Waste Characterization

The Air Force Center for Engineering and the Environment (AFCEE) provided total waste generation data for FY 2002 through FY 2008 (with the exception of FY 2004, which was not available) for Air Force installations.[6] The waste statistics for the Air Force are summarized in Table 5. Per capita generation rates were estimated based on population estimates provided by the DoD SIAD.[7]

Table 5
Air Force Waste Stream Data, 2002 to 2008

	Waste Generation						
Year	**2002**	**2003**	**2005**	**2006**	**2007**	**2008**	**Average**
Population, in thousands	**457**	**464**	**467**	**448**	**446**	**440**	**454**
Total MSW - tons	1,902,944	1,011,119	764,781	2,321,002	840,233	528,852	1,228,155
Total MSW – pcpd	22.8	11.9	9.0	28.4	10.3	6.6	14.8

The reported waste generation at Air Force installations varied substantially throughout the years, ranging from 6.6 to 28.4 pounds per person per day with an average of 14.8. A fourfold difference between low to high is substantial and unusual. No explanation was given from the Air Force to explain the difference in generation rates. It was expected that per capita generation rates would be decreasing as conservation measures were implemented. If the 2006 data is ignored, the per capita generation is steadily reducing since 2002.

Army Solid Waste Characterization

Army solid waste data was obtained from the Solid Waste Annual Report Website[8,9] via the Army's online Installation Management Application Resource Center. Data was collected from four different reports:

- Installation Spreadsheet Totals (FY03 – FY08)
- Headquarters (AEC) Army Report 1 – (Overall)
- Headquarters (AEC) Army Report 2 – (MSW Diversion)
- Measures of Merit (MoM) Elements

The waste statistics for the Army are summarized in Table 6. Per capita generation rates were estimated base on population estimates provided by the DoD SIAD.[10]

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[6] (Carper, 2010)
[7] (Department of Defense, 2010)
[8] (U.S. Army, 2010)
[9] (Eng, 2010)
[10] (Department of Defense, 2010)

Table 6
Army Waste Stream Data, 2003 to 2008

	Waste Generation						
Year	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**Average**
Population, in thousands	**611**	**616**	**635**	**656**	**674**	**715**	**651**
Total MSW - tons	1,759,624	3,544,886	2,209,752	2,328,227	2,859,805	2,237,291	2,489,931
Total MSW - pcpd	15.8	31.5	19.1	19.5	23.2	17.2	21.0

The Army had the highest per capita generation rates of any of the four branches. Generation rates ranged from 15.8 to 31.5 pounds per person per day, with an average of 21.0. No general trend is observed in the generation numbers.

DoD Waste Data Comparison

A summary table of the average waste generation rates across the DoD was compiled for relative comparison between the different branches and for subsequent comparison with reported waste generation rates from detailed studies.

The summary waste generation data across the DoD is provided in Table 7.

Table 7
DoD Waste Stream Data

	Total Waste Generation				
Branch	**Navy**	**Marine Corps**	**Air Force**	**Army**	**DoD Total**
Population, in thousands	**317**	**192**	**454**	**651**	**1,614**
Total MSW - tons	650,200	300,163	1,228,155	2,489,931	4,668,449
Total MSW - pcpd	11.6	8.7	14.8	21.0	15.8

The summary generation numbers indicate a few things about waste generation across the DoD.

- The Army is the single largest generator of solid waste based on its larger population and its higher per capita generation rate.
- The Marine Corps is the smallest generator based on its smaller population and lower per capita generation rate.
- Per capita generation rates range between 8.7 and 21.0 pounds per person per day, with an average of 15.8.
- Average waste generation across the DoD is approximately 4.7 million tons per year

The discrepancy between the per capita generation numbers could be attributable to a number of factors including the possibility that one branch simply generates more waste per capita than the other due to different conservation measures or different activities under command. One would expect the Navy and the Marine Corps, which operate in the naval arena, to have more stringent waste generation policies and practices to minimize wasted space on a vessel afloat. Variation can also be introduced based on reporting methodology in which the different branches or individual bases consider specific wastes differently. For instance, green waste at one base may not be included in waste generation statistics because it is immediately diverted into mulch at the point of generation, while another base may track the green waste because it is generated and then transported before diversion to mulch or other disposal. Likewise, sewage sludge and ash may not be included in the waste generation statistics depending on an individual base's treatment and disposal practices. No information was available from the DoD to determine if different reporting practices were employed at different bases or in different branches.

DoD Waste Data Validation
To further understand and validate the per capita generation rates and to estimate component generation rates, the total waste generation numbers were compared with detailed studies from the Army Corps of Engineers and the U.S. EPA.

Table 8 is populated with waste characterization data from the U.S. EPA report: *Municipal Solid Waste in the United States: 2007 Facts and Figures*[11] and from the Army Corps of Engineers report: *Solid Waste Generation Rates at Army Base Camps.*[12] The EPA report is the most up to date and detailed analysis of the solid waste in the United States. The Army Corps report is the only known waste characterization study conducted at a DoD installation. The characterization was conducted in 2003 and 2006 at two Army base camps to determine the relative generation rates of waste components on a per capita basis.

Table 8
Army Base Camp and U.S. Waste Stream Characterization Data

	2003 (Camp A)		**2006 (Camp B)**		**2007 (US)**	
Component	**pcpd**	**%**	**pcpd**	**%**	**pcpd**	**%**
Paper and Paperboard	1.4	9%	4.1	23%	1.5	33%
Food	1.0	7%	1.5	8%	0.6	12%
Vegetation	0.1	1%	0.2	1%	0.6	13%
Metals	0.1	0%	0.7	4%	0.4	8%
Glass	0.1	1%	0.1	1%	0.2	5%
Wood	11.4	72%	2.9	16%	0.3	6%
Rubber and Leather	0.0	0%	0.0	0%	0.1	3%
Textiles	0.1	0%	0.3	1%	0.2	5%
Plastics	1.2	8%	2.0	11%	0.5	12%
Sewage Sludge[1]	0.2	1%	1.9	10%	-	0%
Ashes[1]	0.0	0%	2.2	12%	-	0%
Other	0.1	1%	2.3	13%	0.1	3%
***Total Waste Generated*[1]**	15.8	100%	18.2	100%	4.6	100%

[1] Sewage sludge and ash were not included in the U.S. EPA waste characterization and are not reflected in the total waste generated

The data provided above suggests a few key things about waste generation at DoD installations.

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[11] (U.S. EPA, 2008)
[12] (U.S. Army Corps of Engineers, 2008)

- Component generation, such as wood waste, can vary considerably from base to base. Wood waste from Camp A was 72 percent of total waste generated, while it represented just 16 percent of total waste generated from Camp B. One possible explanation for the high wood waste fraction of the Camp A waste is that the camp was not fully established and was generating significant construction and shipping waste to bring in new materials. An established camp, like Camp B, may have less wood waste, but higher concentrations of other wastes, as it is more reliant on locally available materials and supplies and is not in active construction.
- Total generation at Army base camps are relatively consistent, but are approximately four times as high as the U.S. National Average.
- The total waste generation rates at the Army base camps are consistent with the projections made in Table 7 for the entire DoD, suggesting that the estimate is reasonable for projections within the DoD. Camp A waste generation rates were identical to the projected average of 15.8 pounds per capita per day.
- Certain fractions of the waste stream can vary considerably from Army base to Army base in both the relative (fraction of total) and the absolute (pounds per capita per day generated) basis.
    - Paper and Paperboard, and Wood generation rates showed the most relative and absolute variation.
    - Metals, Sewage Sludge, Ashes, and Other wastes showed great relative variation, but little absolute variation.
    - Food and Vegetation, Glass, Rubber and Leather, Textiles, and Plastic waste showed some relative variation, but were generally consistent on an absolute basis between camps and when compared with the U.S. EPA national average.
- Food waste generation rates for the two Army base camps were 1.0 and 1.5 pounds pcpd compared to the US average of 0.6 pounds pcpd. Army food waste generation was 7 to 8% of total MSW generation compared to 12% for the US. Total food waste generation by the DoD was estimated to range from 330,000 to 560,000 tons per year using the range of percentages in Table 8 and total MSW generation data in Table 7.

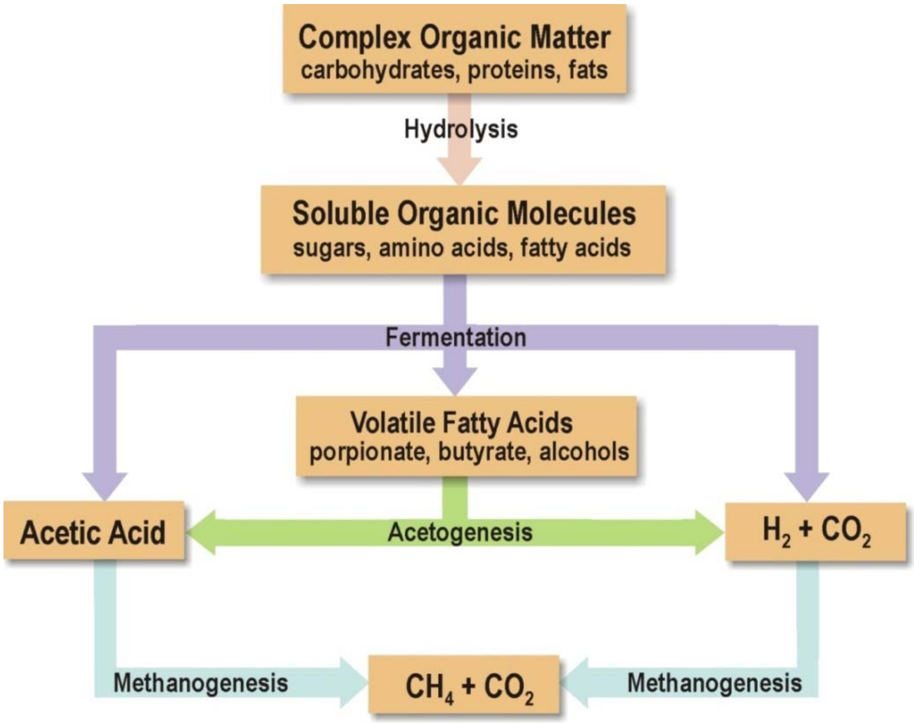
Conclusions from DoD Waste Characterization

The DoD waste characterization analysis was helpful to quantify the relative waste generation rates across installations. Based on the data provided by the different branches and based on the specific analysis performed by the Army Corps of Engineers, it is estimated that solid waste is generated at approximately 15.8 pounds per capita per day. Waste generation by specific component proved to be more difficult to estimate due to differences in waste tracking methodologies and installation activities. There does not appear to be enough data available from the DoD to make a detailed estimate of waste generation by component. Nevertheless, DoD food waste generation was estimated to be 330,000 to 560,000 tons per year.

Suitability of Waste Components for Anaerobic Digestion

Anaerobic digestion is an organic waste treatment technology that uses microbiological communities to break down complex organics to reduce the overall solids mass and volume while generating a biogas energy product. Regardless of the waste stream utilized, anaerobic treatment follows the same biological and chemical pathways using related microbial populations. The anaerobic treatment process is represented in Figure 1.[13]

Figure 1
Anaerobic Digestion Process


Complex Organic Matter
carbohydrates, proteins, fats
Hydrolysis
Soluble Organic Molecules
sugars, amino acids, fatty acids
Fermentation
Volatile Fatty Acids
porpionate, butyrate, alcohols
Acetic Acid
Acetogenesis
$H_2 + CO_2$
Methanogenesis
$CH_4 + CO_2$
Methanogenesis

Due to the relative uniformity of the anaerobic digestion process, and the substantial amount of data available from stable sewage sludge anaerobic digestion systems, general characteristics for digestible waste have been developed. These general characteristics are described below.

---

[13] (EPA, 2011)

Feedstock Characteristics

- **Organic:** The primary characteristic of a good digester feedstock is that it is organic in nature. Anaerobic digestion is biological process that utilizes organic compounds as an energy source. Inorganic compounds are not readily metabolized by the microbial population and are not appropriate for anaerobic digestion.

- **C:N Ratio:** The ideal carbon to nitrogen (C:N) ratio is between 20 and 30 for stable digestion. The higher carbon concentration helps provide sufficient organic matter for the microbiological community to feed on, while the lower nitrogen concentration provides a key nutrient at a low enough concentration to encourage growth while limiting ammonia toxicity. Anaerobic digestion of wastes with lower C:N ratios are possible, but ammonia toxicity becomes problematic and must be monitored carefully. Ammonia toxicity is relatively common when anaerobically digesting chicken waste, which has a C:N ratio between 5 and 10.[14] Digestion at higher C:N ratios is also possible, but it can be difficult to maintain due the absence of nitrogen, which is a rate limiting nutrient for the anaerobic bacteria.

- **Trace Nutrients:** Micronutrients including phosphorus, magnesium, iron, molybdenum, nickel and cobalt are essential for the stable growth of anaerobic populations.[15] In the absence of these micronutrients, the methanogenic archea are growth inhibited and digesters tend towards upsets as volatile fatty acids accumulate, the pH drops, and the microbiological community dies.

- **Absence of Inhibitory Compounds:** Inhibitory compounds such as disinfectants, antibiotics and heavy metals can negatively influence the digester population and result in digester upsets. The ideal digester feedstock will be free of inhibitory compounds. However, use of sanitizers and disinfectants is common and these products contain inhibitors such as quaternary ammonium compounds. Such compounds are found in anaerobic digester sludge and thus are tolerated within certain limits. The exact limits that are inhibitory is a current area of research and is not well defined.

Assessment and Conclusion on the Suitability of DoD Wastes for Anaerobic Digestion
To simplify the assessment of the available DoD waste streams, Table 9 comparing the component waste categories was developed based on the ideal feedstock characteristics discussed previously.

---

[14] (Speece, 1996)

[15] Ibid.

Table 9
Evaluation of DoD Waste Stream for Anaerobic Digestion

Component	Organic Compound?	C:N Ratio	Trace Nutrients Present?	Inhibitor Compounds Present?	Suitable for Anaerobic Digestion?
Paper and Paperboard	**Yes**	145 : 1	No	Maybe	No
Food	**Yes**	**19 : 1**	**Yes**	Maybe	**Yes**
Vegetation	**Yes**	14:1	**Yes**	Maybe	**Maybe**
Metals	No	<5 : 1	No	Yes	No
Glass	No	<5 : 1	No	**No**	No
Wood	**Yes**	250 : 1	No	Maybe	No
Rubber and Leather	No	40 : 1	No	Maybe	No
Textiles	No	12 : 1	No	Yes	No
Plastics	No	>500 : 1	No	Yes	No
Ashes	No	50 : 1	No	Yes	No

Based on the criteria in Table 9, only the food waste and vegetation waste streams are candidates for treatment through anaerobic digestion. Food waste is the best candidate and is well suited for biogas production. Vegetation may be a good amendment to be added to a food waste digestion process. In this case a compost product would be generated in addition to the biogas. All of the other waste streams are either inorganic, have insufficient carbon, nitrogen, or trace nutrients, or are known to have inhibitory compounds latent within the stream.

Typically, after a preliminary assessment of a candidate waste stream is completed, the candidate waste stream is subjected to lab and pilot scale tests to confirm its overall applicability and digestion characteristics. These lab and pilot scales are currently being completed for DoD food wastes as part of this project. Results from this analysis are forthcoming and will be reported in subsequent reports and presentations.

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Appendices

Table A

Complete United States Waste Stream Data

	Thousands of Tons								
Year	**1960**	**1970**	**1980**	**1990**	**2000**	**2004**	**2005**	**2006**	**2007**
Paper and Paperboard	29,990	44,310	55,160	72,730	87,740	86,450	84,840	85,350	83,010
Yard Trimmings	20,000	23,200	27,500	35,000	30,530	31,770	32,070	32,400	32,630
Food Scraps	12,200	12,800	13,000	20,800	26,810	29,410	30,220	31,040	31,650
Metals	10,820	13,830	15,510	16,550	18,910	19,980	20,060	20,660	20,750
Glass	6,720	12,740	15,130	13,100	12,760	12,890	13,320	13,520	13,580
Wood	3,030	3,720	7,010	12,210	13,110	13,890	14,080	14,100	14,210
Rubber and Leather	1,840	2,970	4,200	5,790	6,710	7,150	7,360	7,400	7,480
Textiles	1,760	2,040	2,530	5,810	9,440	10,980	11,380	11,870	11,920
Misc. Inorganic Wastes	1,300	1,780	2,250	2,900	3,500	3,650	3,690	3,720	3,750
Plastics	390	2,900	6,830	17,130	25,540	29,480	29,240	29,810	30,730
Other *	70	770	2,520	3,190	4,000	4,130	4,170	4,310	4,430
Total MSW Generated	88,120	121,060	151,640	205,210	239,050	249,780	250,430	254,180	254,140
	Percent of Total Generation								
Year	**1960**	**1970**	**1980**	**1990**	**2000**	**2004**	**2005**	**2006**	**2007**
Paper and Paperboard	34.0%	36.6%	36.4%	35.4%	36.7%	34.6%	33.9%	33.6%	32.7%
Yard Trimmings	22.7%	19.2%	18.1%	17.1%	12.8%	12.7%	12.8%	12.7%	12.8%
Food Scraps	13.8%	10.6%	8.6%	10.1%	11.2%	11.8%	12.1%	12.2%	12.5%
Metals	12.3%	11.4%	10.2%	8.1%	7.9%	8.0%	8.0%	8.1%	8.2%
Glass	7.6%	10.5%	10.0%	6.4%	5.3%	5.2%	5.3%	5.3%	5.3%
Wood	3.4%	3.1%	4.6%	6.0%	5.5%	5.6%	5.6%	5.5%	5.6%
Rubber and Leather	2.1%	2.5%	2.8%	2.8%	2.8%	2.9%	2.9%	2.9%	2.9%
Textiles	2.0%	1.7%	1.7%	2.8%	3.9%	4.4%	4.5%	4.7%	4.7%
Misc. Inorganic Wastes	1.5%	1.5%	1.5%	1.4%	1.5%	1.5%	1.5%	1.5%	1.5%
Plastics	0.4%	2.4%	4.5%	8.3%	10.7%	11.8%	11.7%	11.7%	12.1%
Other *	0.1%	0.6%	1.7%	1.6%	1.7%	1.7%	1.7%	1.7%	1.7%
Total MSW Generated -%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
	Pounds Per Capita Per Day (pcpd)								
Year	**1960**	**1970**	**1980**	**1990**	**2000**	**2004**	**2005**	**2006**	**2007**
Population, in millions	**180.7**	**205.1**	**227.2**	**249.5**	**282.2**	**293.2**	**295.9**	**298.8**	**301.6**
Paper and Paperboard	0.91	1.18	1.33	1.59	1.70	1.61	1.57	1.57	1.51
Yard Trimmings	0.60	0.62	0.66	0.77	0.59	0.59	0.59	0.59	0.59
Food Scraps	0.37	0.34	0.31	0.46	0.52	0.55	0.56	0.57	0.57
Metals	0.33	0.37	0.37	0.36	0.37	0.37	0.37	0.38	0.38
Glass	0.20	0.34	0.36	0.29	0.25	0.24	0.25	0.25	0.25
Wood	0.09	0.10	0.17	0.27	0.25	0.26	0.26	0.26	0.26
Rubber and Leather	0.06	0.08	0.10	0.13	0.13	0.13	0.14	0.14	0.14
Textiles	0.05	0.05	0.06	0.13	0.18	0.20	0.21	0.22	0.22
Misc. Inorganic Wastes	0.04	0.05	0.05	0.06	0.07	0.07	0.07	0.07	0.07
Plastics	0.01	0.08	0.16	0.38	0.50	0.55	0.54	0.55	0.56
Other *	0.00	0.02	0.06	0.07	0.08	0.08	0.08	0.08	0.08
Total MSW Generated -pcpd	2.7	3.2	3.7	4.5	4.6	4.7	4.6	4.7	4.6

** Includes electrolytes in batteries, fluff pulp, feces, and urine in disposable diapers. Details may not add to total due to rounding*

Waste Summary Data
US Navy
FY05 - FY09

	2005 (tons)	2006 (tons)	2007 (tons)	2008 (tons)	2009 (tons)		Average (tons)
Food	1,579	2,131	6,976	766	1,806		2,652
Glass	1,597	1,020	868	736	846		1,013
Metals	56,611	61,280	57,692	46,932	61,504		56,804
Other (non-food)	25,256	17,169	18,518	34,308	17,579		22,566
Paper & Paperboard	35,068	30,924	28,636	28,257	31,605		30,898
Plastic	1,677	1,413	1,942	1,673	3,244		1,990
Wood	24,558	10,754	12,089	20,110	12,478		15,998
Yard/Green Waste	11,263	2,781	4,116	7,232	2,102		5,499
Total Recycle by Cat	157,609	127,471	130,837	140,014	131,163		137,419
Composting	23,513	21,667	14,533	8,703	13,962		16,476
Recycled Antifreeze	287	240	90	219	206		209
Recycled Lead Acid Batteries	1,237	1,812	2,115	1,431	2,227		1,764
Recycled Used Motor Oil	8,498	5,134	2,385	4,158	4,341		4,903
Total Recycled	191,144	156,324	149,960	154,526	151,900		160,771
Landfilled	367,500	362,669	277,130	261,310	247,078		303,138
Incinerated	45,416	52,469	58,125	58,769	63,967		55,749
Landfilled Antifreeze	311	94	116	463	91		215
Landfilled Lead Acid Batteries	55	238	41	163	163		132
Landfilled Used Motor Oils	7,971	879	898	42	435		2,045
L_Oils(wte)		229	176	60	100		141
LR_Oils(wte)		3,402	3,408	2,571	3,677		3,265
Total Disposed	421,253	419,979	339,894	323,379	315,510		364,003
Total Waste	612,397	576,303	489,854	477,905	467,410		524,774
% Recycled	31%	27%	31%	32%	32%		31%
% Not Recycled	69%	73%	69%	68%	68%		69%
Food Waste % Rcyc	0.8%	1.4%	4.7%	0.5%	1.2%		2%
Food Waste % Total	0.3%	0.4%	1.4%	0.2%	0.4%		1%
F+Y+C % Rcyc	19%	17%	17%	11%	12%		15%
F+Y+C % Total	6%	5%	5%	3%	4%		5%
Number of Installatns	103	105	103	102	95		102

R_Anti	Recycled Antifreeze
R_LAB	Recycled Lead Acid Batteries
R_Oils	Recycyed Used Motor Oils
L_Anti	Landfilled Antifreeze
L_LAB	Landfilled Lead Acid Batteries
L_Oils	Landfilled Used Motor Oils

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Waste Summary Data
US Marine Corps
FY06 - FY09

	2006 (tons)	2007 (tons)	2008 (tons)	2009 (tons)		Average (tons)
Food	4,518	6,610	5,783	1,800		4,678
Glass	639	558	248	331		444
Metals	18,930	37,686	23,580	19,394		24,898
Other (non-food)	2,236	10,294	14,683	7,630		8,711
Paper & Paperboard	10,900	9,825	13,422	15,036		12,296
Plastic	490	771	422	648		583
Wood	14,796	14,520	14,741	22,037		16,524
Yard/Green Waste	2,293	1,289	1,867	2,124		1,893
Total Recycle by Cat	54,804	81,552	74,746	69,001		70,026
Composting	9,064	5,336	6,381	4,273		6,264
Recycled Antifreeze	373	102	325	399		300
Recycled Lead Acid Batteries	1,091	769	2,063	996		1,230
Recycled Used Motor Oil	1,506	1,840	1,025	2,340		1,678
Total Recycled	66,838	89,598	84,539	77,010		79,497
Landfilled	145,126	135,042	133,175	126,041		134,846
Incinerated	21,697	21,597	16,340	16,373		19,002
Landfilled Antifreeze	44	38	36	57		44
Landfilled Lead Acid Batteries	105	4	41	82		58
Landfilled Used Motor Oils	363	44	1	-		102
L_Oils(wte)	37	131	289	-		114
LR_Oils(wte)	759	477	1,237	1,537		1,002
Total Disposed	168,130	157,333	151,120	144,091		155,169
Total Waste	234,969	246,931	235,659	221,101		234,665
% Recycled	28%	36%	36%	35%		34%
% Not Recycled	72%	64%	64%	65%		66%
Food Waste % Rcyc	7%	7%	7%	2%		6%
Food Waste % Total	2%	3%	2%	1%		2%
F+Y+C % Rcyc	24%	15%	17%	11%		16%
F+Y+C % Total	7%	5%	6%	4%		5%
Number of Installatns	19	18	17	18		18

R_Anti	Recycled Antifreeze
R_LAB	Recycled Lead Acid Batteries
R_Oils	Recycyed Used Motor Oils
L_Anti	Landfilled Antifreeze
L_LAB	Landfilled Lead Acid Batteries
L_Oils	Landfilled Used Motor Oils

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Waste Summary Data
US Army
FY03 - FY08

	FY03 (tons)	FY04 (tons)	FY05 (tons)	FY06 (tons)	FY07 (tons)	FY08 (tons)		Average (tons)
Total SW Generated (Tons)	1,759,624	3,544,886	2,209,752	2,328,227	2,859,805	2,237,291		2,489,931
Landfill (Tons)	874,954	739,763	891,997	488,958	517,058	527,811		673,424
C&D Landfill (Tons)	167,919	1,156,898	244,038	366,339	389,730	358,406		447,222
C&D Diverted (Tons)	334,538	1,189,487	488,738	924,944	1,461,907	769,615		861,538
Total C&D Generated (Tons)	502,456	2,346,385	732,776	1,291,283	1,851,637	1,128,021		1,308,760
C&D Diversion (%)	67%	51%	67%	72%	79%	68%		66%
Non-WTE Incinerator (Tons)	28,922	23,244	39,115	51,012	47,701	32,666		37,110
WTE Incinerator (Tons)	63,774	50,357	47,521	41,858	45,987	50,014		49,919
Compost (Tons)*	16,707	14,723	11,846	9,950	11,140	9,073		12,240
Recycle (Tons)	599,442	1,556,464	969,108	1,357,477	1,842,471	1,251,036		1,262,666
SW Diversion (%)	39%	46%	47%	61%	66%	59%		53%
MSW Generated	1,223,252	1,150,971	1,367,642	944,750	964,533	1,041,349		1,115,416
MSW Diverted	253,751	331,837	425,073	362,806	354,745	432,668		360,147
Percent Diverted	21%	29%	31%	38%	37%	42%		32%
WTE	63,774	50,357	47,521	41,860	45,987	50,014		49,919
Commodities Paper	83,014	89,007	90,372	87,370	85,574	76,062		85,233
Commodities Other	115,099	160,403	241,432	192,341	201,569	124,603		172,574

* - equivalent to recycled yard waste which is considered equivalent to generated yard waste

7/7/2010

Based on data pulled from SWARWeb Reports

Waste Summary Data
US Air Force
FY02 - FY08

	FY02 (tons)	FY03 (tons)	FY05 (tons)	FY06 (tons)	FY07 (tons)	FY08 (tons)		Average (tons)
Solid Waste Composted (tons)	54,985	26,055	30,381	24,689	19,022	25,920		30,175
Solid Waste Mulched (tons)	43,503	57,226	42,061	40,538	50,564	18,122		42,002
Solid Waste Recycled (tons)	359,822	193,848	203,195	1,241,843	224,125	154,091		396,154
Solid Waste Reused (tons)	32,082	102,158	75,212	465,727	62,478	24,098		126,959
Solid Waste Donated (tons)	4,607	2,784	3,030	52,652	23,715	2,907		14,949
Total Diverted/Recycled SW(tons)	494,999	382,070	353,869	1,825,450	379,904	225,137		610,240
C&D Debris Diverted (tons)	1,567,537	694,474	1,647,490	1,863,864	974,963	1,409,634		1,359,660
Solid Waste Sent to Disposal Facilities (tons)	1,407,945	629,049	375,249	461,984	424,039	277,828		596,016
C&D sent to Disposal Facilities (tons)	458,742	179,627	236,149	271,803	322,582	329,449		299,725
Solid Waste Incinerated (tons)	-	-	35,663	33,568	36,290	25,887		21,901
C&D Incinerated (tons)	-	-	999	424	524	97		341
SW Disposed (incl Incineration)	1,407,945	629,049	410,912	495,552	460,329	303,715		617,917
SW Diversion Rate	26%	38%	46%	79%	45%	43%		50%
C&D Disposed (incl Incineration)	458,742	179,627	237,148	272,227	323,106	329,546		257,199
C&D Diversion Rate	77%	79%	87%	87%	75%	81%		82%
SW Incineration Rate	0%	0%	5%	1%	4%	5%		3%
SW Compost/Mulch Rate	20%	22%	20%	4%	18%	20%		12%
Total SW Generated	1,902,944	1,011,119	764,781	2,321,002	840,233	528,852		1,228,157
Total C&D Generated	2,026,279	874,101	1,884,638	2,136,091	1,298,069	1,739,180		1,659,726
Total Waste Generated	3,929,223	1,885,221	2,649,419	4,457,093	2,138,302	2,268,032		2,887,883
Total Waste Diverted	2,062,536	1,076,544	2,001,359	3,689,314	1,354,867	1,634,771		1,969,900
Total Waste Diversion Rate	52%	57%	76%	83%	63%	72%		68%

Appendix D: Treatability Study Report

TREATABILITY REPORT

Renewable Energy Production from DoD Installation Solid Waste by Anaerobic Digestion

Project Number: ER-200933

May 24, 2011

Prepared By:

CDM

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ACRONYMS

ADM1	Anaerobic Digestion Model No. 1
Alk	Alkalinity
AOAC	AOAC International
BMP	Biochemical Methane Potential
C	Celsius
CH4	Methane
CO2	Carbon Dioxide
COD	Chemical Oxygen Demand
ESTCP	Energy Science and Technology Certification Program
FOG	Fats, Oils, and Grease
FW	Food Waste
g	gram
GC-FID	Gas Chromatography-Flame Ionization Detector
HRT	Hydraulic Residence Time
kg	Kilogram
L	Liter
ND	Non-detection
ppm	Parts per million
QAC	Quaternary Amine Compound
RPD	Relative Percent Difference
sCOD	Soluble Chemical Oxygen Demand
SELR	Specific Energy Loading Rate
SRT	Solids Residence Time
STP	South Treatment Plant, Renton, Washington
tCOD	Total Chemical Oxygen Demand
TKN	Total Kjeldahl Nitrogen
TOC	Total Organic Carbon
TS	Total Solids
USAFA	United States Air Force Academy
VFA	Volatile Fatty Acid
VS	Volatile Solids

1.0 INTRODUCTION

The Department of Defense Environmental Security Technology Certification Program (ESTCP) is funding CDM to conduct a demonstration of anaerobic digestion for food waste treatment and energy recovery. CDM and ESTCP have selected the United States Air Force Academy (USAFA) as a suitable site for this demonstration. A treatability study was conducted using food wastes collected from Mitchell Hall at USAFA. The study was conducted in accordance with the March 11, 2010 Work Plan and the September 7, 2010 memorandum Response to Treatability Study Work Plan Comments (ER-0933). This treatability study involved the following tasks:

- Collection and characterization of multiple food wastes
- Analysis of food waste digestibility and energy yield in microcosm and bench-scale semi-continuous reactor tests
- Assessment of the utility of the specific energy loading rate (SELR) for design purposes
- Testing of food waste hydrolysis kinetics to provide data for calibration of the ADM1 model for use with food wastes

This report presents the methods, results, and conclusions from this treatability study.

2.0 FOOD WASTE CHARACTERIZATION

2.1 ABSTRACT

Fifteen food waste samples were collected from Mitchell Hall over the course of a five-day period (breakfast, lunch, and dinner), as well as one sample of grease trap waste from the underground oil-water separator adjacent to Mitchell Hall. These samples were characterized for chemical parameters relevant to anaerobic digestion and nutritional food analysis. The average COD of the food wastes was 1,400 g/kg dry weight, and the average VS/TS ratio was 0.85 which suggests that the wastes may be highly degradable.

2.2 SAMPLE COLLECTION

Two five-gallon buckets of grease trap waste were collected from the underground oil-water separator adjacent to Mitchell Hall. Dewatered, ground food waste samples were collected into sealable bags from Mitchell Hall pulper over five days for each meal (Table 2-1). Each sample was approximately 500 grams of material. Two five-gallon buckets of FW-004 (FW-B1 and FW-B2) and FW-011 (FW-B3 and FW-B4) were collected in addition to the normal samples. These food wastes were used for all of the respirometer studies in conjunction with the grease trap waste. Samples were refrigerated at USAFA after collection and shipped overnight to CDM on ice. After receipt, the samples were stored in a 4-6 °C refrigerated cold room until analysis.

Table 2-1 Food Waste Samples

Sample ID	Date Collected	Time Collected	Meal
FW-001	05/17/10	10:00	Breakfast
FW-002	05/17/10	13:00	Lunch
FW-003	05/17/10	19:00	Dinner
FW-004	05/18/10	9:00	Breakfast
FW-B1			
FW-B2			
FW-005	05/18/10	13:00	Lunch
FW-006	05/18/10	19:00	Dinner
FW-007	05/19/10	9:00	Breakfast
FW-008	05/19/10	13:00	Lunch
FW-009	05/19/10	18:30	Dinner
FW-010	05/20/10	9:00	Breakfast
FW-011	05/20/10	13:00	Lunch
FW-B3			
FW-B4			
FW-012	05/20/10	19:00	Dinner
FW-013	05/21/10	9:00	Breakfast
FW-014	05/21/10	13:00	Lunch
FW-015	05/21/10	18:30	Dinner
Grease Trap Waste	05/10/10	N/A	N/A

2.3 METHODS AND RESULTS

The directly-measured characteristics of the food wastes included chemical oxygen demand (COD), volatile solids (VS), total Kjeldahl nitrogen (TKN), total phosphorus, and the moisture, fat, and ash contents. The analytical methods used are outlined in Table 2-2. Sample FW-10 was analyzed in duplicate to assess precision. Characteristics derived from the analyses performed by the contract laboratory are outlined in Table 2-3. Tables 2-4 through 2-6 contain the characterization results, and Table 2-7 contains the average values of the food wastes for each characteristic. The COD analysis was performed in the CDM Bellevue Environmental Treatability Laboratory. Food wastes were homogenized and diluted with de-ionized water prior to analysis. Homogenization was achieved using an industrial blender to create a 10x diluted food waste slurry. Additional dilutions of the slurry were made as necessary to bring the waste within the analytical range of the method. The remaining characterizations were performed by a contract laboratory. Aliquots of each food waste type were dispensed into sample jars and shipped overnight on ice to the contract laboratory. Results were reported on a wet-weight basis but, where noted, they have been converted to dry-weight basis. Total organic carbon (TOC) was also analyzed, but the results were deemed unreliable and are not presented here.

Table 2-2 Directly Measured Food Waste Characteristics

Analysis	Method
Chemical Oxygen Demand	Hach Method 8000
Volatile Solids	Standard Method 2540E
Total Kjeldahl Nitrogen	AOAC Method 981.10
Total Phosphorus	AOAC Method 965.17
Moisture Content	AOAC 925.10
Fat Content	AOAC 922.06
Ash Content	AOAC 900.02A

Table 2-3 Derived Food Waste Characteristics

Analysis	Calculated From
Total Solids	Moisture, by difference
Protein	TKN, by conversion factor
Total Carbohydrates	Moisture, Protein, Fat and Ash, by difference
Calories	Carbohydrates, Protein and Fat, by 4:4:9 rule (contract laboratory standard method for food analysis; assumes Calorie content of 4Calories/gCarbohydrate, 4Calories/gProtein, and 9Calories/gFat)

Table 2-4 Total and Volatile Solids

FW Typw	Volatile Solids (% Wet Weight)	Total Solids (% Wet Weight)	VS/TS
FW-001	23	24	0.94
FW-002	24	26	0.93
FW-003	30	31	0.98
FW-004	19	20	0.94
FW-005	34	62	0.55
FW-006	14	23	0.63
FW-007	32	60	0.54
FW-008	30	56	0.54
FW-009	31	31	0.98
FW-010	16	16	0.97
FW-011	23	25	0.94
FW-012	23	23	0.98
FW-013	30	32	0.94
FW-014	26	27	0.99
FW-015	33	40	0.82
Grease trap waste	67	68	0.98

Table 2-5 Nitrogen, Phosphorus, and COD Content Results

FW Type	TKN (% Dry Weight)	Total Phosphorus (mg/kg Dry Weight)	COD (g/kg Dry Weight)
FW-001	7.0	1070	1630
FW-002	3.7	310	1450
FW-003	2.8	190	1130
FW-004	2.5	160	1880
FW-005	3.7	300	1430
FW-006	2.4	180	790
FW-007	5.5	180	820
FW-008	4.3	230	1100
FW-009	4.0	200	1140
FW-010	2.2	190	1630
FW-011	4.7	320	1810
FW-012	8.5	330	1550
FW-013	9.3	270	1130
FW-014	9.4	360	1170
FW-015	4.2	260	1700
Grease trap waste	0.06	40	1530

Table 2-6 Food Proximate Analysis Results

FW Type	Protein (% Dry Weight)	Fat (% Dry Weight)	Ash (% Dry Weight)	Total Carbohydrates (% Dry Weight)	Calories (kcal/100g Dry Weight)
FW-001	43	17	5.8	34	460
FW-002	23	14	3.9	59	460
FW-003	17	6.2	2.3	74	350
FW-004	16	13	3.0	69	450
FW-005	23	22	1.8	53	500
FW-006	15	6.7	2.2	76	430
FW-007	34	17	1.2	48	480
FW-008	27	21	1.8	50	500
FW-009	25	23	2.2	50	500
FW-010	14	3.7	3.7	79	400
FW-011	29	35	4.5	32	560
FW-012	54	26	2.6	17	520
FW-013	58	24	6.3	11	500
FW-014	59	17	4.5	19	470
FW-015	26	19	3.0	52	410
Grease trap waste	0.3	91	0.3	8.7	850

Table 2-7 Summary of Food Waste Characteristics

Analysis	Average of Food Wastes (not including FOG)	Standard Deviation	FOG
Volatile Solids (% Wet Weight)	26	6	67
Total Solids (% Wet Weight)	33	15	68
VS/TS	0.85	0.18	0.98
TKN (% Dry Weight)	4.9	2.5	0.06
Total Phosphorus (mg/kg Dry Weight)	300	220	40
COD (g/kg Dry Weight)	1400	340	1530
Protein (% Dry Weight)	31	16	0.3
Fat (% Dry Weight)	18	8	91
Ash (% Dry Weight)	3.2	1.5	0.3
Total Carbohydrates (% Dry Weight)	48	22	8.7
Calories (kcal/100g Dry Weight)	470	53	850

3.0 BIOCHEMICAL METHANE POTENTIAL

3.1 ABSTRACT

Biochemical methane potential tests (BMPs) were used to assess the anaerobic digestibility and methane production potential of the food waste samples collected from Mitchell Hall. In these tests, food waste was combined with anaerobic digester sludge, then incubated in sealed, anaerobic serum bottles at 37°C for 38 days. Biogas production was monitored regularly over the course of the experiment using the wet-syringe volume test method. Biogas composition was determined using GC-FID. On average, anaerobic digestion of the food wastes yielded 400 mL of methane per gram of food-waste COD, with a range of 190mL – 700 mL per gram of COD. The high average methane yield suggests that the food wastes were generally well-degraded, and that some of the food wastes may have stimulated additional methane production from the COD already present in the sludge inoculum. Wastes with a higher fat and protein content yielded more methane per gram of COD, which may be due in part to poor degradability of components of the carbohydrate fraction. The fat and/or protein may also have stimulated greater methane yield from the sludge inoculum.

3.2 METHODS

Biological methane potential tests were conducted on the waste samples described in section 2. For each test, 0.15L of anaerobic digester sludge from the King County South Treatment Plant (STP) in Renton, containing approximately 5.9 g COD, was combined with food waste to achieve a loading of approximately 3 g COD/L. The sludge and food waste were added to 250-mL serum bottles, which were then sealed with thick butyl rubber stoppers and aluminum crimp tops and purged with ultra-high-purity nitrogen gas for 2 minutes. The bottles were incubated at 37°C for 38 days.

This experiment tested 15 food waste samples from Mitchell Hall (one in duplicate), plus a sample of grease trap waste. In addition, duplicate bottles containing only digester sludge were used to determine baseline methane production from the sludge. Biogas production was measured using the wet-syringe volume test method. Sampling frequency varied over the course of the experiment, with more frequent sampling at the beginning of the test to correspond to the greater gas production rates anticipated during this period. Samples of the biogas were periodically analyzed by GC-FID, to determine the gas composition. Total methane production was calculated for each bottle, based on biogas production and composition data. The net methane production was calculated by subtracting the average methane production of the negative controls from that of the experimental bottles. The net methane yield was calculated by dividing the net methane production by the COD loading from the added food waste.

3.3 RESULTS

Figure 3-1 shows the net methane accumulation over time for the 17 experimental bottles. The average net methane accumulation for the two sludge-only controls define the zero-line of this figure. All the food wastes produced considerably more methane than the sludge-only controls over the course of the experiment, and none of the bottles experienced a lag before the onset of methane production.

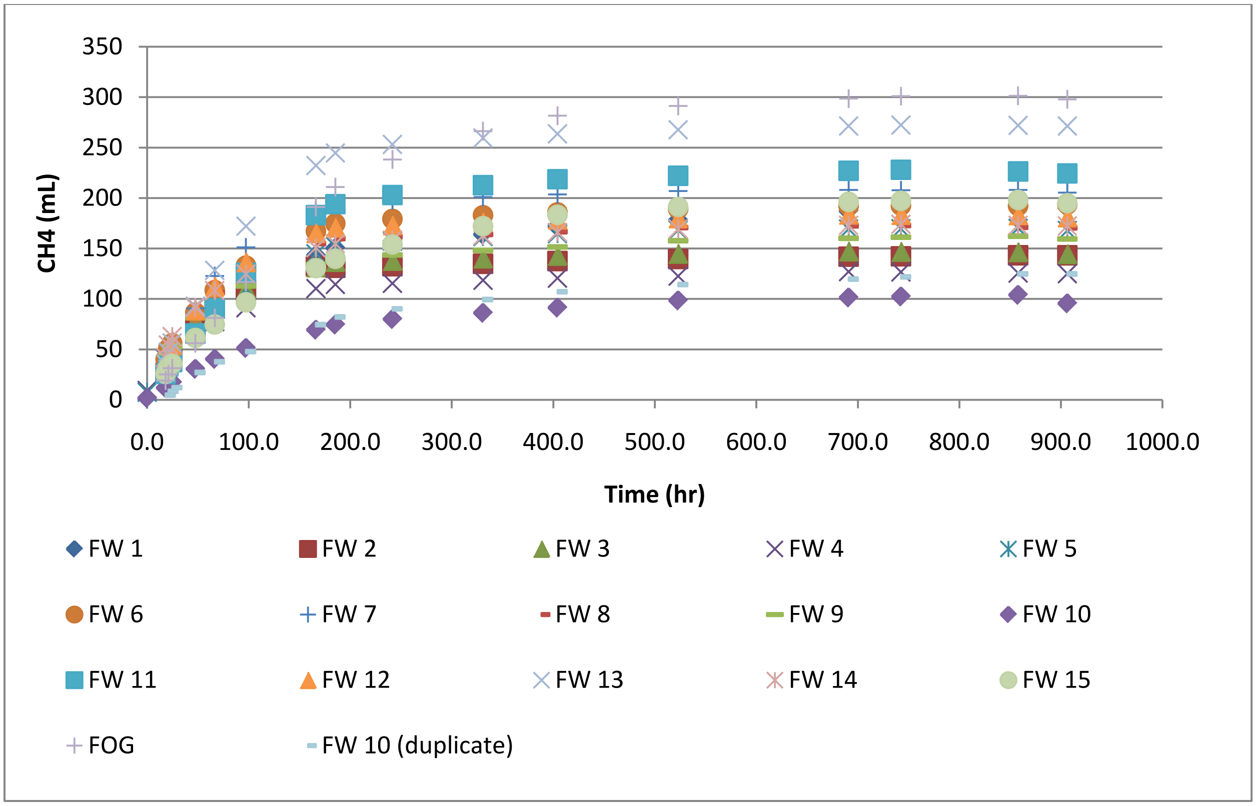


Figure 3-1 BMP Net Methane Accumulation

Table 3-1 shows the food-waste COD loading, the net methane production, and the net methane yield for each of the 17 bottles. The average of the 15 food wastes, not including the grease trap waste or the duplicate, is also contained in Table 3-1. The average net methane yield for the food wastes was 390mL/gCOD of food waste, with values ranging from 190 to 570 mL/gCOD. The yield from grease trap waste was much higher, at 700mL/gCOD.

Table 3-1 Food-Waste COD Loading, Net Methane Production, and Net Methane Yield from BMPs

Sample ID	FW COD load (g)	Net CH4 Production (mL)	Net CH4 Yield (mL CH4/g FW COD)
FW 1	0.49	220	460
FW 2	0.47	150	320
FW 3	0.49	150	310
FW 4	0.42	140	330
FW 5	0.49	200	400
FW 6	0.50	210	420
FW 7	0.46	220	470
FW 8	0.54	190	350
FW 9	0.46	180	380
FW 10	0.45	90	190
FW 11	0.46	230	490
FW 12	0.49	180	380
FW 13	0.49	280	570
FW 14	0.47	170	370
FW 15	0.50	190	390
Grease trap waste	0.46	320	700
FW 10 (duplicate)	0.48	110	230
Average ± std. dev.*	0.48 ± 0.03	190 ± 45	390 ± 90

* The average and standard deviation were calculated with neither the grease trap waste nor the duplicate of food waste 10.

Because of the wide range of methane yields observed in the BMP tests, the food waste characteristics reported in Section 2 were examined for any correlations with the methane yields. Of the food waste characteristics, the sum of the fat and protein contents was found to best explain the variation in the methane yields. The relationship between these factors is shown in Figure 3-2. Three food wastes were identified as outliers based on their unusually high residuals from a regression on all the samples: wastes 3, 12, and 14. These wastes are circled in Figure 3-2, and were excluded when calculating the regression shown in that figure. None of the tested food waste characteristics explains the deviation of these three from the pattern shown by the other wastes.

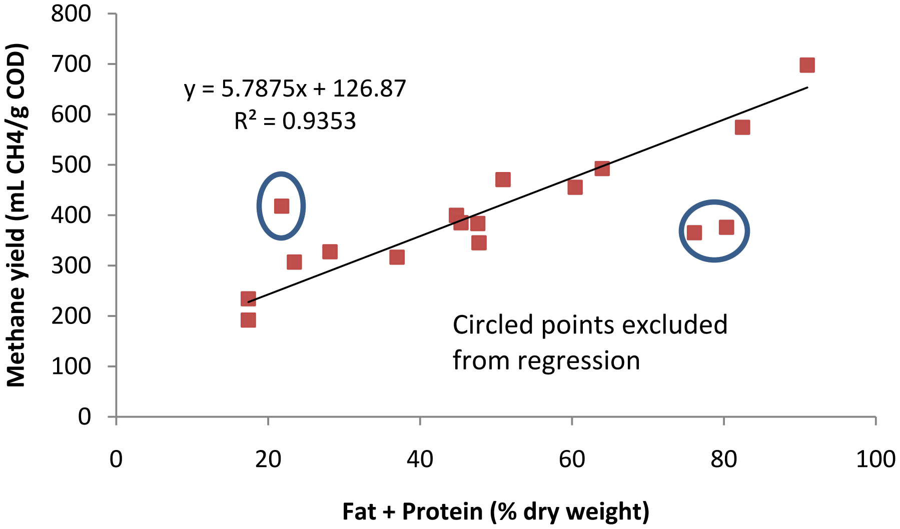


Figure 3-2 Methane Yield as a Function of Fat and Protein Content of the Wastes

4.0 SEMI-CONTINUOUS REACTOR TESTS

4.1 ABSTRACT

In this phase of the treatability study, food wastes from Mitchell Hall were digested in lab-scale, semi-continuous reactors. Initial attempts at digestion of these wastes were unsuccessful, as reactors repeatedly developed instability. Two possible causes of instability were hypothesized. The first cause identified was a low concentration of volatile solids (VS) in the reactors, resulting from dilution of the food waste prior to feeding the digester in combination with the high digestibility of the waste. The second cause identified was nutrient limitation caused by low levels of molybdenum, nickel, and cobalt. After these factors were corrected, stable reactor operation was achieved.

Several further experiments were conducted to define the limits of reactor operation. Addition of quaternary amine compounds (QACs) was tested because these compounds are contained in sanitizers used at Mitchell Hall. The QACs were found to cause reactor failure at concentrations about 2000 to 3000 mg QAC/kg of food waste solids. Multiple COD loading rates were tested, with and without the addition of grease trap waste from the Mitchell Hall. Digestion was successful at 4g COD/L/day both with and without the inclusion of grease trap waste comprising 10% of the total COD. Furthermore, food waste without grease trap waste was successfully digested at rates up to 10g COD/L/day. However, reactors started at 10g COD/L/day with 10% grease trap waste COD failed. Tests comparing grease trap waste to another fat source, canola oil, found that both fats were inhibitory when they accounted for 10% of a 10 gCOD/L/day loading the remainder being food waste. Both fats were successfully digested when they comprised only 5% of a 10g COD/L/day loading. This suggests that the grease-trap waste from Mitchell Hall did not contain any unusual inhibitory substances, and that similar inhibitory levels may be expected from other fat sources. Experiments with ramped loading rates demonstrated that 10% grease trap waste COD additions could be achieved at a 10g COD/L/day loading, if start-up occurred at either lower COD loadings rates or lower grease trap waste COD percentages followed by gradual increase of the relevant parameter.

The performance of stable reactors was compared at different loading rates of total COD and grease trap waste COD. Higher COD loading rates increased total methane production from a given reactor volume, but decreased the methane yield from the COD applied. At lower COD loading rates, grease trap waste addition increased methane production and methane yield by about 20%, but at higher COD loading rates the benefit of grease trap waste addition was less clear. VS destruction was greater at the lower COD loading rates, but was not apparently affected by grease trap waste. Some of these differences were attributable to differences in solids retention time (SRT). Lower COD loading rates were associated with longer SRTs because the feed COD and VS concentrations were kept constant.

The specific energy loading rate (SELR) was also examined. The SELR is analogous to the specific activity of an enzyme. Whereas the specific activity measures the substrate concentration per mass of enzyme per time, the SELR measures the energy loading per unit biomass per time. The SELR of the reactors was compared to measures of reactor stability and performance, to assess whether the reactors had a maximum SELR beyond which the capacity of the methanogenic biomass is exceeded. Reactors receiving a higher SELR generally had lower

methane yields and higher VFA/alkalinity ratios. Prior to trace nutrient supplementation, instability was observed at SELR values greater than approximately 0.2gCOD fed/g reactor VS/day. Following the addition of trace nutrients, reactors were stable at SELR values up to approximately 0.4gCOD fed/g reactor VS/day. These results suggest that the SELR may be a useful design parameter, but various factors can affect the acceptable SELR threshold.

4.2 METHODS

4.2.1 Food Waste Slurry

To ease in feed addition and help ensure a homogenized mixture the reactors were fed a food waste slurry. The feed slurry was prepared in an industrial blender by homogenizing food waste (with or without grease trap waste). Tap water was added to dilute the slurry to a target COD concentration (gCOD/L FW Slurry). This concentration was varied from 75 to 275gCOD/L over the course of the treatability study; the concentrations used in particular experiments are specified in the following sections. After trace nutrient deficiencies were identified (Section 4.3.1), a trace metals solution replaced a portion of the tap water in the slurry. This solution was made with de-ionized water and the compounds listed in Table 4-1. The nutrient solution was added to the food waste slurry at a concentration of 10mL/L. Final slurry consistency was similar to peanut butter and could be fed into reactors using a syringe.

Table 4-1 Trace Metals Solution for Addition to the Food Waste Slurry at a Concentration of 10mL/L.

Compound	Concentration (mg / 100mL)
$NiSO_4*6H_2O$	10.9
$Co(NO_3)_2*6H_2O$	13.6
$Na_2MoO_4*2H_2O$	16.6
H_3BO_3	150

Two standard feeds slurries were used for a variety of the experiments, USAFA Mix and USAFA grease trap waste Mix. USAFA mix was a 50-50 mixture (mass basis) of FW-004 and FW-011. In USAFA grease trap waste Mix, 10% of the COD was from grease trap waste and the balance of the COD came from the 50-50 mixture of FW-004 and FW-011.

4.2.2 Respirometer

Biogas accumulation, production rate and concentration were measured using the Columbus Instruments Respirometer System (Figure 4-1). The system in the used for this project has extended range methane and carbon dioxide sensors, a 40 channel expansion interface and ran version 2.0.0.9 of the Micro-Oxymax software.

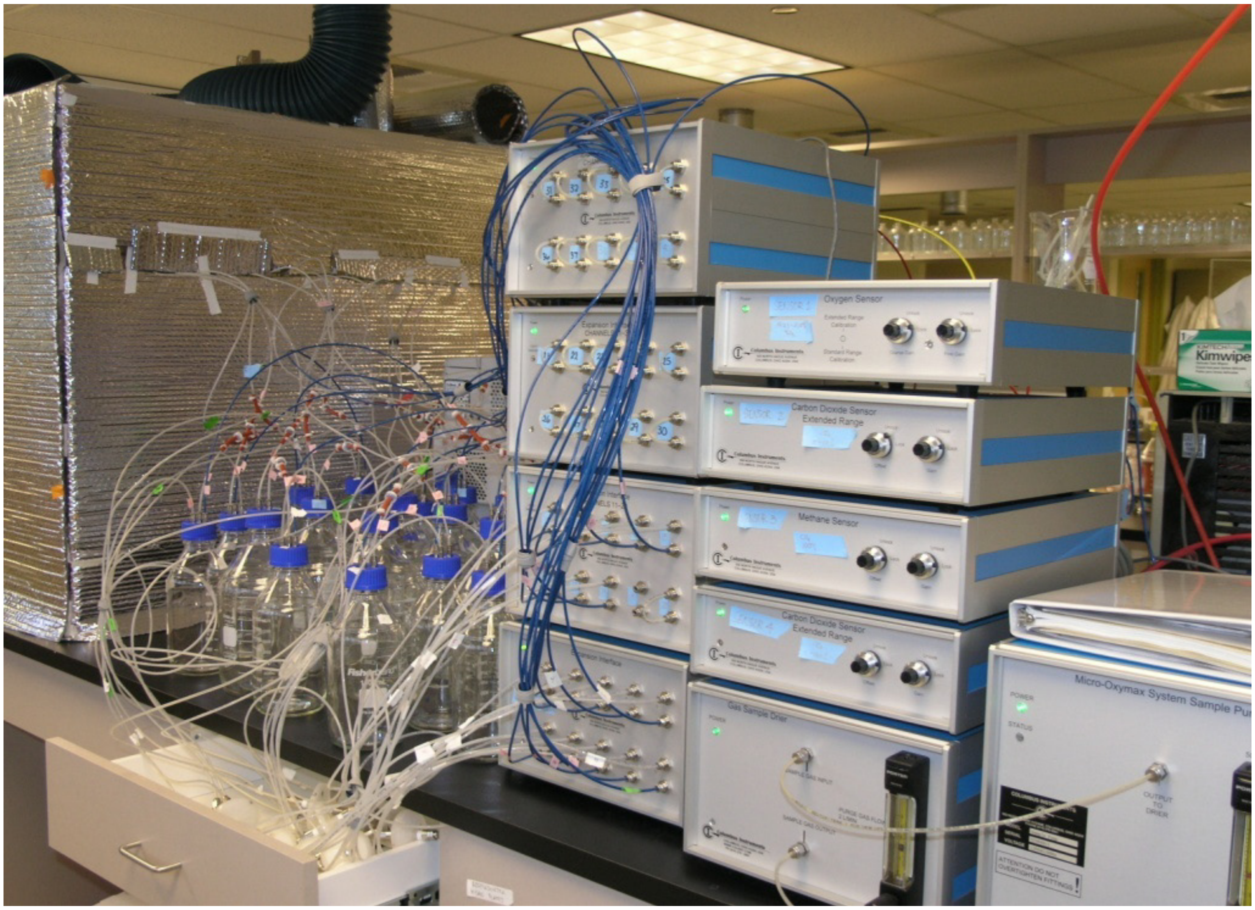


Figure 4-1 Columbus Instruments Respirometer System

As biogas is produced, the gas is collected in a glass sample collection bottle. The respirometer uses nitrogen to circulate the sample gas through the sensors to determine the gas concentration, temperature and pressure. The biogas volume, composition and production rate is calculated by the Micro-Oxymax software.

4.2.3 Carboy Configuration and Operation

The carboy bioreactors were consisted of a 20L Nalgene carboy and 3 port caps fitted with Swagelok and polycarbonate quick connects, seen in Figure 4-2.

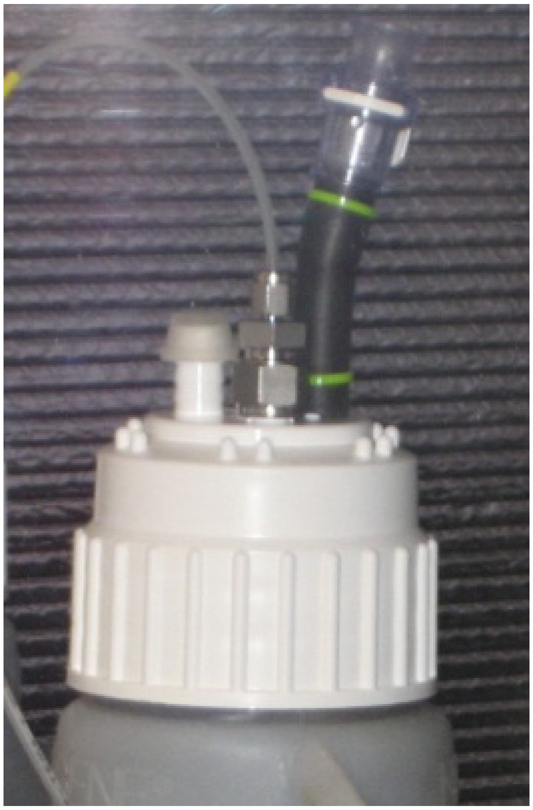


Figure 4-2 Carboy Cap with Headplate Connections

The three headplate connections are the sample port, gas line to the respirometer and feed port. The sample port is the hosebarb connection on the left of the headplate. A second hosebarb on the inside of the cap is connected with ½” tubing running beneath the liquid level. Samples were obtained by connecting tube lines to the outer hosebarb and pumping out sludge with a peristaltic pump. The metal Swagelok fittings at the center of the headplate connect to a gas line that carried accumulated gas to the respirometer via a separate gas reservoir. Food waste slurries were injected into the feed line using a syringe.

Reactor mixing was achieved using a shaker base in an incubator. Carboys were started from STP anaerobically digested sludge and maintained at a one-gallon working volume. The headspace of the carboys was flushed with high-purity nitrogen after inoculation and any time that the carboy was opened. Carboys were fed a 2 day feed load on Mondays and Wednesdays and a three day feed load Fridays. Samples were pulled just prior to feeding. The COD concentration of the feed slurry was adjusted over time in the range of 75 to 275g/L. The VS concentration varied in proportion to the COD concentration, from 35 to 135g/L, which allowed exploration of the effects of low VS loading. The TS concentration also varied, from 38 to 143g/L.

4.2.4 Glass Reactor Configuration and Operation

Reactors constructed from 2L media bottles, illustrated in figure 4-3, were used for the majority of the semi-continuous digester experiments. The large fitting on the headplate served as a feeding and sampling port. Catheter-tip syringes were inserted into the ¼” vinyl tubing for feeding and sampling; at all other times the tubing was held closed by a pinch-cock, as shown in the figure. The two small fittings were both for gas lines. One gas line connected to the respirometer via a gas reservoir. This line also had a quick-connect fitting, allowing the reactor to be disconnected from the gas reservoir during sampling and feeding. The other gas line connected to a tedlar bag. This bag was kept closed except during feeding and sampling. During sludge sampling, the bag was opened so that the sample volume withdrawn would be displaced by the biogas collected in the bag, rather than creating a vacuum that would lead to intrusion of ambient air. During feeding, the volume of feed added displaced the biogas back into the bag. Liquid sampling was conducted by inversion of the reactor, pictured in Figure 4-4.

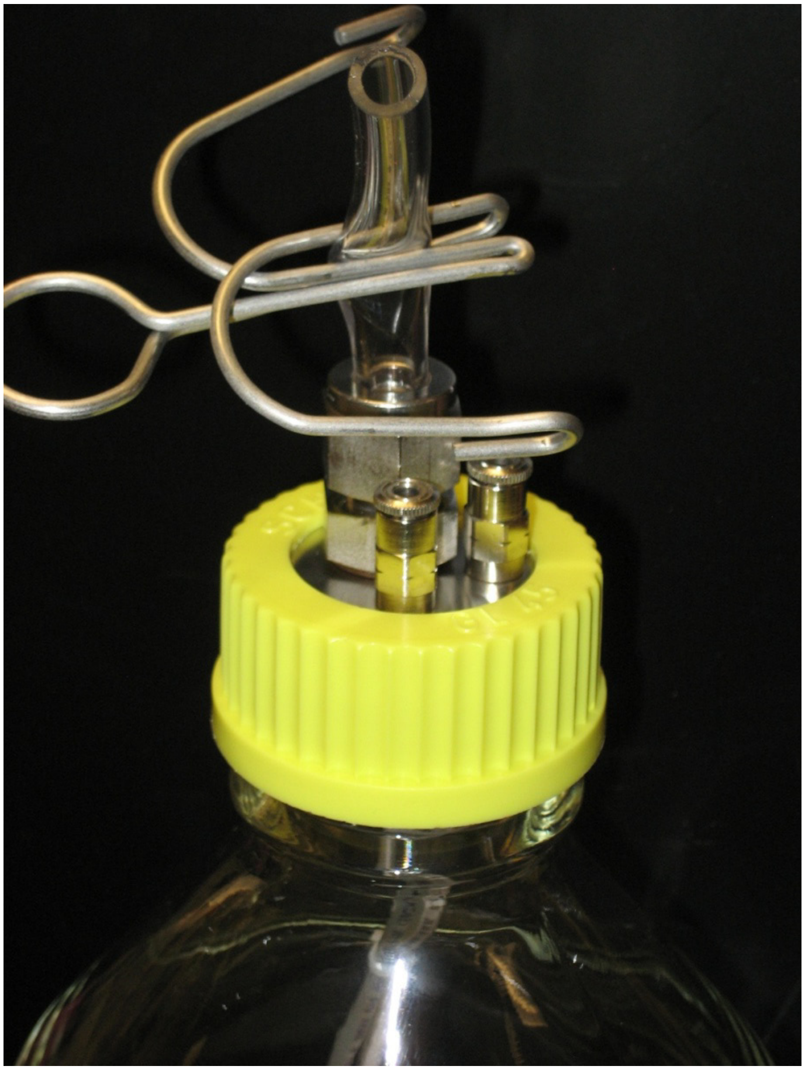


Figure 4-3 Configuration of 2L Semi-Continuous Reactor Bottle

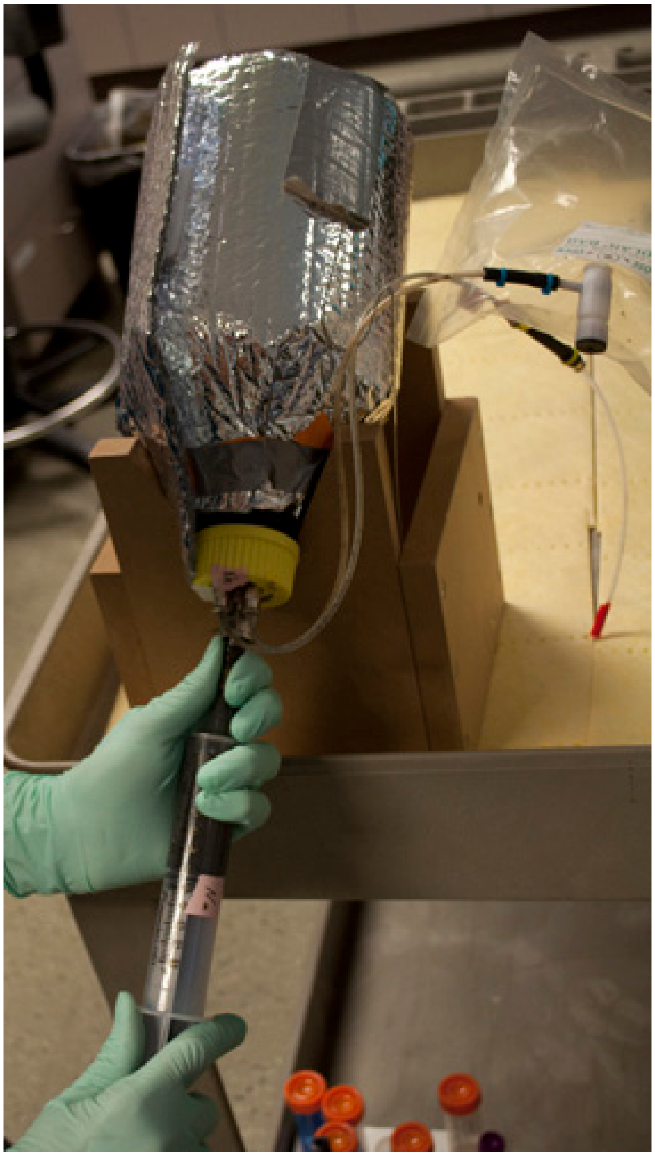


Figure 4-4 Sampling of 2L,Semi-Continuous Reactor

Reactors were inoculated with STP anaerobically digested sludge, then flushed with high-purity nitrogen to remove oxygen from the reactor headspace. Similarly to the carboys, the reactors were mixed on a shaking table in a 37°C incubator, as pictured in Figure 4-5. Sampling and feeding occurred on Monday, Wednesday, and Friday. On Monday and Wednesday the reactors were fed double the daily COD load and on Friday the reactors were fed triple the daily COD load, using feed slurries with a total COD concentration of 230 g/L. This COD concentration corresponded to VS and TS concentrations of about 140 g/L and 150 g/L, respectively. Sampling was conducted immediately prior to feeding. Samples were analyzed for pH and VFAs three times per week. COD, alkalinity, and TS and VS were analyzed weekly.

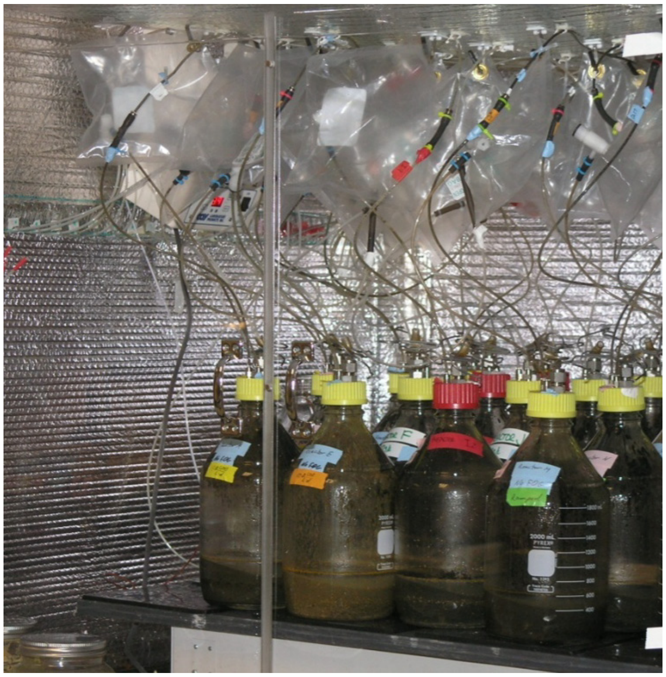


Figure 4-5 Reactors on Shaking Table in Incubator

4.2.5 Digestion Tests

4.2.5.1 QAC Inhibition

Seven reactors were used to determine the inhibitory concentration of QACs used in a sanitizer at USAFA Mitchell Hall. The reactors were fed a constant 6 g COD/L/day of mixed USAFA food waste. In addition, a the commercial QAC-containing sanitizer used at USAFA (Formula F362 No Rinse Sanitizer; State Chemical, Cleveland, Ohio) which contains 4.5% QACs by weight was added to the reactors at the concentrations shown in Table 4-2.

Table 4-2 QAC Inhibition Test Design

Reactor	QAC Concentration (mg QAC/kg feed TS)	Feed Load
UQ0	0	6 gCOD/L/day, USAFA Mix
UQ1	65	
UQ2	650	
UQ3	1300	
UQ4	1900	
UQ5	3200	
UQ6	6500	

4.2.5.2 Grease Trap Waste and COD Ramping

Tables 4.3 through 4.5 summarize the experimental conditions used to determine stable methods of starting up the digesters, evaluating potential toxicity of USAFA grease trap waste, and characterize steady state operating conditions.

Table 4.3 Experimental Conditions of Ramped Reactors

Reactor	**Ramp Basis**	**Ramp Rate**	**Inoculum**	**Start Condition**	**Final Condition**
1	COD Load	First order increase of COD loading over 53 days	STP Digested Sludge	4 gCOD/d/L of USAFA Mix	10 gCOD/d/L of USAFA Mix
2	COD Load	First order increase of COD loading over 53 days	STP Digested Sludge	4 gCOD/d/L of USAFA waste mix with 10% grease trap waste COD	10 gCOD/d/L of USAFA mix with 10% grease trap waste COD
3	COD Load	First order increase of COD loading over 53 days	STP Digested Sludge with Walnut Shell Grit	4 gCOD/d/L of USAFA Mix	10 gCOD/d/L of USAFA Mix
4	Grease trap waste concentration	First order increase of grease trap waste COD percentage over 35 Days	STP Digested Sludge acclimated to 10 gCOD/d/L of USAFA Mix	10 gCOD/d/L of USAFA Mix at 2% grease trap waste COD	10 gCOD/d/L of USAFA Mix at 10% grease trap waste COD
5	Grease trap waste concentration	First order increase of grease trap waste COD percentage over 24 Days	STP Digested Sludge acclimated to 10 gCOD/d/L of USAFA Mix	10 gCOD/d/L of USAFA Mix at 2% grease trap waste COD	10 gCOD/d/L of USAFA Mix at 10% grease trap waste COD

Table 4.4 Experimental Conditions for Evaluating Grease Trap Waste Inhibition

Reactor	Feed type	Feed loading
6	USAFA mix	10 gCOD/d/L
7	USAFA Mix with 5% canola oil COD	
8	USAFA Mix with 5% grease trap waste COD	
9	USAFA Mix with 10% canola oil COD	
10	USAFA Mix with 10% grease trap waste COD	

Table 4.5 Experimental Conditions for Longer-Term Steady State Operation

Reactor	Feed type	Feed loading
11	USAFA Mix	4 gCOD/d/L
12	USAFA Mix with 10% grease trap waste COD	4 gCOD/d/L
13	USAFA Mix	10 gCOD/d/L
14	USAFA Mix with 10% grease trap waste COD	10 gCOD/d/L

4.3 RESULTS

4.3.1 Instability Resulting from Low-VS Feed and Trace Nutrient Limitation

During preliminary operation of the carboy digesters, repeated instability was observed. Two factors were identified as probable contributors: insufficient feed-VS concentration, and trace nutrient limitation.

Figure 4-6 shows the relationship between the VS concentrations in the feed and VS in the reactors. These are plotted with the theoretical reactor effluent concentration, calculated by Equation 4-1. For these wastes, the undegradable VS fraction was assumed to be 15%, and the cell yield to be 0.12g biomass VS per 1g feed VS consumed.

$$\begin{aligned} Reactor\ VS = {} & Feed\ VS * undegradable\ VS\ fraction \\ & + Feed\ VS * degradable\ VS\ fraction * cell\ yield \end{aligned} \qquad 4\text{-}1$$

As predicted by the theory, lower VS concentrations developed in reactors receiving lower VS feed concentrations. The reactors being fed less than 5% VS developed instability in the form of elevated VFA/alkalinity ratios, lowered pH, and poor methane production. The COD load to these reactors was approximately 2.2gCOD/L/day which is not considered high. Higher VS concentrations developed in the sludge of reactors that received feed with a VS concentration of greater than 10%, and these reactors performed more stably. These reactors had COD loadings that ranged from 0.5 to 3.3gCOD/L/day. Thus low VS was concluded to be the cause of instability rather than COD loading. The specific energy loading rate (SELR) was calculated for these reactors and was also greater in the unstable region (less than 5% VS feed) than in the stable region (greater than 10% VS feed). These data indicate that the energy loading rate (i.e., g COD/d) was too great for the effective microbial population in the digester represented in terms of g digester VS. As a result of these observations, the feed VS was kept above 10% during further reactor operations.

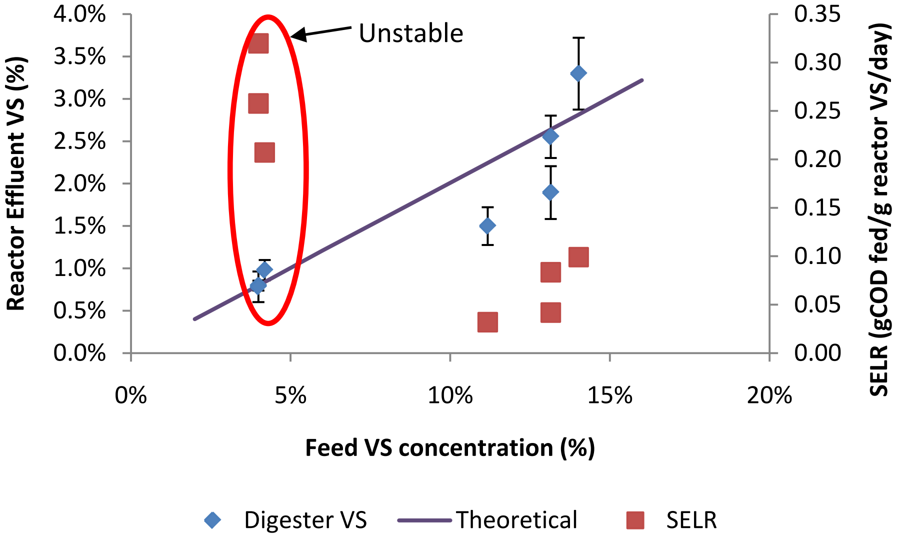


Figure 4-6 Reactor VS Concentrations, SELR, and Reactor Stability in Relation to Feed VS Concentration

Despite increased feed VS concentrations and increased digester VS concentrations, the reactors continued to experience some instability. As part of a process to identify causes of the instability, the trace metals content of the food waste was tested. Figure 4-7 compares the trace nutrient content of the food waste to required concentrations. The required concentrations in the food waste were calculated from literature values for nutrient levels required for the growth of methanogens and multiplying by 20. The factor 20 was used to account for concentration metals during volatile solids destruction and microbiological assimilation of the nutrients. The food waste was found to be deficient in nickel, cobalt, and possibly molybdenum. After the trace nutrient limitation was identified, these three nutrients were added to the feed. Boron was also added at a concentration of 11 mg/kg (dry-weight basis); although the need for this element is not well-established, it is recommended in some anaerobic culture media.

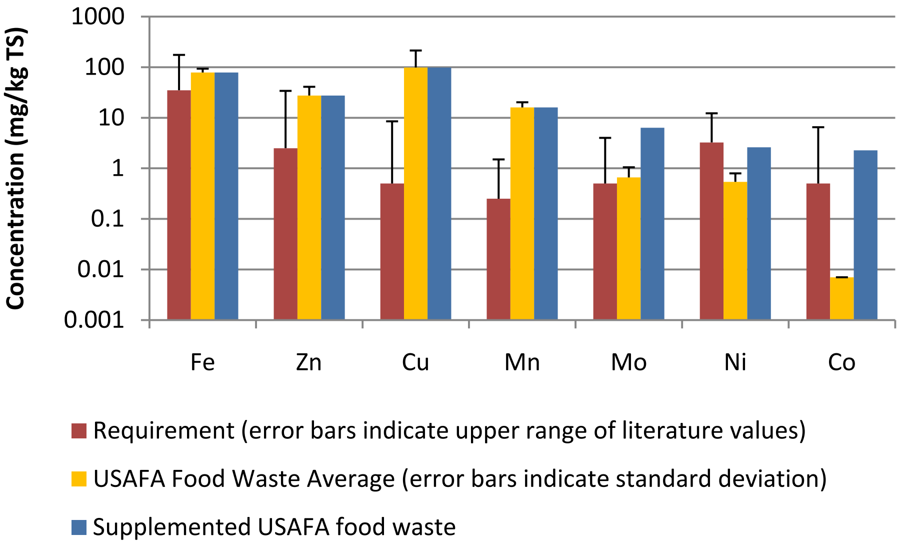


Figure 4-7 Comparison of Trace Metals Requirements

4.3.2 Effects of Quaternary Amine Compounds

Because the food-waste collection system at Mitchell Hall uses a quaternary amine compound (QAC) sanitizer in the rinse-water, the effects of QAC additions to the food waste were studied. The concentrations of QAC applied were shown in Table 4-2.

This experiment demonstrated increasing inhibition at QAC concentrations above 2000mg QAC/kg food-waste TS. These results are illustrated in Figure 4-8. The reactors receiving the highest QAC concentration, UQ5 and UQ6, both failed before the experiment concluded. The other four experimental reactors maintained a pH similar to that of the control reactor throughout the experiment, although UQ4, with the third-highest QAC concentration (1,900 mg/kg TS), developed an elevated VFA/Alkalinity ratio indicative of possible instability.

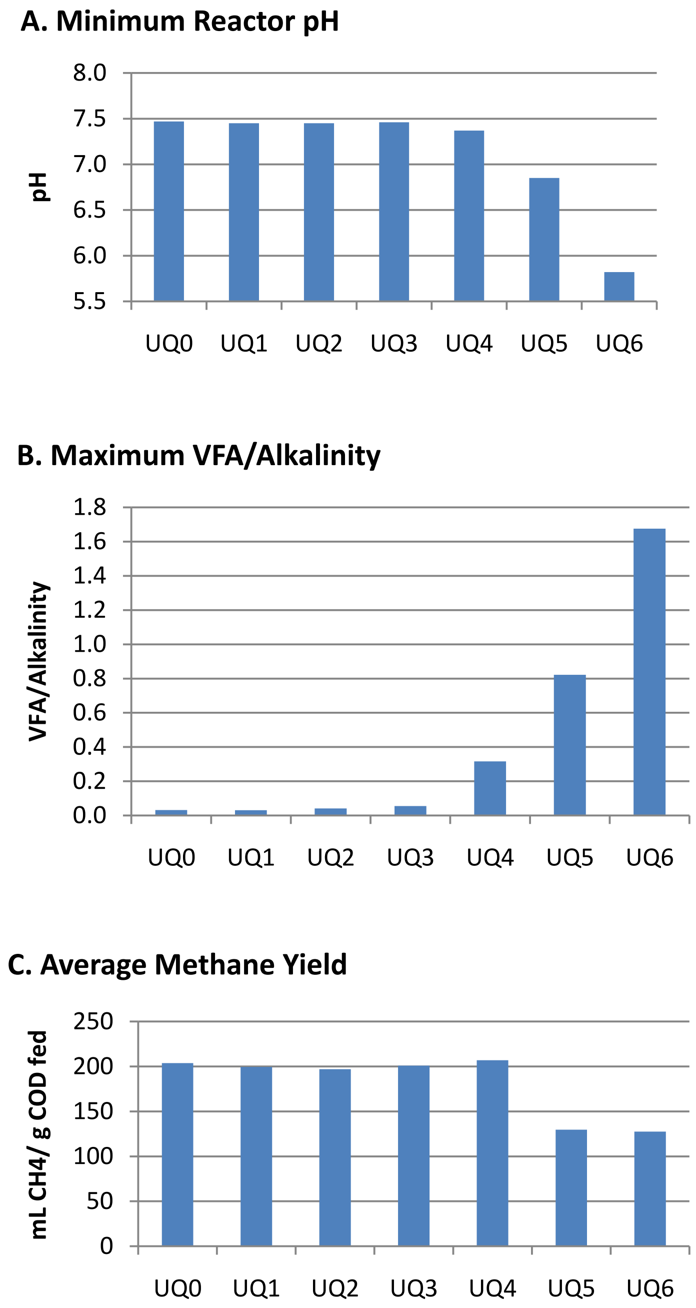


Figure 4-8 Effects of the addition of quaternary amine compounds (QAC) on reactor stability. (A): Minimum pH measured in each reactor during operation; (B) Maximum VFA/Alkalinity ratio; (C) Average methane yield.

4.3.3 Grease Trap Waste Inhibition and Digester Startup

During early tests of reactor loading, reactors started at a loading of 10gCOD/L/day failed when grease trap waste was included as 10% of the COD load. In contrast, reactors started at that same COD load but without grease trap waste were stable. In order to determine whether the grease trap waste from the grease traps at Mitchell Hall was inherently inhibitory, the performance of reactors receiving grease trap waste was compared to that of reactors receiving canola oil. Five conditions were compared in this test where all five received the USAFA food waste mix plus different amounts of grease trap waste or canola oil and the COD loading was kept constant at 10 g/L/d. As shown in Figure 4-9, the reactors receiving 10% of their COD as either grease trap waste or canola oil failed immediately: gas production was consistently low in these reactors, VFA accumulated rapidly, and pH dropped below 6.5 within one week of operation. In contrast, the reactors receiving 5% of their COD load as either grease trap waste or canola performed stably, and with methane production rates similar to those seen in the control with no grease trap waste or canola oil. These results clearly demonstrated that USAFA grease trap waste is not inherently inhibitory but elevated concentrations of any fat can be inhibitory when fed at a high COD loading rate.

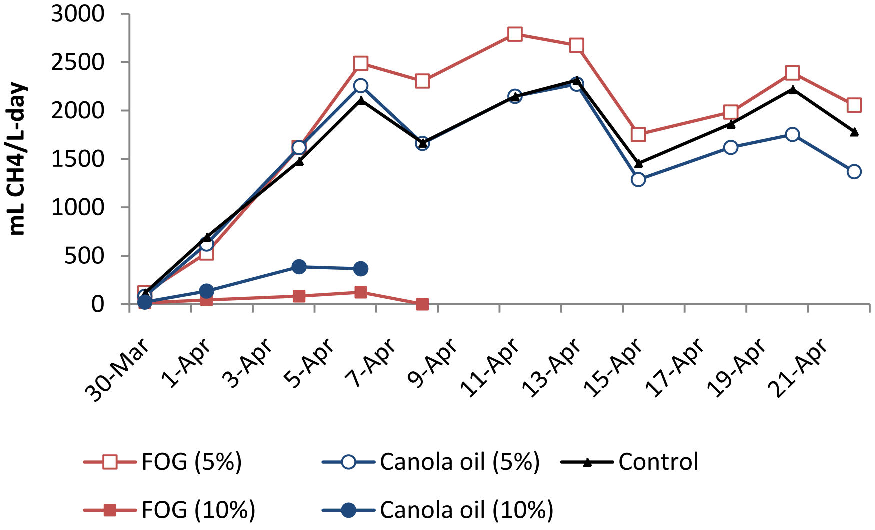


Figure 4-9 Methane production from reactors receiving grease trap waste and canola oil

Experiments were also performed to identify methods for startup of the digesters and how to attain stable operation with high COD loading rates and grease trap waste content. Four conditions were compared: immediate loading of 10gCOD/L/day without grease trap waste, immediate loading of 10gCOD/L/day with 10% grease trap waste, immediate loading of 10gCOD/L/day with ramping of grease trap waste from 0% to 10%, and ramping a 10% grease trap waste COD feed from 4gCOD/L/day to 10gCOD/L/day. The methane production rates from these reactors are shown in Figure 4-10. As expected based on results presented in Figure 4-9, immediate feeding of 10gCOD/L/d of USAFA food waste without grease trap waste was stable but inclusion of grease trap waste at this COD loading rate was unstable. Both ramping approaches (i.e., gradual increase of COD loading or grease trap waste percentage) led to stable digestion of a 10gCOD/L/day loading with 10% grease trap waste. These data demonstrate that stable digestion with 10% grease trap waste COD at a total COD loading rate of 10 g/L/d is possible, but startup must include one of the two ramping procedures.

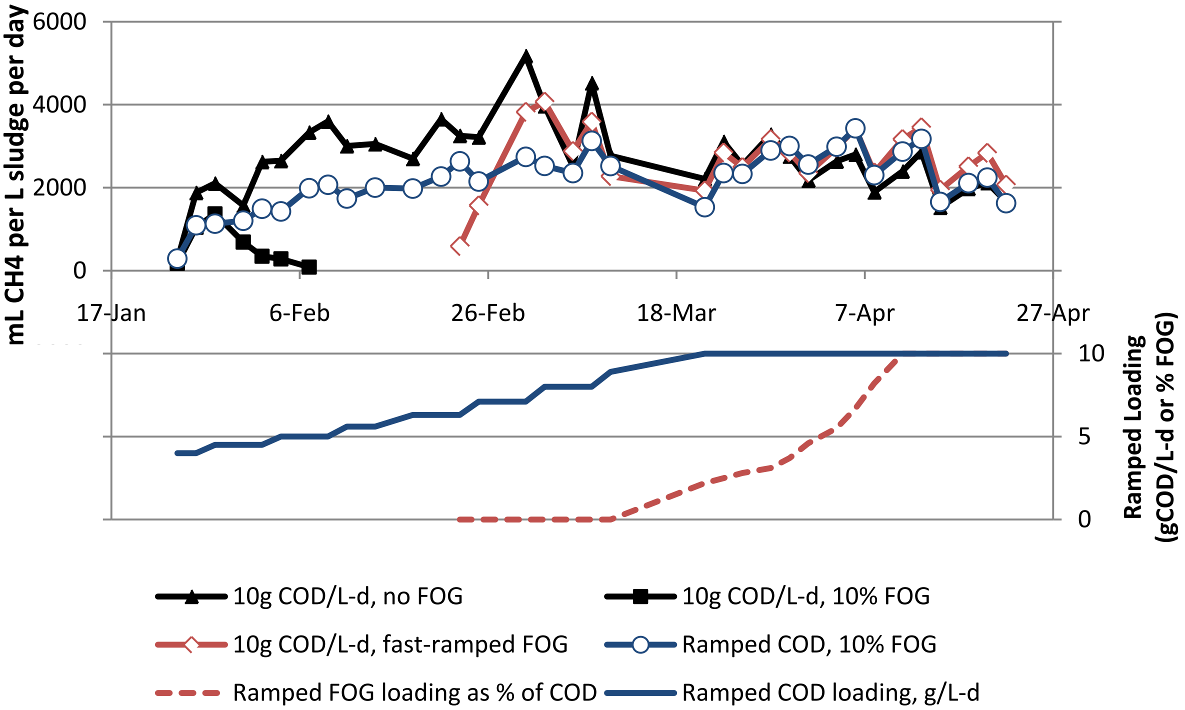


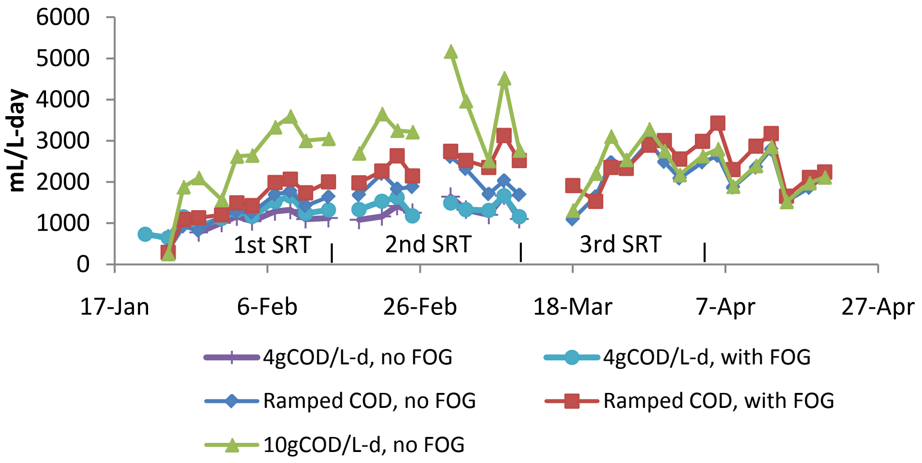
Figure 4-10 Methane production from ramped grease trap waste reactors

4.3.4 Performance of Reactors at Ramped and Stable Loading Rates

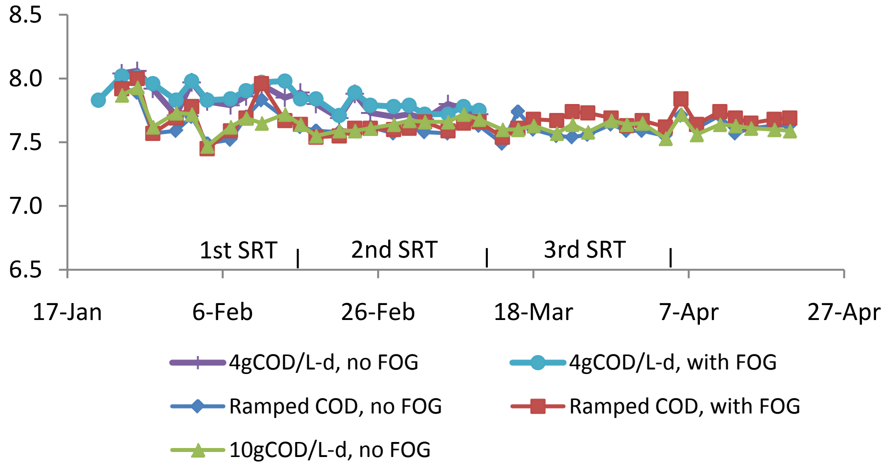
The performance of stable reactors was characterized at four different loading conditions: 4 gCOD/L/day with no added grease trap waste, 4gCOD/L/day with 10% of the COD from grease trap waste, 10gCOD/L/day with no added grease trap waste, and 10gCOD/L/day with 10% grease trap waste. As mentioned in section 4.3.2, immediate loading of 10gCOD/L/day with 10% grease trap waste resulted in reactor failure, so this condition was studied in reactors that had been acclimated to this loading condition through ramping. An additional reactor was ramped from 4gCOD/L/day to 10gCOD/L/day, without grease trap waste, to explore whether a ramped start-up resulted in better performance than immediate loading. The ramping process was completed in these reactors on 18 March, after which they were operated at a steady 10gCOD/L/day. Figure 4-11 shows several performance characteristics over time for reactors at steady and ramped loadings, with and without grease trap waste. Also shown are the elapsed SRTs for the 10gCOD/L/day loading rate.

Figure 4-11 (a) shows methane production, normalized to the working volumes of the reactors. Methane production was higher for the 10gCOD/L/day loading than for lower loadings, but it was also more variable during the first two SRTs. Some of this variability is likely to be associated with respirometer precision and accuracy, and will be discussed further in Section 6.2, but some of the variability might also indicate that the reactor had not yet fully adapted to that loading. Figure 4-11 (a) also shows that the ramped reactors, once reaching a 10gCOD/L/day loading, had similar methane production to the un-ramped 10gCOD/L/day reactor. Figure 4-11 (b) shows the pH of these reactors, all of which stabilized at pH of 7.6-7.7. The VFA/alkalinity ratios, shown in Figure 4-11 (c), remained below 0.1 for all the reactors, although the steady 10gCOD/L/day reactor and the ramped reactors tended to have higher values than the steady 4gCOD/L/day reactors. As shown in Figure 4-11 (d), the VS in the reactors remained between 2.5 and 3.3%, with slightly lower values in the 4gCOD/L/day reactor and during the early part of the ramping process. These data demonstrate that stable operation over a period of greater than 3 SRTs was observed in low and high COD loading rates both with and without grease trap waste.

A. Methane production



B. pH



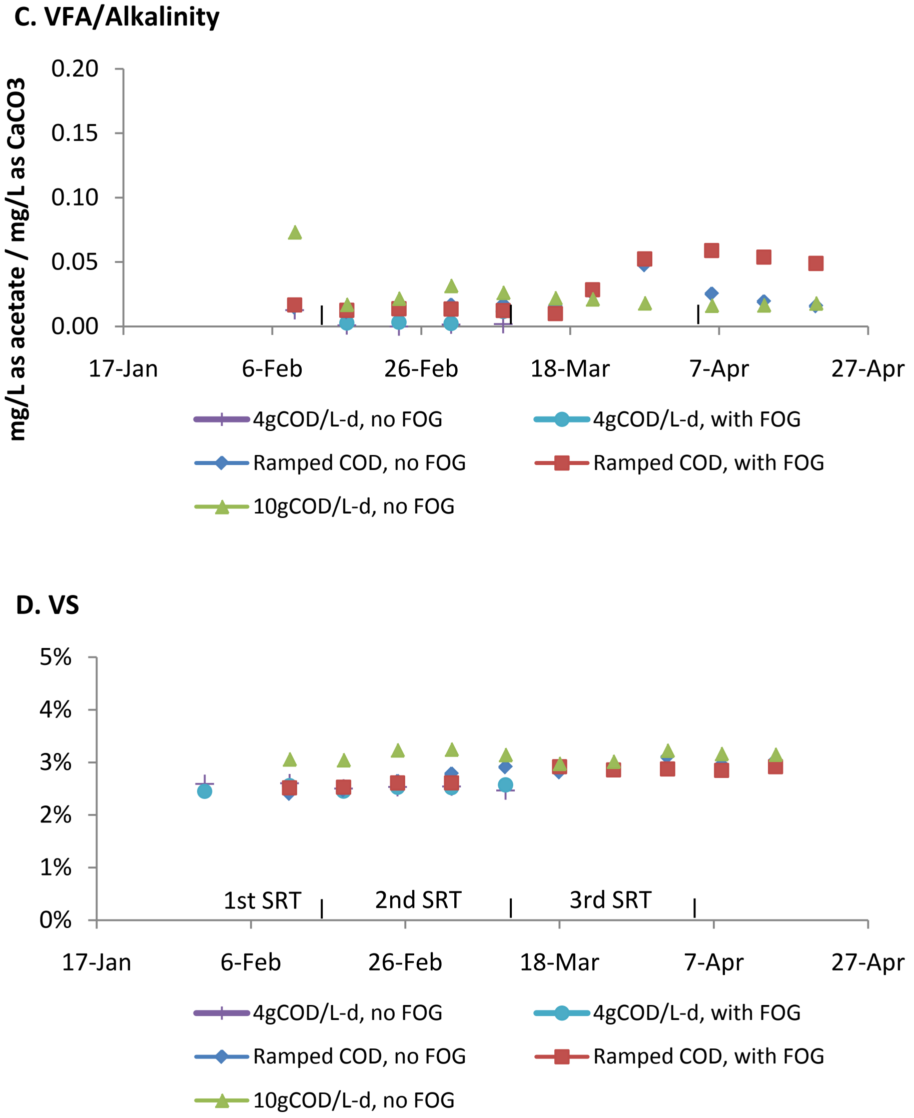
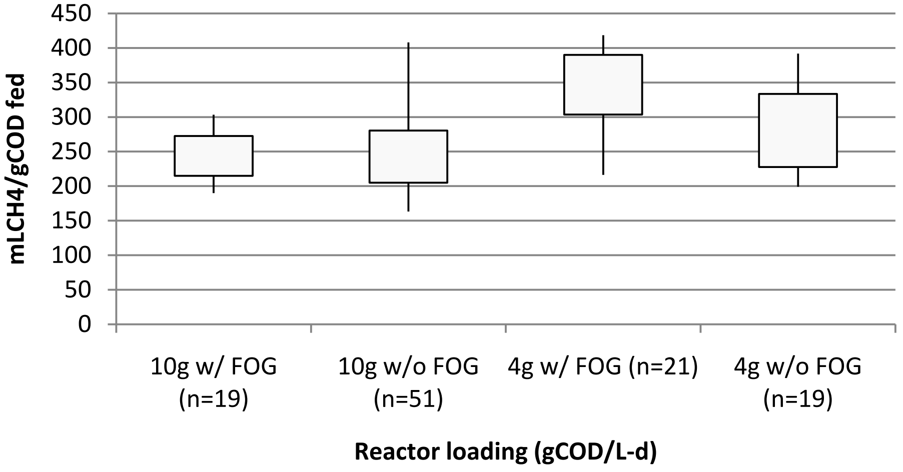


Figure 4-11 Reactor Performance by methane production, pH, VFA/acetate ratio and VS concentration over time (Ramping completed on 18 March)

Figure 4-12 summarizes the methane yields and VS destruction rates observed in reactors receiving steady loadings of either 4gCOD/L/day or 10gCOD/L/day, with and without grease trap waste. These values were calculated from the reactors that were included in Figure 4-11, as well as from reactors used in the grease trap waste ramping experiments. The methane yield was higher at lower COD loading rates. This is in contrast to the methane production, which is higher with higher loading rates. There was also an increased methane yield from grease trap waste additions with a 4gCOD/L/day loading, but that increase was not observed at a 10gCOD/L/day loading. The VS destruction rates were also increased in the 4gCOD/L/day reactors compared to the 10gCOD/L/day reactors, but grease trap waste addition had no apparent effect.

A. Methane yield



B. VS Destruction

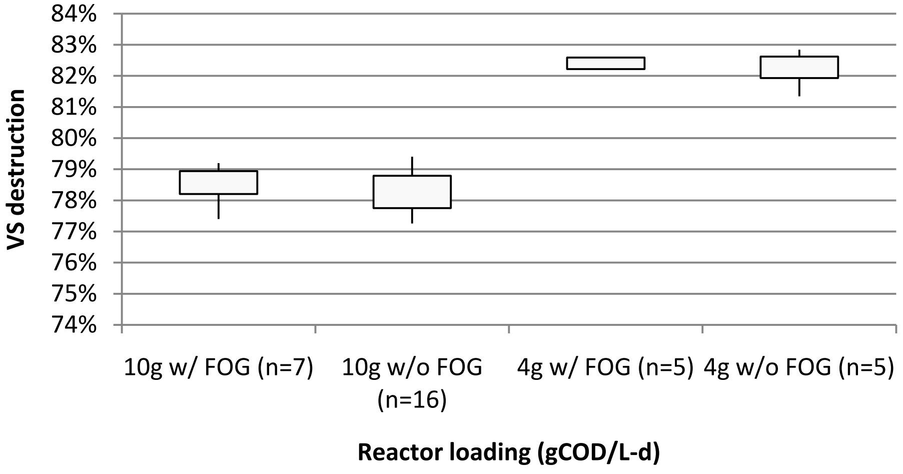
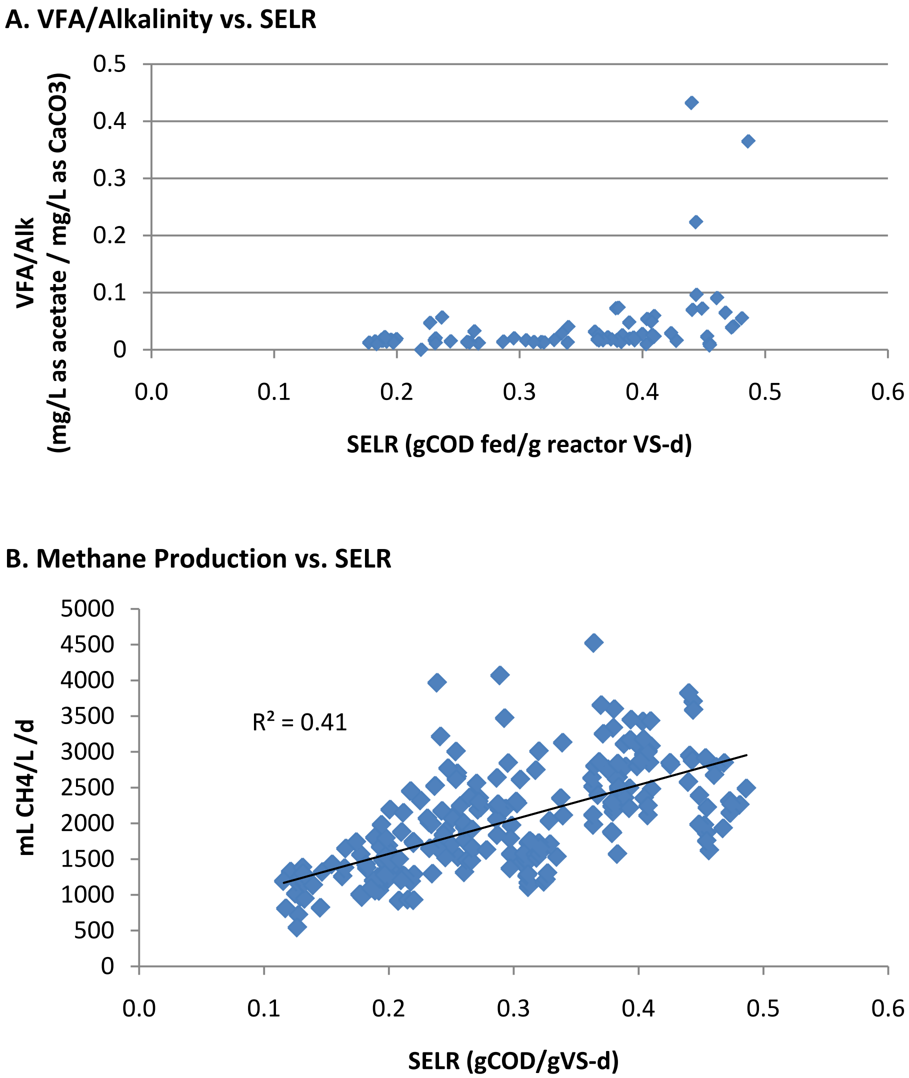


Figure 4-12 Reactor performance at steady loading rates. Boxes 25-75 percentile, whiskers 5-95 percentile.

In order to assess the utility of the specific energy loading rate (SELR) as a guideline for stable reactor loading rates, the VFA/alkalinity ratios observed during reactor operation were compared to the SELR. A VFA/alkalinity ratio of greater than 0.1 has been suggested as an indicator of reactor instability. The SELR was also compared to both the methane production and the methane yield. Figure 4-13 shows the relationship between SELR and these three factors, for reactors that were neither suffering acute inhibition from QAC addition nor receiving high grease trap waste loadings without acclimation. Reactors with an SELR of <0.4gCOD fed/g reactor VS/day generally maintained VFA/alkalinity values well below 0.1, although those loaded at more than 0.38 approached that threshold. At SELRs from 0.4 to 0.5, the VFA/alkalinity ratios were generally higher than at lower loadings, with a few excursions well above 0.1. Methane production increased with SELR, and methane yield decreased. These trends are similar to those seen with comparisons among loading rates. There was substantial variation in the relationships of methane production and methane yield to SELR. This variation reflects the day-to-day variability of the gas production data, but also suggests that other factors may be influencing gas production.



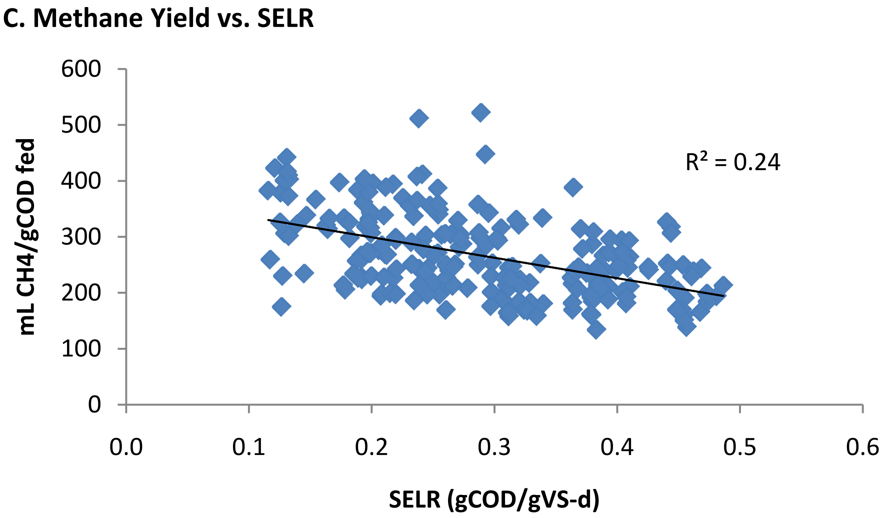

C. Methane Yield vs. SELR

Figure 4-13 Reactor performance characteristics plotted against the specific energy loading rate (SELR). (A): VFA/alkalinity; (B): Methane production; (C): Methane yield.

Table 4-6 presents summary statistics for the steady state reactors at four conditions. These data formed the based for development of performance objectives for the demonstration.

Table 4-6 Summary Statistics for Steady State Digester Operation

Parameter	4 g COD /L/d w/o 10% FOG	4 g COD/L/d w/ 10% FOG	10 g COD/L/d w/o 10% FOG	10 g COD/L/d w/ 10% FOG
% Energy conversion	76 ± 10	92 ± 11	75 ± 16	74 ± 8
mL CH4/g VS load	450 ± 130	550 ± 140	410 ± 130	460 ± 80
mL CH4/g COD load	290 ± 70	350 ± 60	260 ± 80	250 ± 40
mL CH4/L/d	1200 ± 290	1400 ± 210	2600 ± 770	2600 ± 560
% CH4 in biogas	65 ± 1	66 ± 1	67 ± 4	70 ± 3
g COD/g VS/d (SELR)	0.16 ± 0.03	0.18 ± 0.03	0.33 ± 0.06	0.35 ± 0.07
g VS/L/d (volumetric loading)	2.6 ± 0.5	2.4 ± 0.4	6.3 ± 1.2	5.8 ± 1.2
g COD/L/d (volumetric loading)	4.1 ± 0.8	4.2 ± 0.7	10.2 ± 1.9	10.3 ± 1.9
VFA/Alk	0.01 ± 0.002	0.02 ± 0.003	0.03 ± 0.02	0.04 ± 0.02
% VS destruction	82 ± 1	82 ± 1	78 ± 1	78 ± 1
% TS destruction	78 ± 1	78 ± 1	75 ± 1	75 ± 1
SRT (d)	58 ± 12	58 ± 12	24 ± 6	23 ± 5

5.0 MODEL CALIBRATION AND HYDROLYSIS KINETICS OF FOOD WASTE AND GREASE TRAP WASTE

5.1 ABSTRACT

A batch test was run on the respirometer in order to determine the hydrolysis kinetics of two food wastes with and without 10% grease trap waste. Data collected in the hydrolysis test will be used to calibrate the Mathcad ADM1 model.

5.2 METHODS & MATERIALS

5.2.1 Acclimation Period

Three weeks prior to commencing the experiment four reactors of Renton Municipal Digestion sludge were started on a semi-continuous feed of 4.0 g COD/L/day of mixed food waste with 10% grease trap waste to develop acclimated inoculum. During the acclimation period the reactors were kept incubated at 37° C and fed on a Monday/ Wednesday/Friday schedule. Digester health was monitored by pH checks on feed days. Additional analysis was completed for informational purposes, including alkalinity, total and soluble COD, ammonia concentration, VFA analysis, total and volatile solids and conductivity.

5.2.2 Hydrolysis Test

Sludge from the four acclimation reactors was pooled and then split into five hydrolysis reactors for the experiment. Temperature, SRT, HRT, start volume and COD dose were constant for the five reactors. Each reactor was dose fed 12 gCOD/L at T = 0 according to the test conditions. Food waste source and composition were the variable test conditions, outlined in Table 5.1.

Table 5-1 Hydrolysis Test Conditions

Test Variable	Reactor 1	Reactor 2	Reactor 3	Reactor 4	Reactor 5
Food Waste Composition (% COD Basis)	FW-B1 100%	FW-B1 90%	FW-B3 100%	FW-B3 90%	FW-B1 100%
Grease trap waste (% COD Basis)	0%	10%	0%	10%	0%

Gas production rates and percentages were monitored at regular intervals using the respirometer. Reactors were sampled at specified time points and reactor volume changes were recorded over time so the gas production data can be normalized to the batch volume. Sample points and analyses performed are outlined in table 5-2.

Table 5-2 Hydrolysis Reactor Sample Schedule

Day	Time (hrs)	Analyses
1	Inoculum	TS, VS, VFA, sCOD, pH, Ammonia, Alkalinity
1	t=0 (post-feed)	TS, VS, VFA, sCOD, pH, Ammonia, Alkalinity
1	2, 4, 6, 8, 10	pH, VFA, sCOD, Ammonia
2	24, 28, 32	pH, VFA, sCOD, Ammonia
3	48	pH, VFA, sCOD, Ammonia
3	56	TS, VS, VFA, sCOD, pH, Ammonia, Alkalinity

5.3 RESULTS

A summary of the acclimation and hydrolysis reactors results are provided below. Interpretation of these data is not discussed at this time since calibration of the ADM1 model is required and will be conducted separately.

Table 5-3 Acclimation Reactor Analytics Summary

		ACC 1	**ACC 2**	**ACC 3**	**ACC 4**
pH	Average	7.6	7.7	7.7	7.6
	StDev	0.1	0.1	0.2	0.1
	Min	7.5	7.5	7.5	7.5
	Max	8.0	7.9	8.0	7.8
Alkalinity (mg/L as $CaCO_3$)	Average	12000	11000	11000	12000
	StDev	120	610	310	420
	Min	12000	11000	11000	11000
	Max	12000	12000	12000	12000
tCOD (mg/L as COD)	Average	42000	45000	45000	47000
	StDev	3200	28000	1700	8800
	Min	39000	43000	44000	39000
	Max	45000	48000	47000	56000
sCOD (mg/L as COD)	Average	1600	1500	1600	1500
	StDev	220	80	84	250
	Min	1400	1500	1600	1300
	Max	1900	1600	1700	1700
Ammonia (mg/L as N)	Average	2400	2400	2400	2400
	StDev	280	300	260	240
	Min	2200	2200	2200	2600
	Max	2600	2600	2600	2600
Volatile Solids (% Wet Weight)	Average	2.2%	2.2%	2.1%	2.1%
	StDev	0.0%	0.2%	0.1%	0.3%
	Min	2.2%	2.0%	2.0%	1.9%
	Max	2.2%	2.3%	2.2%	2.3%
Total Solids (% Wet Weight)	Average	3.1%	3.0%	2.9%	2.9%
	StDev	0.2%	0.2%	0.1%	0.5%
	Min	3.0%	2.9%	2.8%	2.6%
	Max	3.3%	3.1%	3.0%	3.2%
Conductivity (mS/cm)	Single Point	17	17	17	17

Table 5-4 Acclimation Reactor VFA Summary

		ACC 1	ACC 2	ACC 3	ACC 4
Acetate (ppm)	Average	109	89	88	82
	StDev	26	14	13	15
	Min	88	63	67	66
	Max	170	110	110	120
Propionate (ppm)	Average	14	4.7	4.4	2.5
	StDev	16	5.4	4.7	2.2
	Min	0	0	0	0
	Max	45	16	13	5.8
Isobutyrate (ppm)	Average	1.4	0	0	0
	StDev	2.4	0	0	0
	Min	0	0	0	0
	Max	6.4	0	0	0
Butyrate (ppm)	Average	1.5	0	0	0
	StDev	1.8	0	0	0
	Min	0	0	0	0
	Max	4.0	0	0	0
Isovalerate (ppm)	Average	6.9	3.6	3.2	3.4
	StDev	3.5	1.4	1.4	3.6
	Min	3.2	1.6	1.6	0
	Max	13.3	6.0	5.1	12.0
Valerate (ppm)	Average	0	0	0	0
	StDev	0	0	0	0
	Min	0	0	0	0
	Max	0	0	0	0

Table 5-5 Hydrolysis Reactor Summary

Reactor #	**1**	**2**	**3**	**4**	**5**
Feed Source (COD Basis)	100% FW-B1	90% FW-B1 10% grease trap waste	100% FW-B3	90% FW-B3 10% grease trap waste	100% FW-B1 (duplicate of Rx 1)
COD Load (gCOD/Day/L)	12	12	12	12	12
Total Methane Accumulation (mL)	1700	1700	1800	1900	1700
% Methane (Average)	65%	66%	67%	67%	66%
Total Carbon dioxide Accumulation (mL)	900	860	860	880	850
% Carbon dioxide (Average)	35%	34%	33%	33%	34%

Tables 5-6 Hydrolysis Reactor 1 Analytics

Sample Point	pH	sCOD (mg/L as COD)	Ammonia (mg/L as N)	Alkalinity (mg/L as $CaCO_3$)	% VS (% Wet Weight)	% TS (% Wet Weight)
Inoculum	7.8	1700	2400	12000	2.2%	2.9%
Post Feed	7.6	3900	2300	11000	2.9%	3.6%
T = 2 hr	7.5	3300	2500	-	-	-
T = 4 hr	7.6	3100	2600	-	-	-
T = 6 hr	7.6	3000	2200	-	-	-
T = 8 hr	7.6	2800	2300	-	-	-
T = 10 hr	7.6	2700	2300	-	-	-
T = 24 hr	7.6	2000	2400	-	-	-
T = 28 hr	7.7	1800	2600	-	-	-
T = 32 hr	7.7	2000	2700	-	-	-
T = 48 hr	7.6	1900	2700	-	-	-
T = 56 hr	7.6	1800	2800	12000	2.4%	3.1%

Tables 5-7 Hydrolysis Reactor 1 VFA Results

Sample Point	Acetate (ppm)	Propionate (ppm)	Iso-butyrate (ppm)	Butyrate (ppm)	Iso-Valerate (ppm)	Valerate (ppm)
Inoculum	105	2	ND	ND	4	ND
Post Feed	268	15	3	1	11	ND
T = 2 hr	512	63	9	11	20	2
T = 4 hr	519	95	13	20	24	7
T = 6 hr	460	108	16	15	27	6
T = 8 hr	348	114	17	3	26	2
T = 10 hr	196	118	20	ND	28	ND
T = 24 hr	82	2	ND	ND	2	ND
T = 28 hr	100	4	ND	ND	4	ND
T = 32 hr	107	3	ND	ND	4	ND
T = 48 hr	93	ND	ND	ND	2	ND
T = 56 hr	102	ND	ND	ND	3	ND

ND = Less than 1.5 ppm or non-detection

Tables 5-8 Hydrolysis Reactor 2 Analytics

Sample Point	pH	sCOD (mg/L as COD)	Ammonia (mg/L as N)	Alkalinity (mg/L as $CaCO_3$)	% VS (% Wet Weight)	% TS (% Wet Weight)
Inoculum	7.8	1800	2300	12000	2.3%	2.6%
Post Feed	7.6	3400	2300	11000	2.8%	3.5%
T = 2 hr	7.5	3200	2500	-	-	-
T = 4 hr	7.6	3000	2600	-	-	-
T = 6 hr	7.6	3000	2400	-	-	-
T = 8 hr	7.7	3000	2400	-	-	-
T = 10 hr	7.6	2900	2300	-	-	-
T = 24 hr	7.7	2000	2500	-	-	-
T = 28 hr	7.7	1900	2400	-	-	-
T = 32 hr	7.7	2100	2700	-	-	-
T = 48 hr	7.7	2100	2800	-	-	-
T = 56 hr	7.6	1800	2700	12000	2.3%	3.1%

Tables 5-9 Hydrolysis Reactor 2 VFA Results

Sample Point	Acetate (ppm)	Propionate (ppm)	Iso-butyrate (ppm)	Butyrate (ppm)	Iso-Valerate (ppm)	Valerate (ppm)
Inoculum	119	2	ND	ND	4	ND
Post Feed	269	12	2	ND	10	ND
T = 2 hr	502	64	9	12	22	3
T = 4 hr	444	70	10	16	21	4
T = 6 hr	409	71	10	19	21	5
T = 8 hr	362	100	16	30	30	11
T = 10 hr	337	90	17	16	30	9
T = 24 hr	123	4	3	ND	4	ND
T = 28 hr	119	ND	ND	ND	4	ND
T = 32 hr	118	2	ND	ND	4	ND
T = 48 hr	110	ND	ND	ND	4	ND
T = 56 hr	106	ND	ND	ND	3	ND

ND = Less than 1.5 ppm or non-detection

Tables 5-10 Hydrolysis Reactor 3 Analytics

Sample Point	pH	sCOD (mg/L as COD)	Ammonia (mg/L as N)	Alkalinity (mg/L as $CaCO_3$)	% VS (% Wet Weight)	% TS (% Wet Weight)
Inoculum	7.8	1800	2300	12000	2.3%	3.0%
Post Feed	7.6	2900	2300	11000	2.8%	3.6%
T = 2 hr	7.6	2900	2500	-	-	-
T = 4 hr	7.7	2700	2700	-	-	-
T = 6 hr	7.6	2600	2300	-	-	-
T = 8 hr	7.7	2500	2300	-	-	-
T = 10 hr	7.6	2500	2400	-	-	-
T = 24 hr	7.7	2300	2700	-	-	-
T = 28 hr	7.7	2100	2800	-	-	-
T = 32 hr	7.8	2100	2800	-	-	-
T = 48 hr	7.7	2000	2900	-	-	-
T = 56 hr	7.6	2100	3100	12000	2.3%	3.1%

Tables 5-11 Hydrolysis Reactor 3 VFA Results

Sample Point	Acetate (ppm)	Propionate (ppm)	Iso-butyrate (ppm)	Butyrate (ppm)	Iso-Valerate (ppm)	Valerate (ppm)
Inoculum	131	ND	ND	ND	4	ND
Post Feed	219	11	2	ND	9	ND
T = 2 hr	285	41	11	7	25	2
T = 4 hr	238	29	7	6	17	2
T = 6 hr	252	56	23	15	53	8
T = 8 hr	197	31	9	5	18	2
T = 10 hr	184	50	27	4	52	3
T = 24 hr	132	4	24	ND	27	ND
T = 28 hr	133	3	17	ND	14	ND
T = 32 hr	126	2	3	ND	4	ND
T = 48 hr	103	ND	ND	ND	4	ND
T = 56 hr	108	ND	ND	ND	4	ND

ND = Less than 1.5 ppm or non-detection

Tables 5-12 Hydrolysis Reactor 4 Analytics

Sample Point	pH	sCOD (mg/L as COD)	Ammonia (mg/L as N)	Alkalinity (mg/L as $CaCO_3$)	% VS (% Wet Weight)	% TS (% Wet Weight)
Inoculum	7.8	1800	2400	12000	2.3%	3.1%
Post Feed	7.6	2800	2400	11000	2.8%	3.6%
T = 2 hr	7.6	2900	2600	-	-	-
T = 4 hr	7.7	2900	2800	-	-	-
T = 6 hr	7.7	2800	2100	-	-	-
T = 8 hr	7.7	2900	2300	-	-	-
T = 10 hr	7.6	2800	2400	-	-	-
T = 24 hr	7.7	2500	2800	-	-	-
T = 28 hr	7.8	2400	2700	-	-	-
T = 32 hr	7.8	2400	3000	-	-	-
T = 48 hr	7.7	2200	2900	-	-	-
T = 56 hr	7.7	2200	3000	12000	2.4%	3.1%

Tables 5-13 Hydrolysis Reactor 4 VFA Results

Sample Point	Acetate (ppm)	Propionate (ppm)	Iso-butyrate (ppm)	Butyrate (ppm)	Iso-Valerate (ppm)	Valerate (ppm)
Inoculum	108	2	ND	ND	4	ND
Post Feed	202	16	4	ND	13	2
T = 2 hr	222	38	13	6	28	2
T = 4 hr	223	52	18	8	38	4
T = 6 hr	204	57	18	8	38	5
T = 8 hr	218	68	20	10	42	6
T = 10 hr	224	82	27	16	54	8
T = 24 hr	130	36	45	ND	79	ND
T = 28 hr	134	5	45	ND	84	ND
T = 32 hr	130	3	41	ND	83	ND
T = 48 hr	127	2	8	ND	76	ND
T = 56 hr	109	ND	ND	ND	78	ND

ND = Less than 1.5 ppm or non-detection

Tables 5-14 Hydrolysis Reactor 5 Analytics

Sample Point	pH	sCOD (mg/L as COD)	Ammonia (mg/L as N)	Alkalinity (mg/L as $CaCO_3$)	% VS (% Wet Weight)	% TS (% Wet Weight)
Inoculum	7.77	1810	2420	12000	2.3%	3.0%
Post Feed	7.59	3880	2430	11000	2.9%	3.6%
T = 2 hr	7.55	3470	2560	-	-	-
T = 4 hr	7.60	3270	2660	-	-	-
T = 6 hr	7.58	2953	2280	-	-	-
T = 8 hr	7.59	2913	2260	-	-	-
T = 10 hr	7.57	2720	2360	-	-	-
T = 24 hr	7.68	2060	2660	-	-	-
T = 28 hr	7.70	2080	2620	-	-	-
T = 32 hr	7.72	1860	2660	-	-	-
T = 48 hr	7.62	1880	2840	-	-	-
T = 56 hr	7.56	1690	2860	13000	2.4%	3.2%

Tables 5-15 Hydrolysis Reactor 5 VFA Results

Sample Point	Acetate (ppm)	Propionate (ppm)	Iso-butyrate (ppm)	Butyrate (ppm)	Iso-Valerate (ppm)	Valerate (ppm)
Inoculum	110	ND	ND	ND	4	ND
Post Feed	228	10	ND	ND	9	ND
T = 2 hr	488	61	8	9	19	3
T = 4 hr	474	83	9	16	18	5
T = 6 hr	458	122	14	9	27	5
T = 8 hr	314	123	15	2	25	2
T = 10 hr	191	129	19	ND	26	ND
T = 24 hr	127	5	6	ND	6	ND
T = 28 hr	121	4	ND	ND	5	ND
T = 32 hr	132	2	ND	ND	4	ND
T = 48 hr	126	2	ND	ND	5	ND
T = 56 hr	103	2	ND	ND	4	ND

ND = Less than 1.5 ppm or non-detection

6.0 QUALITY ASSURANCE

This section presents the deviations from the Work Plan and evaluation of the data quality.

6.1 DEVIATIONS FROM THE WORK PLAN

The following deviations from the work plan were made:

- HRT and SRT were varied as a function of COD loading. Varying them independently of COD loading would have required feeding a more diluted waste, which was determined to be detrimental to reactor operation.

- Carbon-to-nitrogen-to-phosphorus ratios were explored during the BMP tests, rather than reactor tests, but were not found to be predictive of digestibility within the range encountered. Although neither of these macro-nutrients was found to be limiting, trace nutrient concentrations were identified as an important limitation.

- Biomass carriers were tested in only one condition: ramped COD loading without grease trap waste. The performance of this reactor did not differ from that of the ramped reactor without walnut shells (data not shown).

- Pre-hydrolysis was not tested, as the high digestibility of the food waste rendered it unnecessary.

- Cycling of food/oil waste compositions has been deferred to the pilot demonstration.

- An explicit test of the effects of QACs at varying concentrations was added.

- A test comparing the Mitchell Hall grease-trap grease trap waste to canola oil was conducted to determine whether observed inhibitory effects were due to high lipid loading, or to an inhibitory factor unique to this grease trap waste source.

6.2 EVALUATION OF DATA QUALITY

Data precision was assessed by calculating the relative percent difference (RPD) of laboratory analyses, presented in Table 6-1. A single replicate was calculated for the Exova food waste characterization and BMP test. Multiple replicates were performed for the food waste characterization COD to ensure method precision, and the resulting average deviation is shown. Reactor Studies analyses were performed with approximately 20% replication, and the RPDs shown are the average values. All analyses meet the precision goal (RPD<35%) of the work plan.

Table 6.1: Summary of Analytical RPDS

Phase	Analysis	RPD Average
Food Waste Characterization	Chemical Oxygen Demand	2%
	Volatile Solids	10%
	Total Kjeldahl Nitrogen	1%
	Total Phosphorus	10%
	Moisture Content	3%
	Fat Content	12%
	Ash Content	7%
	COD (average)	7%
BMP	Methane Yield	19%
Reactor Studies (average)	pH	0.33
	Alkalinity	4.2
	tCOD	5.1
	sCOD	1.9
	TS	1.6
	VS	1.6
	NH4	7.3

The continuous respirometry analyses could not be performed in duplicate, so RPDs cannot be determined. However, certain factors were observed to affect the quality of the respirometry data. The gas composition sensors malfunction when exposed to excessive pressures. These pressures develop when gas production is very high relative to the headspace and sample bottle volume. This can occur if the sludge is too active (e.g. from a high COD loading rate), the working volume is too great, the headspace volume is insufficient, and/or the sampling interval is too long. However, gas composition measurements are also inaccurate if gas production is too low, so an optimization process was necessary to arrive at a good combination of working volume, sample-bottle size, and sampling interval for the different COD loading rates. Therefore the methane production values should be used primarily for comparison among different treatments, rather than as indicators to absolute values for various design parameters.

7.0 CONCLUSIONS

7.1 BMP TESTS

7.1.1 General Degradability of Mitchell Hall Food Wastes

The average net methane yield from the food wastes tested was 400mL CH4/gCOD loaded, which suggests that the wastes tested were highly degradable by anaerobic digestion. There were no major inhibitory effects apparent, as none of the bottles experienced a lag before the onset of methane production.

7.1.2 Methane Yield Correlated to Fat and Protein Content

The methane yield was quite variable between the wastes, and it was found that there was a correlation with the fat and protein content of the food waste. Several factors may have contributed to this correlation. Lignocellulose and some other types of carbohydrates are poorly degradable, so the fat and protein may have represented a more highly-degradable fraction. Furthermore, in standard analytical procedures for food the fat, protein, and ash contents of the material are analyzed; the remainder is assumed to be carbohydrates but these are not measured directly. Therefore, certain non-food materials, such as plastics, would be included in the carbohydrate fraction. The presence of such recalcitrant organics would reduce the apparent methane yield, and would also contribute to the apparent correlation between methane yield and the fat and protein content.

7.1.3 High Fat Content and grease trap waste Addition may Enhance Digestion

Many of the wastes tested produced yields above 400mL CH_4/gCOD, which is the theoretical value for full conversion (Tchobanoglous *et al.*, 2003). The grease trap waste produced the highest yield, with 700mL CH4/gCOD. This supports the readily-degradable nature of this waste, but more importantly suggests that it enhanced digestion of the sewage sludge inoculum. Recent studies have shown enhanced methane yields from the addition of high-fat wastes to sewage sludge (Kabouris *et al.*, 2009; Luostarinen *et al.*, 2009; Davidsson *et al.*, 2008). However, digestion of high-fat wastes can be problematic as well as beneficial. Degradation of fats produces long-chain fatty acids, which are potentially-toxic intermediates. Excessive loading of fats has been observed to lead to the inhibition of anaerobic digestion (Koster and Cramer, 1987; Hatamoto *et al.*, 2007). Therefore, tests to determine the acceptable grease trap waste loadings were included in the semi-continuous reactor tests, described in Section 4.

7.2 SEMI-CONTINUOUS REACTOR STUDIES

The semi-continuous reactor studies demonstrated successful digestion of food wastes from Mitchell Hall at a variety of loadings, with and without the addition of grease trap waste. This phase of the treatability study also identified several critical operational parameters.

7.2.1 Supplemental Co, Ni and Mo Addition

Trace metals analysis revealed that these food wastes are deficient in cobalt and nickel, and perhaps molybdenum. These three elements are required for enzymatic cofactors, and are among the trace metals that have been identified as critical to successful anaerobic digestion (Speece, 1996).

7.2.2 High Volatile Solid Concentrations Necessary in Feed

Feeding waste at a high VS concentration proved necessary for stable reactor operation. The food wastes were highly degradable, with VS destruction rates greater than 75%. Feeding the waste at VS concentrations seen in traditional anaerobic sludge digestion resulted in reactor solids concentrations too low to support stable operation. Reactor performance improved when the food waste VS concentrations were kept at greater than 10%.

7.2.3 Inhibition at High QAC Concentrations

Experiments demonstrated inhibition above 2000 mg QAC/kg Food Waste TS. Estimates suggest that the QAC concentrations at Mitchell Hall may approach this threshold, so assessment of QAC inhibition during the demonstration is necessary.

7.2.4 Multiple Approaches to Reactor Start Up

Reactor performance data suggest guidelines for successful start-up of food waste digestion from a sewage-sludge digester inoculum. No special acclimation of the inoculum was needed during reactor start-up for low COD loadings (4gCOD/L/day) with or without grease trap waste. The stability of high COD loaded reactors (10gCOD/L/day) depended on the presence of grease trap waste. Reactors started at high load without grease trap waste showed transiently elevated VFA/alkalinity ratios. This suggests there might be an unstable period during which the reactor would by vulnerable to further upset. Reactors started at high a COD load with 10% of COD from grease trap waste did not develop stable digestion. However, the experiments demonstrated that stable performance at high COD loadings with and without grease trap waste is achievable with a period of reactor acclimation through ramping.

7.2.5 High COD Loads Achievable Through Ramping

Stable digestion was achieved at COD loadings up to 10gCOD/L-d, with and without grease trap waste. Successful start up was demonstrated both by ramping the grease trap waste concentration from 2 to 10% and ramping the load of a 10% grease trap waste reactor from 4 to 10 gCOD/L/day.

7.2.6 Grease Trap Waste Effects Dependent on the Concentration and COD Load

Beneficial effects were seen during BMPs in conditions of a low COD load with high lipid contents. Some negative effects were observed with grease trap waste addition at high COD in the reactor studies. Starting newly-inoculated reactors with a 10gCOD/L/day loading was successful when a grease trap waste-free food-waste or low grease trap waste concentration (less than or equal to 5% of the COD) mix was used. Including grease trap waste as 10% of the COD at start-up led to reactor failure. Similar effects were seen when canola oil was used in place of grease trap waste, indicating that the failure was attributable to lipid loading in general rather than to any inhibitory factor unique to the grease trap waste from the Mitchell Hall grease traps. The breakdown of fats is known to produce long-chain fatty acids, which are potentially-inhibitory intermediates. These results show that while addition of fats may have beneficial effects either the percent of COD from grease trap waste or total COD load must be low at reactor start up.

7.2.7 Performance Trade Offs With COD Load

Comparison of performance between reactors operated at steady loadings of 4gCOD/L/day and 10gCOD/L/day showed that there was a trade-off between the methane production per reactor volume and COD. Reactors with high COD loading had a higher methane production per reactor volume, while the greater methane yield per COD loading occurred at the lower loading rate. There was also greater VS destruction at the lower loading rate. This was likely due, at least in part, to the longer SRT of the low load reactors, as it varies inversely with the loading rate when the feed concentration is kept constant.

The loading rate also changed the effects of grease trap waste addition. In reactors receiving 4gCOD/L/day, grease trap waste addition increased the methane yield, but no such increase was observed in reactors receiving 10gCOD/L/day. Grease trap waste did not apparently affect the VS destruction rate at either COD loading rate, which suggests that for these wastes the higher methane yields were a function of greater grease trap waste digestibility, rather than enhanced VS destruction.

7.2.8 Utility of SELR

Within the range tested, SELR had a weak positive correlation to methane production, but a weak negative correlation to methane yield. Reactor stability was found to decrease at higher SELRs, although the acceptable threshold appeared to be affected by factors such as trace nutrient limitation. For nutrient-supplemented reactors that were not subjected to inhibitors (e.g. QAC addition or high loadings of grease trap waste without prior acclimation), SELRs above 0.4 were associated with elevated VFA/alkalinity ratios. This suggests that the SELR may be a useful design parameter for determining safe loading levels.

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Appendix E: ADM1 Model Development

Anaerobic Digestion of Food Waste: Mechanistic Modeling, Hydrolysis Kinetics, Digester Stability, and Biomethane Production Efficiency

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INTRODUCTION

Anaerobic digestion has commonly been used in municipal wastewater treatment facilities to destroy solids produced from the wastewater treatment process. Methane biogas production from solids destruction and no aeration energy requirement are major benefits compared to aerobic digestion of solids. More recently anaerobic digestion has been considered for other community wastes including food wastes (Gabb, 2008), fat, oils and grease waste (Li et al. 2002, Stoll and Gupta 1997), and food processing and rendering wastes (Muller et al., 2009) because of its ability to produce a beneficial energy product from these waste materials. Feasibility studies performed on food waste from the United States Air Force Academy (USAFA) have shown high energy conversion efficiency of organic solids to biomethane and indicate that this is a feasible and economically promising technology for disposal of food wastes from military establishments and other institutions.

Dynamic simulation models for activated sludge systems have been developed by an International Water Association (IWA) Task Group (Gujer et al. 1999, Henze et al. 1999) and have been commonly accepted and applied for design and operational analysis on a number of commercial platforms. Similarly a comprehensive dynamic simulation model for anaerobic digestion, termed ADM1, has been developed by another IWA Task Group (Batstone et al. 2002) and has been generally accepted for its application to anaerobic digestion of municipal sludge. ADM1 has also been applied to other wastes such as grass silage, pig slurry, microalgae, and other combined wastes (Fezzani and Ben Cheikh 2008, Girault et al. 2011, Koch et al. 2010, Mairet et al. 2011). An important aspect of anaerobic digestion is maintaining stable operation under variable loads with a suitable balance between carbon processing from fermentation bacteria and utilization of the acetate and hydrogen produced by the more sensitive methanogenic bacteria. The ADM 1 model provides a useful tool to evaluate the effects of transient loadings and operating conditions on digester performance and stability.

In contrast to relatively frequent and constant feeding patterns normally used for municipal sludge digestion, the feeding patterns for anaerobic digesters of food wastes at military installations may be intermittent with significant loading spikes every two to three days. The goal of this study was to apply the ADM1 model for anaerobic digestion of food waste so that the effect of design and feeding strategies could then be evaluated for subsequent pilot plant testing and demonstration and full-scale applications. In addition, the ADM1 model was incorporated into Mathcad15 to provide a relatively inexpensive available software package for other users. Anaerobic digestion of USAFA food waste was studied in laboratory digesters and in bottle tests and provided information for model calibration.

The calibrated model was then used to evaluate the effect of different operating conditions for the pilot plant demonstration of food waste digestion. Of particular interest were digester responses to loading rate increases and periods of starvation or reduced loading rate. The effect of waste composition, hydrolysis characteristics, feeding strategy, and endogenous decay rate were also evaluated with the calibrated model.

CHAPTER I: ADM1 MODEL DESCRIPTION

The Anaerobic Digester Model 1 (ADM1) was selected as the model platform to describe anaerobic digestion of food waste. ADM1 is the product of a collaborative effort by the International Water Association (IWA) Task Group for Mathematical Modeling of Anaerobic Digestion Processes, and, has been applied for a broad range of anaerobic process applications (Batstone et al. 2002). While adjustments to the model were needed to account for this new application, the overall model structure was maintained. This chapter provides an overview and process description of the “default ADM1”, followed by the specific changes that were made to address food waste digestion, denoted as the “modified ADM1.” All of the information regarding the ADM1 model is in reference to the work presented by Batstone et al. (2002).

ADM1 describes the fate of organic substrates in anaerobic digestion on a chemical oxygen demand (COD) basis using a system of differential and algebraic equations. The COD is conserved in the conversion of particulate feed to its soluble intermediates, and eventually to final products of methane gas and biomass. Michaelis-Menten and first order kinetic rate equations describe how fast the COD conversions occur. The COD conversion steps of the default ADM1 is described in Figure 1. Petersen matrices from Batstone (2002) describing all of the soluble and particulate dynamic state variables for the default ADM1 are in Appendix A.

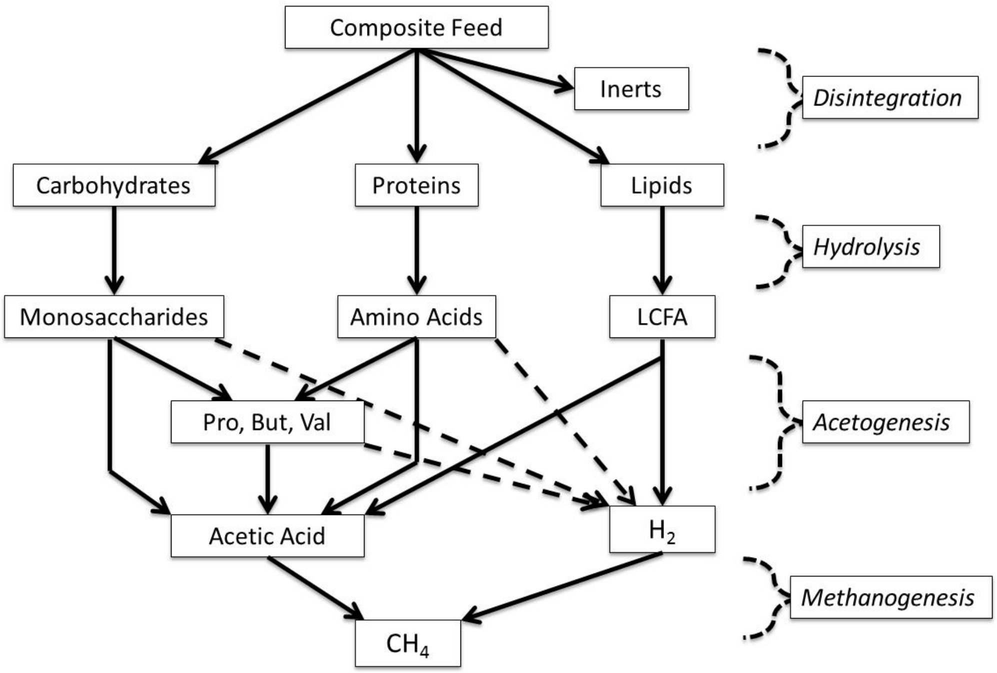

Composite Feed
Inerts
Disintegration
Carbohydrates
Proteins
Lipids
Hydrolysis
Monosaccharides
Amino Acids
LCFA
Pro, But, Val
Acetogenesis
Acetic Acid
H_2
Methanogenesis
CH_4

Figure 1. Flowchart of COD conversion pathways in the ADM1

The first step described by the ADM1 is disintegration, which is defined as the breakdown of composite particulate COD material into particulate carbohydrates, proteins, and lipids components, as well as soluble and particulate inert material. This step is a physical mechanism, and was included in the ADM1 to allow the use of individual hydrolysis rates for the particulate carbohydrate, protein, and lipid substrates.

The particulate substrate components produced by disintegration are then solubilized in a hydrolysis step. This enzymatic process converts complex particulates into their corresponding soluble monomers. Monosaccharides, amino acids, and long chain fatty acids comprise the soluble products of hydrolysis for carbohydrates, proteins, and lipids, respectively and are the substrates for acidogenesis and acetogenesis. Although hydrolysis is complex and has many steps, it is described by a simple first order kinetics model in ADM1.

Next, the soluble monomers are fermented to volatile fatty acids (VFAs) in an acidogenesis step. The ADM1 includes propionate, butyrate, and valerate as intermediate VFAs. Substrate utilization is determined by Michaelis-Menten kinetics in the ADM1 for all of the post hydrolysis processes:

$$R_S = \frac{k_m S X}{K_s + S} \qquad (1)$$

where:

R_s = substrate utilization rate, gCOD/L-d

k_m = maximum specific substrate utilization rate, gCOD/g biomass COD-day

S = substrate concentration, gCOD/L

X = biomass concentration utilizing substrate, S, g biomass COD/L

Ks= half-velocity coefficient, gCOD/L

The acetogenesis step describes the degradation of higher molecular weight organic acids to acetate, hydrogen, and carbon dioxide. In order to maintain thermodynamically favorable acetogenesis reactions, hydrogen must be kept at a low concentration by the hydrogen-utilizing methanogens.

Methanogenesis is the last step of anaerobic digestion. Two types of methanogens are considered in the ADM1 model: acetoclastic and hydrogen-utilizing methanogens. Acetoclasts cleave acetate into methane and carbon dioxide, while hydrogen-utilizers form methane by combining hydrogen and carbon dioxide. Two main genera of acetoclasts are *Methanosarcina* and *Methanosaeta* and the ADM1 suggests their presence is mutually exclusive in anaerobic digesters. The more common occurring *Methanosaeta* (Zinder, 1993) with their corresponding ADM1 Michaelis-Menten kinetic coefficients were assumed for this digester application. All of the suggested parameter values for the default ADM1 are provided in Appendix B.

The ADM1 also includes dynamic calculation of the inorganic carbon and nitrogen concentrations in the digester. These equations are used in conjunction with acid-base equilibria and a charge balance to calculate the digester pH, and soluble CO_2, HCO_3, and ammonia concentrations. The inorganic carbon (HCO_3 and CO_2) concentrations are determined by a carbon balance and acid-base equilibrium. Soluble inorganic carbon enters the system through hydrolysis of the composite feed, and leaves through advection, volatilization of CO_2, reduction to CH_4, and uptake by biomass. The carbon content (moleC/gCOD) of each component of the digester must be known in order to implement the balance. The total soluble inorganic carbon is calculated using the carbon balance equation, and acid-base speciation equations determine the fractions of inorganic carbon as HCO_3 and CO_2. The inorganic nitrogen is calculated in the same way, but the volatilization of NH_3 is negligible so it is not included in the balance. Algebraic acid-base equilibria equations are used to determine the fraction of acids in ionic form. A charge balance, comprised of the ionized VFAs, NH_4^+, H^+, HCO_3^-, and OH^-, is used to calculate the pH. The inorganic carbon and nitrogen balances, acid-base equilibria, and charge balance equations are critical to the ADM1, as the performance and stability of digesters are greatly affected by pH, alkalinity, and ammonia. These parameters are also frequently measured in digesters, and can be used to compare model predictions to digester performance, or to calibrate the ADM1 to a particular application.

Another critical component of anaerobic digestion included in the ADM1 is liquid-gas transfer. Soluble hydrogen, CO_2, and methane are produced in anaerobic digesters, and exit the digester as dissolved components in the digester liquid and as a flux from the liquid to the gas phase. Therefore, a gas-flux term is included for soluble inorganic carbon, methane, and hydrogen in the model. The ADM1 dynamically calculates specific mass transfer rates for these gasses using their liquid concentration, partial pressure, Henry's constant, and an overall mass transfer coefficient, k_La. The k_La depends on mixing and temperature, and the ADM1 suggests that this parameter can be estimated from comparison to other systems with a known k_La. The ADM1 liquid-gas equations are presented in Appendix C.

The internal recycling of COD through biomass decay is also tracked by the ADM1. Biomass decay is assumed to follow first order kinetics with respect to the biomass concentration and the rate of COD production rate is proportional to the biomass decay rate as the cells release substrates which are then available for anaerobic metabolism. The released COD is treated as an addition to the particulate composite feed material. The composition of the decay products is therefore the same as the composite feed. This presents an issue when applying the ADM1 to other applications, as the feed source composition may be different from that for biomass. However, because of the low biomass yield in anaerobic processes (<5% of the feed COD), the error introduced by assumptions of a similar recycled COD composition is relatively small.

The ADM1 includes inhibition modeling in order to better describe digester response under stressed conditions. There are many forms of inhibition considered by the ADM1. The anaerobic microbial community is sensitive to pH and ammonia and hydrogen concentrations. LCFAs and VFAs can also be inhibitory at elevated concentrations. Nitrogen deficiency in digesters is also considered. The ADM1 incorporates empirical, competitive, and non-competitive forms of inhibition models to account for the effect of these inhibitors. The models decrease the rate of a given anaerobic process by multiplying the rate equation by an inhibition factor, I, where $0 \leq I \leq 1$.

pH inhibition is modeled based on experimental pH boundaries where either 50% inhibition or complete inhibition occur. These boundaries are unique to each group of microbes in the anaerobic community. Two empirical equations are used which determine the inhibition factor for any given pH:

Empirical Upper and Lower Inhibition:

$$I = \frac{1 + 2 \times 10^{0.5(pH_{LL} - pH_{UL})}}{1 + 10^{(pH - pH_{UL})} + 10^{(pH_{LL} - pH)}} \tag{2}$$

where:

I = Inhibition factor ($0 \leq I \leq 1$)

pH = digester pH

pH_{LL} = lower pH limit where the group of organisms is 50% inhibited

pH_{UL} = upper pH limit where the group of organisms is 50% inhibited

Empirical Lower Inhibition Only:

$$I = \begin{cases} e^{\left[-3\left(\frac{pH - pH_{UL}}{pH_{UL} - pH_{LL}}\right)^2\right]} & \text{if } pH \leq pH_{UL} \\ 1 & \text{if } pH > pH_{UL} \end{cases} \qquad (3)$$

where:

pH_{LL} = lower pH limit where the group of organisms is completely inhibited

pH_{UL} = upper pH limit where the group of organisms is not inhibited

The ADM1 provides both types of pH inhibition functions to give flexibility to the user. The upper and lower equation is useful in strongly buffered systems where upper pH inhibition is more likely to occur, and the lower only equation in low pH systems. An example of the selection of the pH_{LL} and pH_{UL} values for each equation is provided for acetate-utilizing methanogens: For upper and lower inhibition, pH_{LL} of 6.5 and pH_{UL} of 7.5 are where 50% inhibition occurs, and no inhibition occurs at the optimal pH of 7. For lower only, the methanogens will be completely inhibited below the pH_{LL} of 6 and not inhibited above the pH_{UL} of 7.

Hydrogen and free ammonia (NH_3) inhibition are both modeled in the ADM1 using a non-competitive inhibition equation that is based only on the inhibitor concentration and an inhibition constant.

$$I = \frac{1}{1 + \frac{S_I}{K_I}} \qquad (4)$$

where:

S_I = inhibitor concentration, gCOD/L

K_I = inhibition constant, gCOD/L

Hydrogen inhibition is included for fatty acid, propionate, and C_4 compound utilization. The suggested inhibition constants, K_I, vary from 4×10^{-6} - 1×10^{-5} gCOD/L depending on the group of syntrophic hydrogen producing or utilizing organisms. The ADM1 notes that other conditions such as pH, weak acids, and acetate concentration can affect the thermodynamic inhibition level.

Weak acids and bases in their non-ionic form can move freely through cell membranes and cause inhibition (Henderso.Pj 1971). The ADM1 chose to include NH_3 inhibition, but exclude other weak acids and bases. NH_3 ($pK_a = 9.25$) is the main free base in anaerobic digesters, and relevant concentrations can be present in strongly buffered systems. Other weak acids such as HAc, HPr, HBu, and HVa have low pK_a values (4.7-4.9), so the free forms of these acids predominate at low pH. NH_3 inhibition is included only for acetate utilizing organisms in the ADM1, and the suggested K_I is 1.8×10^{-3} M.

The final type of inhibition included in the ADM1 is inorganic nitrogen deficiency, which is modeled as a secondary substrate required for all other substrate uptake. The model is designed to inhibit uptake when $S_{IN} \approx 0$, and follows the form of Equation (4).

The ADM1 task group decided to omit some processes that were not encountered frequently enough to include them in a broadly applicable anaerobic digestion model. These processes include glucose alternative products, sulfate reduction and sulfide inhibition, weak acid and base inhibition, LCFA inhibition, homoacetogenesis, and solids precipitation.

CHAPTER II: ADM1 MODIFICATIONS FOR FOOD WASTE DIGESTION

ADM1 was modified for this food waste digestion application with consideration to model calibration needs and lab results, and the need to provide stable model computation under transient load simulations. The modified ADM1 includes different hydrolysis and endogenous decay equations, simplified pH calculations and inhibition equations, and consideration of the food waste protein composition.

Modeling of the initial disintegration and hydrolysis of biodegradable particulate COD (bpCOD) is critical to describing the behavior of anaerobic digesters. Because of the importance of hydrolysis in anaerobic digestion, a literature review was done on hydrolysis models and a wide range of approaches were found. Previous applications and successes of each model were considered as well as their applicability to food waste hydrolysis in order to select a feasible model that could be calibrated to laboratory data on food waste digestion in this study.

While it is understood that hydrolysis is a complex, multi-step process, a simple first-order model is most commonly used to describe solids hydrolysis in anaerobic digestion (Eastman and Ferguson 1981, Pavlostathis and Gossett 1988, Siegrist et al. 2002, Vavilin et al. 1996). The rate of change of the particulate material is directly proportional to the particulate concentration.

$$\frac{dX_c}{dt} = -kX_c \qquad (5)$$

where:

X_c = concentration of particulate feed (mg/L)

k= first order kinetic rate coefficient (day^{-1})

t = time (day)

The surface area of the feed solids has also been identified as the parameter that controls the particulate hydrolysis rate (Hobson 1987, Mshandete et al. 2006). Sanders et al. (2000) and Palmowski and Mueller (2000) used a first order model to describe surface area dependent hydrolysis.

$$\frac{dX}{dt} = -kA \tag{6}$$

where:

X = mass of particulate feed (mg)

A = particle surface area (m^2)

k= surface based hydrolysis constant (mg/m^2-d)

t = time (day)

A complication of applying this model is that the feed solids must be characterized in terms of the available surface area, which typically requires particle size distribution measurements. The more heterogeneous the feed source, the wider the distribution of particle sizes that are likely present. In addition, the particulate mass, surface area, and particle size distribution are all interrelated, making the relationship even more difficult to characterize.

One common variation on the first order hydrolysis models, which is used in ADM1, is fractionation of the feed solids composition to account for its particulate protein, carbohydrate, lipid, and inert components, and to apply a separate first order coefficient to each (Miron et al. 2000).

$$\frac{dX_{ch}}{dt} = -k_{ch}X_{ch} \tag{7}$$

$$\frac{dX_{pr}}{dt} = -k_{pr}X_{pr} \tag{8}$$

$$\frac{dX_{li}}{dt} = -k_{li}X_{li} \tag{9}$$

where:

X_{pr}, X_{ch}, X_{li} = particulate protein, carbohydrate, and lipid COD concentrations that come from the composite feed material, X_c, with known fractions of proteins, carbs, and lipids

k_{pr}, k_{ch}, k_{li} = first order rate coefficient for proteins, carbohydrates and lipids (gCOD/gX-d)

The hydrolysis rate coefficient values summarized in the parameter review appendix in the ADM1 (Batstone et al. 2002) vary widely from 0.04 – 106 day^{-1}, 0.01 – 2.7 day^{-1}, and 0.01 – 0.4 day^{-1} for k_{ch}, k_{pr}, and k_{li} respectively. This suggests that these values need to be calibrated to the specific feed source and operating conditions in order to more accurately model hydrolysis. Calibration requires tracking the particulate degradable protein, carbohydrate, and lipid substrates during testing, which is a difficult analytical task.

Considering the feed as a combination of readily biodegradable, slowly degradable, and non-degradable components allows more flexibility in calibrating hydrolysis when these components appear to exist (Hobson 1983). Using this approach, Straub (2006) implemented a rapidly and slowly biodegradable dual hydrolysis model within the ADM1 and found this model more suitable for simulating lab-scale and pilot-scale data in dynamic batch operation at elevated solids loadings with wastewater treatment plant primary and secondary waste sludge. The dual hydrolysis model assumes the hydrolysis rates for proteins, carbohydrates, and lipids are the same as they are not distinguished as different fractions in the model. The simple first order dual hydrolysis model is shown as follows:

$$\frac{dX_{rh}}{dt} = -k_{rh}X_{rh} \tag{10}$$

$$\frac{dX_{sh}}{dt} = -k_{sh}X_{sh} \tag{11}$$

where:

X_{rh}, X_{sh} = particulate rapidly and slowly hydrolysable COD (gCOD/L), where the feed material, X_c, is composed of some fraction of X_{rh} and X_{sh}.

k_{rh}, k_{sh} = first order rate coefficients for rapidly and slowly degradable particulate components, gCOD/gX-d.

Some models account for the effect of the biomass concentration. A Michaelis-Menten model assumes that in addition to the particulate concentration, the hydrolysis rate is also proportional to the biomass concentration.

$$\frac{dS}{dt} = -kX\left(\frac{S}{K_S + S}\right) \tag{12}$$

where:

K_s= half saturation constant (mg/L)

S= particulate organic concentration (mg/L)

X = biomass concentration (mg/L)
k = maximum specific hydrolysis rate (mgS/mgX-day)

In a modification of the Michaelis-Menten model, a Contois function based model assumes that the particulate organic to biomass ratio as more important than particulate concentration alone in controlling the particulate hydrolysis rate. Noike (1985) expressed cellulose degradation using this model and calculated biomass concentration by subtracting the insoluble saccharides from the volatile suspended solid concentration.

$$\frac{dS}{dt} = -kX\left(\frac{S/X}{K_c + S/X}\right) \qquad (13)$$

where:
K_c= Contois half saturation constant (mg/L)
S= particulate organic concentration (mg/L)
X = biomass concentration (mg/L)
k = maximum specific hydrolysis rate (mgS/mgX-day)

Vavillin et al. (1996) argued that first order models are less effective than the Contois model at low SRTs.. To calibrate biomass dependent models, the active biomass must be obtained through measurement or estimation based on substrate utilization rates. Estimating the fraction of biomass active in particulate hydrolysis can be a difficulty in using the Michaelis-Menten or Contois models.

The dual hydrolysis model was found to be a simple and most practical approach for describing food waste hydrolysis in the modified ADM1. The data collected during hydrolysis degradation tests exhibited similar behavior to that seen in the work done by Straub (2008), with municipal sludge. There were two relatively distinct particulate degradation characteristics; a fast initial first-order degradation followed by a slower apparent first-order degradation, which is characteristic of the dual hydrolysis model (Figure 2).

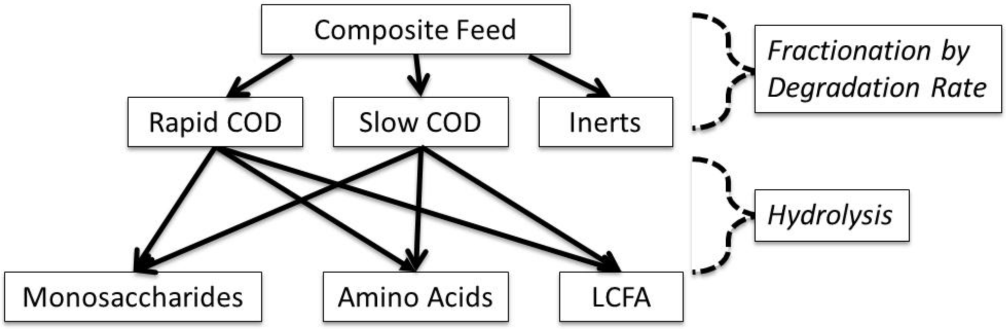


Figure 2. Partitioning and fate of particulate COD in the dual-hydrolysis model in the modified ADM1

For organizational purposes and to maintain the structure of the model, the composite particulate feed variable, X_c, was retained in the dual hydrolysis model. The fractionation or "disintegration" of feed to rapid, slow, and inert components occurs instantly in the model, so that this step has no effect on the hydrolysis rate. X_c can be thought of as a placeholder feed particulate COD input parameter which instantaneously converts to rapid, slow, and inert COD fractions.

The dual hydrolysis model can account for different hydrolysis kinetics for the protein, carbohydrate, and lipid fractions of the feed solids by changing the proportions of these components in the partitioning of the influent COD between the rapid and slowly degraded portions. The overall composition of the composite feed as protein, carbohydrate, and lipid COD cannot be changed, so for a given composite feed composition the following equalities must be maintained:

$$f_{pr,xc} = f_{rh,xc} f_{pr,rh} + f_{sh,xc} f_{pr,sh} \tag{14}$$

$$f_{ch,xc} = f_{rh,xc} f_{ch,rh} + f_{sh,xc} f_{ch,sh} \tag{15}$$

$$f_{li,xc} = f_{rh,xc} f_{li,rh} + f_{sh,xc} f_{li,sh} \tag{16}$$

where:

$f_{pr,xc}$, $f_{ch,xc}$, $f_{li,xc}$ = fraction of protein, carbohydrate, and lipids in the particulate feed COD, X_c

$f_{rh,xc}$, $f_{sh,xc}$ = fraction of rapidly and slowly hydrolysable COD in the particulate feed COD, X_c

$f_{pr,rh}$, $f_{ch,rh}$, $f_{li,rh}$ = fractions of protein, carb, and lipid in rapid hydrolysable COD respectively

$f_{pr,sh}$, $f_{ch,sh}$, $f_{li,sh}$ = fractions of protein, carb, and lipid in slow hydrolysable COD respectively

Because we did not have data that could support changing the relative hydrolysis rates of protein, carbohydrates, and lipids in the food wastes, their composition in the rapidly and slowly hydrolysable feed COD were kept the same. Beyond the hydrolysis step, the remaining biological conversion processes in the model were left unchanged.

Another very significant deviation from the default ADM1 structure was in the determination of the digester H^+ concentration. The default ADM1 combines a charge balance, inorganic carbon balance, and acid-base equilibrium of the carbonate system to calculate $[H^+]$, $[HCO_3^-]$, and $[CO_{2(aq)}]$. A different more straight forward approach was used to determine the digester H^+ concentration and was based on calculating the bicarbonate concentration as a function of the NH_4^+ concentration in the digester. In anaerobic digesters, bicarbonate production is directly proportional to the ammonia production through the deamination of amino acids (Tchobanoglous et al. 2003).

$$NH_3 + H_2O + CO_2 \xrightarrow{\text{yields}} NH_4^+ + HCO_3^- \qquad (17)$$

With a pKa of 9.25, ammonia is almost entirely found as NH_4^+ at relevant digester pH (≈94% as NH_4^+ at pH = 8 and ≈99.4% at pH = 7). The modified ADM1 replaces the inorganic nitrogen term directly with NH_4^+, and solves the bicarbonate concentration by subtracting the molar VFA concentrations from the NH_4^+ concentration. The CO_2 is calculated from the difference of total inorganic carbon and bicarbonate in the system. The acid-base equilibrium between CO_2 and HCO_3^- was then used to determine the pH. The same pH prediction was obtained from simulations using the modified and default ADM1 models. The benefit of this simplification is that it allows the model to converge on solutions under dynamic conditions that caused model failure using the default equations.

Another aspect considered to be very relevant for modeling anaerobic digestion of food waste is the carbon and nitrogen content of the amino acids produced from protein hydrolysis. The nitrogen content of amino acids is critical, as this parameter dictates ammonia production in the ADM1, which in turn controls the bicarbonate concentration and pH in the digester. The carbon content of the amino acids is also important because it affects the inorganic carbon balance, which affects CO_2 content in the biogas. The default ADM1 suggests a value of 0.007 mole N/g COD for N_{aa}, but does not provide the basis for this estimation. The mole N/ g amino acid COD (N_{aa}) and COD is unique for each of the known twenty amino acids. The average nitrogen and carbon contents of the list of amino acids provided in the ADM1 are 0.0094 moles N/g COD and 0.0319 moles C/g COD respectively. In lieu of measurements of the carbon and nitrogen content in food waste fed to anaerobic digestion, the modified ADM1 assumes the average value for nitrogen and carbon contents of the twenty amino acids.

The modified ADM1 for food waste digestion considered how particulate COD released from biomass decay is recycle back to the system. In the default ADM1, particulate cell debris produced from cell decay is treated as an addition to the feed particulate COD with the same protein, carbohydrate, lipid and inert fractions. This approximation may be suitable for digesters fed sludge produced from domestic wastewater treatment, but in the case of food waste the biomass debris composition can be very different from that of the feed material. An additional variable for the products of endogenous decay (X_{ed}) was implemented to act as a separate feed with its separate defined composition description. The X_{ed} production rate is determined in the same way as in the default ADM1, but it is then instantly partitioned based on the composition of the cell to soluble sugars, amino acids, fatty acids, and particulate inerts. This modification does not have a large impact on simulation results, because the biomass yield is <5% of the feed COD, but it more accurately describes the flow of COD in the ADM1 for food waste applications.

The rate of protein, carbohydrate, lipid addition from biomass decay is based on the biomass debris production rate, its relative composition, and conversion factors of cell protein, carbohydrate, and lipids to COD. The majority of the cell is composed of protein on a dry weight basis, but there are some carbohydrates and lipids present, as well as DNA and RNA (

Table 1).

Table 1. Typical cell composition on a dry weight basis (Rittmann and McCarty, 2001)

Component of Cell	% (as dry weight)
Protein	50-60
Carbohydrate	10-15
Lipid	6-8
DNA	3
RNA	15-20

The COD conversion values used for carbohydrates and lipids were determined on glucose and palmitic acid respectively and are 1.07 gCOD/gCarb (Miron et al., 2002) and 2.88 gCOD/gLipid (Eastman and Ferguson 1981). Hattingh et al (1967) noted that the ratio of 6.25 g Pr/g N commonly applied in the literature is not appropriate for anaerobic biomass and instead recommended a ratio of 5.15 g Pr/g N. When this number is combined with the average N_{aa} determined above, a value of 1.47 g COD/ g protein is obtained. Sanders et al (1996) used a similar conversion of 1.5 g COD/ g protein. In order to be consistent with the nitrogen content of amino acids on a COD basis, and because of Hattingh's work specifically addressing the protein content of anaerobic sludge, 1.47 g COD/g protein was used for conversions in the modified ADM1. Assuming an inert fraction of 0.25, the range of dry weight values from

Table 1 and COD conversion values the fractions of protein, carbohydrate, lipid, and inert COD composition of biomass debris from endogenous decay was estimated at 0.55, 0.09, 0.11, and 0.25 respectively.

The modified ADM1 has the ability to quantify the existing digester sludge conditions prior to changing from one feed type to another. The existing sludge will contain unhydrolyzed bpCOD, characterized by preexisting rapidly and slowly degradable COD (X_{rh0} and X_{sh0}), with different characteristics than the new feed. This ability is relevant to the pilot plant digester startup, which involves seeding the digesters with sludge from the USAFA digester fed municipal waste sludge.

The modified ADM1 also includes the ability to account for the digester being fed more than one feed source with different composition and hydrolysis characteristics. Codigestion applications could involve municipal sludge digestion plus food waste or other sources. The model can easily be expanded to include as many feed sources as needed. This study did not use any secondary feed sources, so it was not utilized for our simulations.

The default ADM1 includes various inhibition functions to describe the effect on process rates in the model depending on digester conditions. The modified ADM1 has identified pH inhibition of acetoclastic methanogens to be the most critical of these inhibition functions. Inhibitory effects for these organisms are typically seen when the pH drops below 7. Other organisms do not experience inhibition until lower pH values are seen. The methanogenic populations also play a role in controlling VFA and hydrogen concentrations, making them critical to other metabolic processes and the stability of anaerobic digesters (Eldem et al. 2004).

The default ADM1 handles pH inhibition using a piecewise function which cannot be dynamically solved. The modified ADM1 replaces the piecewise function with a continuous “S-curve” function.

$$I = A + \frac{C}{\left(1 + Te^{-B(pH - M)}\right)^{1/T}} \quad (18)$$

where:

I= inhibition factor ($0 \le I \le 1$)

A = lower asymptote

C = upper asymptote

M = variable controlling the pH corresponding to the upper maximum

B = variable controlling the steepness of the curve

T = variable controlling where maximum inhibition occurs - nearer the lower or upper asymptote.

Optimizing these values to fit the piecewise empirical pH inhibition function at pH below 7.0 for acetoclastic methanogens from the default ADM1 provided a continuous inhibition function with an excellent fit of $R^2 = 0.9996$ (Table 2). The curve in Figure 3 describes the inhibition function that was included in the modified ADM1 as a dynamic variable, which is multiplied by the acetate uptake rate function to determine the effective rate of acetate utilization.

Table 2. S-curve parameters for approximating the ADM1 piecewise low pH inhibition function for acetoclastic methanogens

Variable	Fitted Value
A	0
C	1
T	2.01
B	8.67
M	6.57

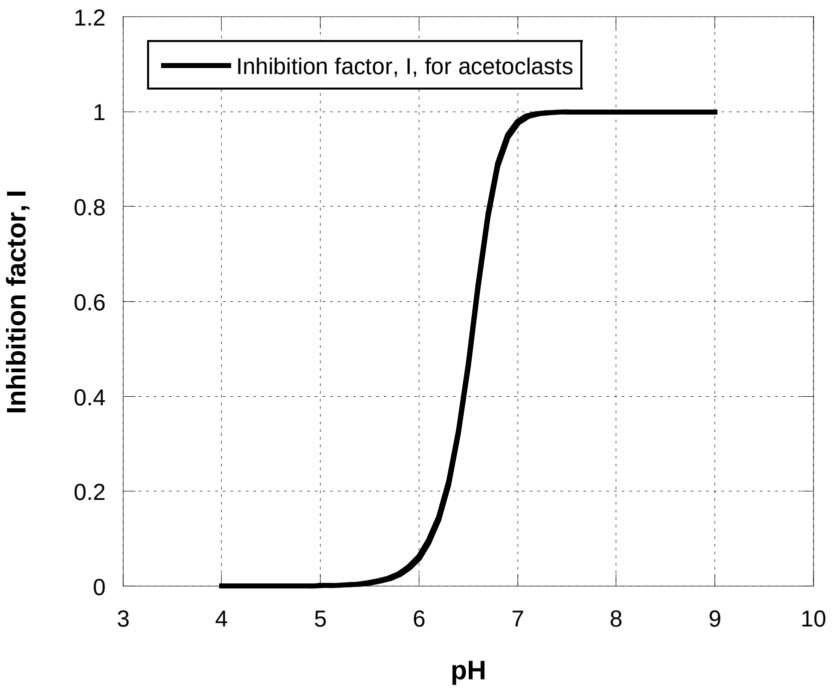


Figure 3. Inhibition factor, I, vs. pH for inhibition of acetoclastic methanogens used in the modified ADM1

The modifications to the default ADM1 were initially made to tailor the model to better describe important food waste characteristics for anaerobic digestion. These were replacing the disintegration/hydrolysis model with a dual hydrolysis model and more careful consideration of the carbon and nitrogen contents of amino acids in food waste. Other changes involving the feed composition include routing the products of endogenous decay through a new variable, X_{ed}, and the addition of preexisting digester bpCOD variables X_{rh0} and X_{sh0}. Changing the mechanism for calculating the [H^+] concentration and making the pH inhibition function continuous were less about addressing food waste digestion, and more about ensuring model stability for transient loading simulations. Petersen matrices including the dual hydrolysis model, preexisting bpCOD variables, and modified endogenous decay model are in Appendix D.

CHAPTER III: MODEL IMPLEMENTATION

This section describes how the modified ADM1 in Mathcad is applied for a single stage continuously stirred tank reactor (CSTR). The same approach will also describe both batch and semi-batch mixed reactors. The general mathematical approach is provided first, followed by an implementation example for a batch reactor.

Mathcad combines equations, text, and graphics in a user friendly interface which can solve complex systems of differential equations. The anaerobic digester liquid phase, gas phase, and acid-base equilibrium equations are implemented as a differential and algebraic equation (DAE) system within Mathcad. Mathcad solves the DAE using an ordinary differential equation (ODE) solver. This solver dynamically detects the most appropriate solving method to be used for the system. The methods that can be applied using the ODE solver are Adams-Bashforth, fixed-step Runge-Kutta, adaptive-step Runge-Kutta, and Radau algorithm.

The mass balance equations for each component of the ADM1 are written as a combination of the advection terms for a CSTR and the sum of the specific kinetic rates for each process that affects said component. The following equation shows the general mass balance for a soluble component but the same equations can be applied to the particulate components in the liquid phase, $X_{liq,i}$.

$$\frac{dS_{liq,i}}{dt} = \frac{qS_{in,i}}{V_{liq}} - \frac{qS_{liq,i}}{V_{liq}} + \sum_{j=1-21} \rho_j \nu_{i,j} \qquad (19)$$

where:

$S_{liq,i}$ = soluble component of i in the liquid phase, gCOD/L or mol/L

q = flow rate (assuming $q_{in} = q_{out}$)

$\sum_{j=1-21} \rho_j \nu_{i,j}$ = sum of the specific kinetic rates for process j multiplied by $v_{i,j}$ as defined in Appendix D.

The differential equation for Sva is provided here as an example and can be compared with the Petersen matrices in Appendix D as a guide for writing the remaining differential equations:

$$\frac{dS_{va}}{dt}=\frac{q(t)S_{in,va}}{V_{liq}}-\frac{q(t)S_{va}}{V_{liq}}+\left(1-Y_{aa}\right)f_{va,aa}k_{m,aa}\frac{S_{aa}}{K_{S,aa}+S_{aa}}X_{aa}-k_{m,c4}\frac{S_{va}}{K_{S,c4}+S_{va}}X_{c4}\frac{1}{1+S_{bu}/S_{va}} \quad (20)$$

where:

$S_{va,(aa,bu)}$ = concentration of total soluble valerate, amino acids, and butyrate respectively in the digester, gCOD/L.

Y_{aa} = yield of biomass on amino acids, $gCOD_X/gCOD_S$

$f_{va,aa}$ = fractional yield of valerate by catabolism of amino acids

$k_{m,aa,(c4)}$ = Monod maximum specific uptake rate for amino acids and C_4 compounds respectively, $gCOD_S/gCOD_X$-d

$K_{S,aa,(c4)}$ = half saturation values for amino acids and C4 compounds respectively, $gCOD_S/L$

The only exception for writing the soluble differential equations is for the soluble components that also exit the reactor in the gas phase as well as in the liquid flow. Liquid/gas transfer rates, $\rho_{T,i}$, must be subtracted from the differential equations for soluble H_2, CH_4, and CO_2 to account for transfer to the gas phase.

The gas phase mass balance equations are similar to the liquid phase equations, but there are no advective inflow terms and the gas transfer rate must be included for each gas.

$$\frac{dS_{gas,i}}{dt}=-\frac{q_{gas}S_{gas,i}}{V_{gas}}+\rho_{T,i}\frac{V_{liq}}{V_{gas}} \quad (21)$$

where

q_{gas} = gas flow rate, L_{gas}/d, more details in Appendix C

$\rho_{T,i}$ = specific gas transfer rate, mol gas/ L-day, more details in Appendix C

The V_{liq}/V_{gas} term is needed because the gas transfer rate is dependent on the liquid volume.

To determine the inorganic carbon states in the ADM1, the following acid-base equilibria equations are included as algebraic constraints in the DAE system:

$$S_{IC}-S_{CO_2}-S_{HCO_3^-}=0 \quad (22)$$

$$S_{HCO_3^-} - \frac{K_{a,CO_2} S_{IC}}{K_{a,CO_2} + S_{H^+}} = 0 \qquad (23)$$

where:

S_{IC} = total soluble inorganic carbon concentration (mol/L)

$K_{a,CO2}$ = acid-base equilibrium coefficient for CO_2/HCO_3^-

S_{H+} = H^+ concentration (mol/L)

All of the liquid phase, gas phase, and acid-base equilibria equations are written in a solve block in Mathcad. A solve block is a defined region of space within Mathcad that lets the ODE solver know which variables it is solving and how they are related to one another. The other key component of a Mathcad solve block is some form of boundary conditions. The boundary conditions used for the implementation of ADM1 are the values when time = 0 (initial conditions). These values (gCOD/L or mol/L) have a very significant impact on the model results, particularly over small time intervals, making their determination critical for accurate simulations. For instance, the initial reactor biomass concentrations are necessary to determine if substrates will increase with time in the digester following feeding. Because ADM1 uses Michaelis-Menten kinetics, the initial conditions for the soluble components are also important in determining the initial substrate uptake rates. As was the case for the lab scale digesters used in this study, food waste digesters or codigesters are often seeded with sludge from a preexisting anaerobic digester. Ideally, if sufficient operating and performance data is available for the seed digester, it can be modeled with ADM1 to provide a best estimate of the initial conditions to use in the solve block. The initial conditions of the seed digester may be largely unknown in some cases. When this is the case, estimates can be made by using conditions from known digesters with similar characteristics.

Once the solve block is setup, the ODE solver, Odesolve, is called for some user defined time interval and number of steps, where the step size is equal to the time interval divided by the number of steps. Mathcad then solves each dynamic variable in the DAE system, and uses a spline function to interpolate between each point to achieve a continuous result over the time interval. The step size therefore needs to be sufficiently small to capture variation over short time periods. After solving the DAE system, the user can make any desired calculations using the results. The calculations can be setup in advance, referencing the solver solutions as newly defined variables, or be made as needed after the solver has been run.

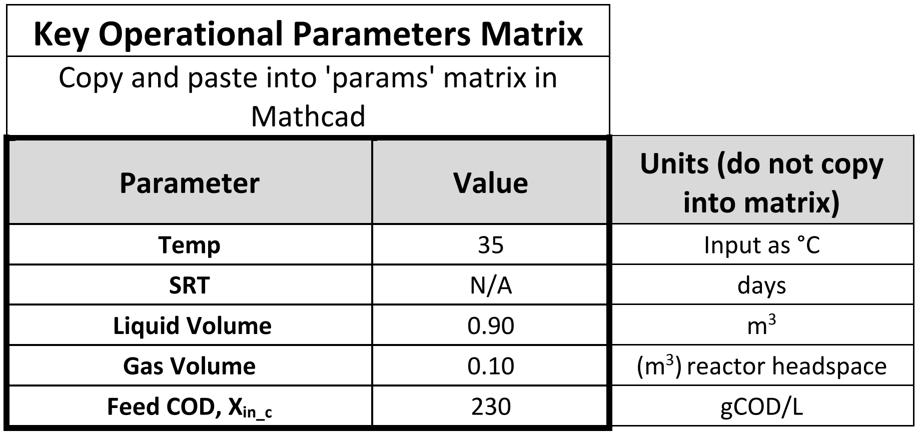
The ADM1 solution is dependent on the inputs provided by the user. Some of these inputs include kinetic rate coefficients, flowrate, COD concentration, feed composition, inhibition constants, temperature, reactor initial conditions, and reactor volume. The more accurately the user defines the system with these inputs, the more useful the model outputs will be. Because of the vast number of inputs required by ADM1, organization and ease of modification are both important for modeling under various operating conditions.

In order to make the ADM1 as user friendly as possible within Mathcad, the input values for every aspect of the model are defined in Microsoft Excel tables (Table 3 - Table 10). Mathcad is compatible with Excel, in that the user may copy Excel tables into Mathcad sheets, and vice versa. In the Mathcad ADM1 file, all of the input variables are defined by referencing Excel compatible tables. When the user wants to make changes to any inputs, they only need to make the changes to the values in Excel, and copy the corresponding tables to the inputs section of the Mathcad file. By saving the Excel inputs file for any defined input conditions, the user can easily recreate those conditions in Mathcad simply by copying the tables back into their model file. This compatibility is very useful because anyone with access to the Excel inputs file template can define a set of conditions to be modeled. Example input tables are provided in conjunction with a simulation example of a single batch feeding to a laboratory scale anaerobic reactor. The reactor is fed food waste with a known composition and COD concentration. The reactor is batch fed over a one hour period with an amount that corresponds to an average daily loading rate of 12gCOD/L-d for the week. The user is interested in the response of the reactor for the first 24 hours following the feeding.

Each of the following input tables are copied into Mathcad from their corresponding Excel table:

The Key Operational Parameters Table defines the temperature, SRT, working and gas volumes, and feed COD concentration (Table 3). The only operational parameter not included in this table is the flow rate, q, because it must be uniquely defined for the given feeding strategy of the simulation.

Table 3. Key Operational Parameters Table as defined in Excel for the batch feed example



Key Operational Parameters Matrix

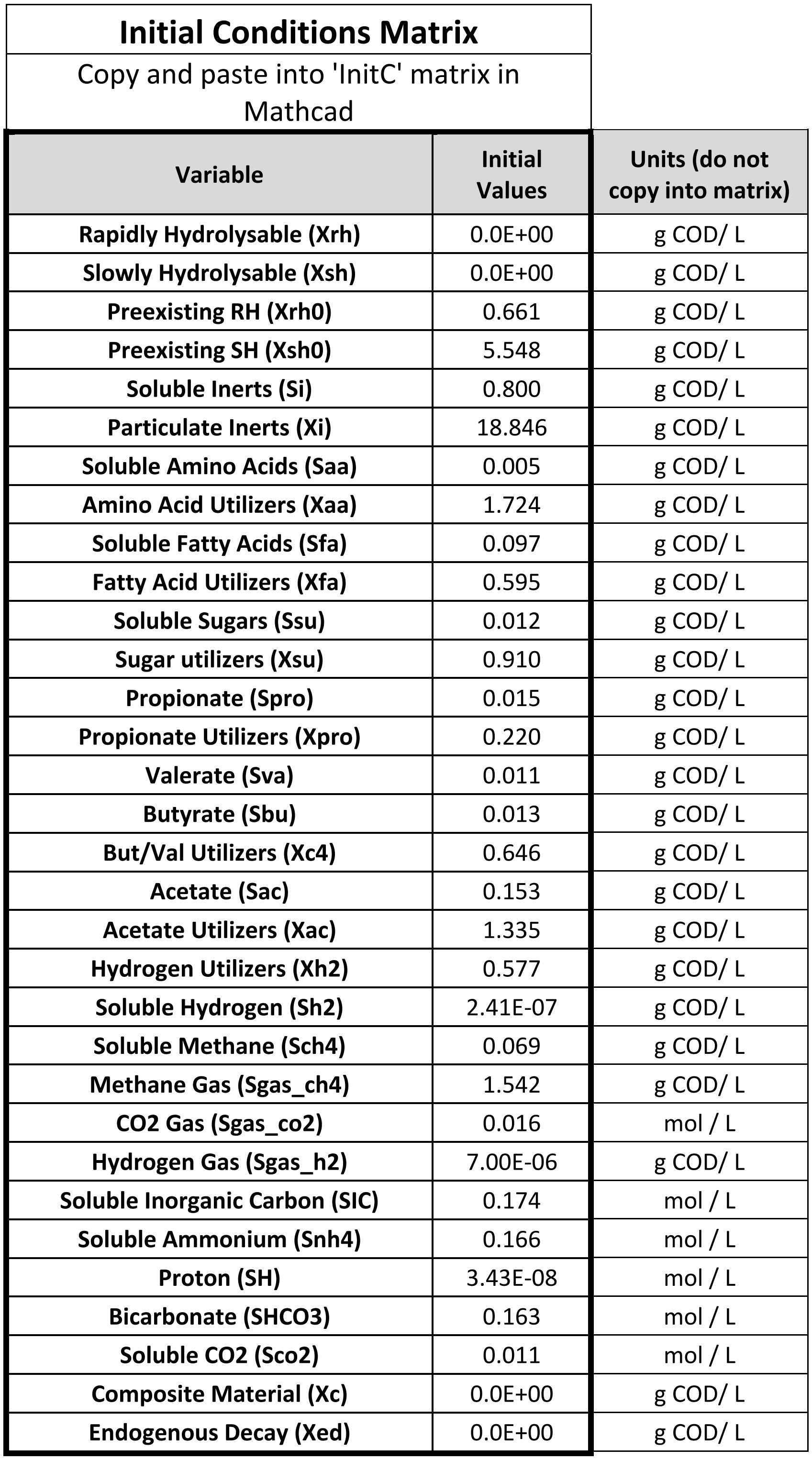
Copy and paste into 'params' matrix in Mathcad

Parameter	**Value**	**Units (do not copy into matrix)**
Temp	35	Input as °C
SRT	N/A	days
Liquid Volume	0.90	m^3
Gas Volume	0.10	(m^3) reactor headspace
Feed COD, X_{in_c}	230	gCOD/L

Mesophilic conditions at 35^{0}C are assumed for this example. The SRT is not relevant for this 24 hour batch test, so it will not be used in the determination of the feed volume. The reactor volume is 1 m^3 (0.9 m^3 liquid working volume, and 0.1 m^3 of gas volume). The feed concentration was determined in preliminary lab tests for the food waste to be 230 g COD/L. The bold outlined section of Table 3, and the remaining input tables denotes what is to be copied into Mathcad. The ADM1 Mathcad file has variable definitions already written that reference these tables. Once the tables have all been copied into the program the variables will all be defined within Mathcad.

The Initial Conditions Table defines the boundary conditions at time = 0 to be used in the ODE solve block (Table 4).

Table 4. Initial Conditions Table as defined in Excel for the batch feed example



Initial Conditions Matrix

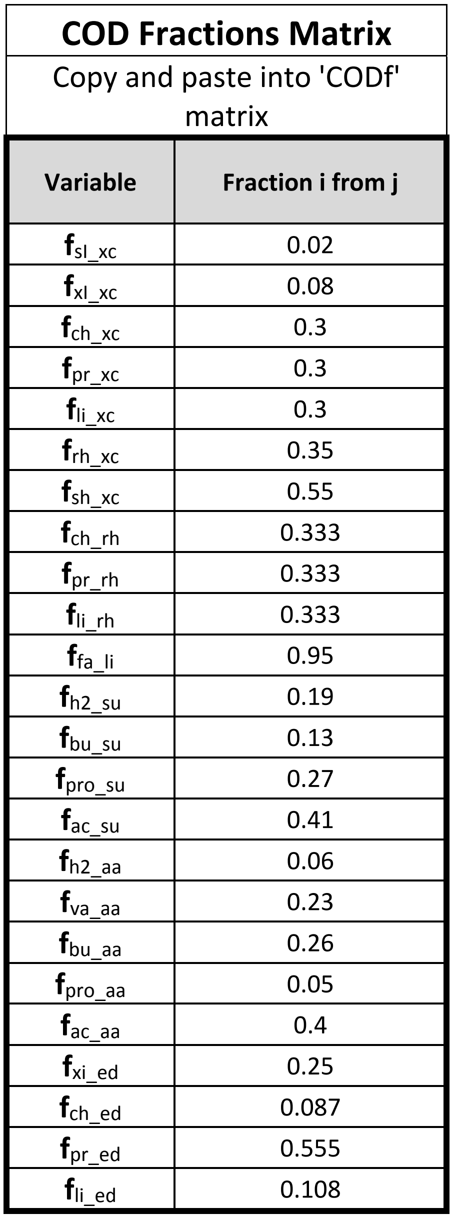
Copy and paste into 'InitC' matrix in Mathcad

Variable	Initial Values	Units (do not copy into matrix)
Rapidly Hydrolysable (Xrh)	0.0E+00	g COD/ L
Slowly Hydrolysable (Xsh)	0.0E+00	g COD/ L
Preexisting RH (Xrh0)	0.661	g COD/ L
Preexisting SH (Xsh0)	5.548	g COD/ L
Soluble Inerts (Si)	0.800	g COD/ L
Particulate Inerts (Xi)	18.846	g COD/ L
Soluble Amino Acids (Saa)	0.005	g COD/ L
Amino Acid Utilizers (Xaa)	1.724	g COD/ L
Soluble Fatty Acids (Sfa)	0.097	g COD/ L
Fatty Acid Utilizers (Xfa)	0.595	g COD/ L
Soluble Sugars (Ssu)	0.012	g COD/ L
Sugar utilizers (Xsu)	0.910	g COD/ L
Propionate (Spro)	0.015	g COD/ L
Propionate Utilizers (Xpro)	0.220	g COD/ L
Valerate (Sva)	0.011	g COD/ L
Butyrate (Sbu)	0.013	g COD/ L
But/Val Utilizers (Xc4)	0.646	g COD/ L
Acetate (Sac)	0.153	g COD/ L
Acetate Utilizers (Xac)	1.335	g COD/ L
Hydrogen Utilizers (Xh2)	0.577	g COD/ L
Soluble Hydrogen (Sh2)	2.41E-07	g COD/ L
Soluble Methane (Sch4)	0.069	g COD/ L
Methane Gas (Sgas_ch4)	1.542	g COD/ L
CO2 Gas (Sgas_co2)	0.016	mol / L
Hydrogen Gas (Sgas_h2)	7.00E-06	g COD/ L
Soluble Inorganic Carbon (SIC)	0.174	mol / L
Soluble Ammonium (Snh4)	0.166	mol / L
Proton (SH)	3.43E-08	mol / L
Bicarbonate (SHCO3)	0.163	mol / L
Soluble CO2 (Sco2)	0.011	mol / L
Composite Material (Xc)	0.0E+00	g COD/ L
Endogenous Decay (Xed)	0.0E+00	g COD/ L

The initial conditions were determined by running a simulation of the seed anaerobic digester until steady state was achieved. These values are read into the solve block to act as the boundary conditions needed for the ODE solver.

The COD Fractions Table defines the fraction of COD that is produced from a given substrate, $f_{product,substrate}$ (Table 5). This table also defines the composition of the feed material (the fraction of COD as rapidly hydrolysable, slowly hydrolysable, and inert from the composite feed material).

Table 5. COD Fractions Table as defined in Excel for the batch feed example



COD Fractions Matrix

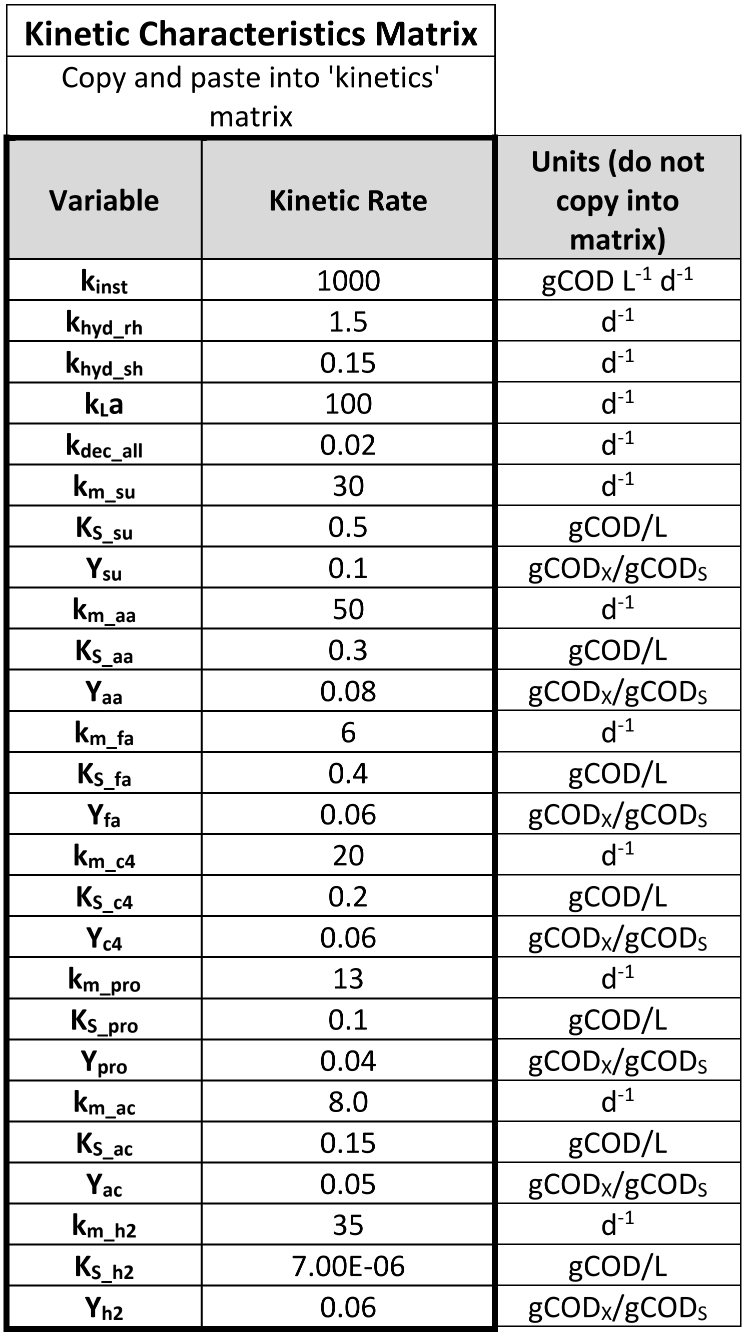
Copy and paste into 'CODf' matrix

Variable	Fraction i from j
f_{sI_xc}	0.02
f_{xI_xc}	0.08
f_{ch_xc}	0.3
f_{pr_xc}	0.3
f_{li_xc}	0.3
f_{rh_xc}	0.35
f_{sh_xc}	0.55
f_{ch_rh}	0.333
f_{pr_rh}	0.333
f_{li_rh}	0.333
f_{fa_li}	0.95
f_{h2_su}	0.19
f_{bu_su}	0.13
f_{pro_su}	0.27
f_{ac_su}	0.41
f_{h2_aa}	0.06
f_{va_aa}	0.23
f_{bu_aa}	0.26
f_{pro_aa}	0.05
f_{ac_aa}	0.4
f_{xi_ed}	0.25
f_{ch_ed}	0.087
f_{pr_ed}	0.555
f_{li_ed}	0.108

The first ten rows of the COD fractions table need to be defined by the user to best represent the digester feed COD. For this example, the composite material is composed of 10% inerts (2% soluble and 8% particulate) and 30% each carbohydrates, proteins, and lipids as COD. Batch hydrolysis experiments were performed to determine that this particular feed can be considered 35% rapidly hydrolysable, 55% slowly hydrolysable and 10% inert. The fraction of carbohydrates, lipids, and proteins in the slowly hydrolysable COD are calculated from the overall fractions in the composite feed, X_c, and the fractions in the rapid COD using equations 14, 15, and 16. These balances ensures that the overall amount of carbohydrate, lipid, and protein COD fed to the digester is conserved. In this example, as well as other model simulations, the fractions of carbohydrates, lipids, and proteins in the rapidly hydrolysable portion of the feed are the same as in the composite feed excluding the inert fraction. The calculations for the corresponding fractions in the slow COD will therefore be equal to the rapid fractions.

The Kinetic Characteristics Table defines the various first order kinetic rates such as the rapid hydrolysis rate and Monod maximum specific uptake rates, as well as the half saturation values and yields needed to determine the overall kinetic rate equations for substrate uptake (Table 6).

Table 6. Kinetic Characteristics Table as defined in Excel for the batch feed example



Kinetic Characteristics Matrix

Copy and paste into 'kinetics' matrix

Variable	Kinetic Rate	Units (do not copy into matrix)
k_{inst}	1000	gCOD L^{-1} d^{-1}
k_{hyd_rh}	1.5	d^{-1}
k_{hyd_sh}	0.15	d^{-1}
k_La	100	d^{-1}
k_{dec_all}	0.02	d^{-1}
k_{m_su}	30	d^{-1}
K_{S_su}	0.5	gCOD/L
Y_{su}	0.1	$gCOD_X/gCOD_S$
k_{m_aa}	50	d^{-1}
K_{S_aa}	0.3	gCOD/L
Y_{aa}	0.08	$gCOD_X/gCOD_S$
k_{m_fa}	6	d^{-1}
K_{S_fa}	0.4	gCOD/L
Y_{fa}	0.06	$gCOD_X/gCOD_S$
k_{m_c4}	20	d^{-1}
K_{S_c4}	0.2	gCOD/L
Y_{c4}	0.06	$gCOD_X/gCOD_S$
k_{m_pro}	13	d^{-1}
K_{S_pro}	0.1	gCOD/L
Y_{pro}	0.04	$gCOD_X/gCOD_S$
k_{m_ac}	8.0	d^{-1}
K_{S_ac}	0.15	gCOD/L
Y_{ac}	0.05	$gCOD_X/gCOD_S$
k_{m_h2}	35	d^{-1}
K_{S_h2}	7.00E-06	gCOD/L
Y_{h2}	0.06	$gCOD_X/gCOD_S$

Like the COD fractions matrix, the kinetic rates matrix is also a combination of user defined and ADM1 default values. k_{inst} operationally transfers the influent composite feed material into rapid, slow, and inert fractions as well as the products of endogenous decay into soluble sugars, amino acids, and fatty acids. As long as this rate is set to a value much higher that all of the other kinetic rates, it can be assumed the transfer occurs instantly in the model. The values of X_c and X_{ed} are therefore always zero in the model. The k_{hyd_rh} and k_{hyd_sh} values are determined experimentally from the same tests used to determine the fractions of rapid and slowly hydrolysable COD in the composite material. The k_La, in this example, assumed to be 100 d^{-1}, also has to be estimated by the user.

The Carbon and Nitrogen Contents Table defines the carbon and nitrogen contents as moleC/gCOD or moleN/gCOD of each component in the model (Table 7).

Table 7. Carbon and Nitrogen Contents Table as defined in Excel for the batch feed example

C+N Contents Matrix

Copy and paste into 'C_N' matrix

Variable	**C or N Content**	**Units (do not copy into matrix)**
$\mathbf{C}_{\mathrm{ch}}$	0.0313	moleC gCOD^{-1}
$\mathbf{C}_{\mathrm{li}}$	0.022	moleC gCOD^{-1}
$\mathbf{C}_{\mathrm{su}}$	0.0313	moleC gCOD^{-1}
$\mathbf{C}_{\mathrm{fa}}$	0.0217	moleC gCOD^{-1}
$\mathbf{C}_{\mathrm{va}}$	0.024	moleC gCOD^{-1}
$\mathbf{C}_{\mathrm{bu}}$	0.025	moleC gCOD^{-1}
$\mathbf{C}_{\mathrm{pro}}$	0.0268	moleC gCOD^{-1}
$\mathbf{C}_{\mathrm{ac}}$	0.0313	moleC gCOD^{-1}
$\mathbf{C}_{\mathrm{h2}}$	0	moleC gCOD^{-1}
$\mathbf{C}_{\mathrm{ch4}}$	0.0156	moleC gCOD^{-1}
$\mathbf{C}_{\mathrm{IC}}$	1	moleC gCOD^{-1}
$\mathbf{C}_{\mathrm{IN}}$	0	moleC gCOD^{-1}
$\mathbf{C}_{\mathrm{biom}}$	0.0313	moleC gCOD^{-1}
$\mathbf{C}_{\mathrm{aa}}$	0.03194	moleC gCOD^{-1}
$\mathbf{N}_{\mathrm{bac}}$	0.00625	moleN gCOD^{-1}
$\mathbf{N}_{\mathrm{aa}}$	0.009414	moleN gCOD^{-1}

The carbon and nitrogen contents of most components are straightforward, and taken as default values provided by the ADM1. The values for amino acids are more difficult to determine, as discussed in the modified ADM1 description. For this example, the average carbon and nitrogen content for amino acids as mole/gCOD were used.

The Acid Base Equilibria Table defines the pK and temperature adjustment θ values for relevant acid-base pairs found in digesters (Table 8). The following temperature adjustment equation is used for equilibrium and Henrys constants:

$$K_2 = K_1 e^{\theta(T_2 - T_1)} \qquad (24)$$

where:

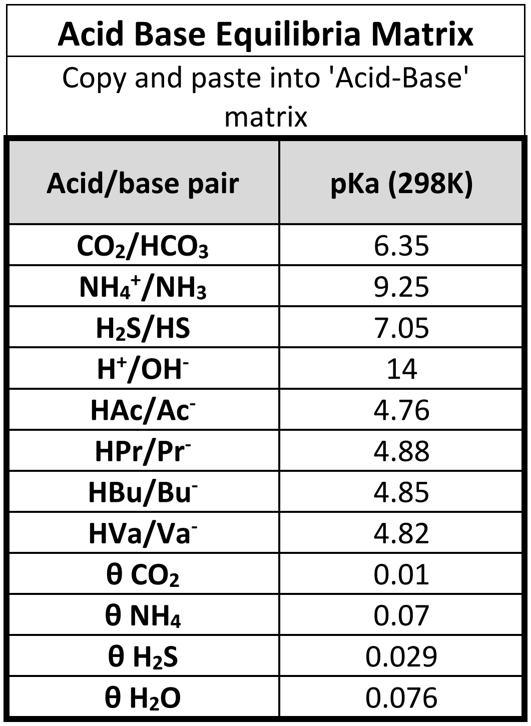
K_1 = equilibrium or Henrys constant at T_1

K_2 = equilibrium or Henrys constant at T_2

T_1 = temperature at which K_1 is defined, Kelvin

T_2 = temperature at which K_2 is to be defined, Kelvin

Table 8. Acid Base Equilibria Table as defined in Excel for the batch feed example



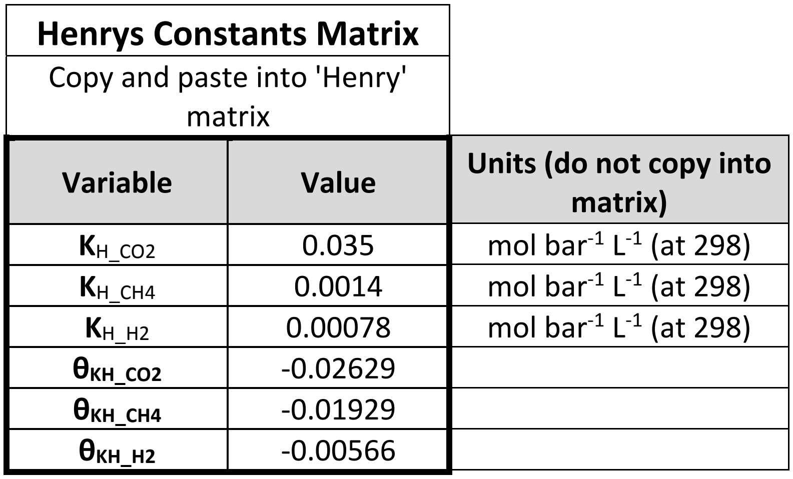
Acid Base Equilibria Matrix

Copy and paste into 'Acid-Base' matrix

Acid/base pair	pKa (298K)
CO_2/HCO_3	6.35
NH_4^+/NH_3	9.25
H_2S/HS	7.05
H^+/OH^-	14
HAc/Ac^-	4.76
HPr/Pr^-	4.88
HBu/Bu^-	4.85
HVa/Va^-	4.82
θ CO_2	0.01
θ NH_4	0.07
θ H_2S	0.029
θ H_2O	0.076

The Henry's Constants Table defines the Henry's gas constants (bar M^{-1}) and θ values for CO_2, CH_4, and H_2 gases (Table 9).

Table 9. Henrys Constants Table as defined in Excel for the batch feed example



Henrys Constants Matrix

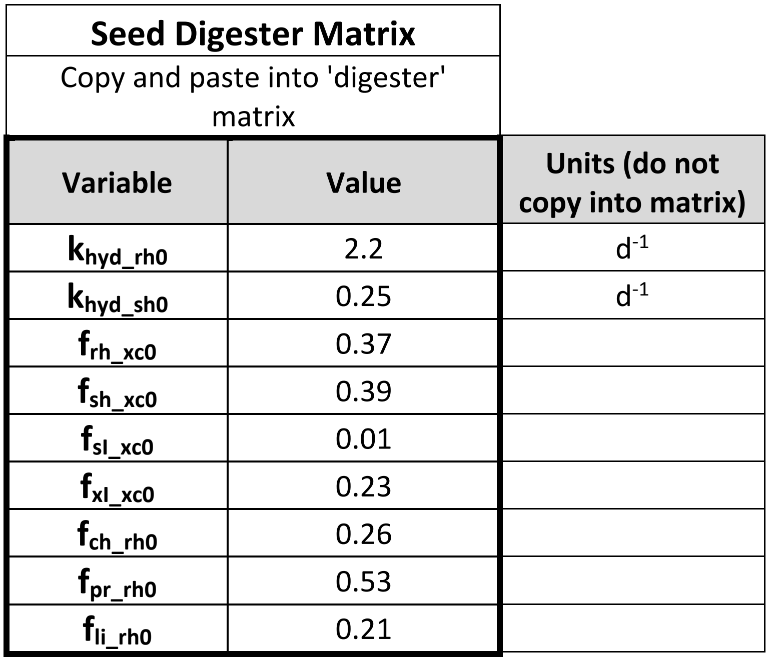
Copy and paste into 'Henry' matrix

Variable	Value	Units (do not copy into matrix)
K_{H_CO2}	0.035	mol bar^{-1} L^{-1} (at 298)
K_{H_CH4}	0.0014	mol bar^{-1} L^{-1} (at 298)
K_{H_H2}	0.00078	mol bar^{-1} L^{-1} (at 298)
θ_{KH_CO2}	-0.02629	
θ_{KH_CH4}	-0.01929	
θ_{KH_H2}	-0.00566	

The Henrys constants and acid-base equilibria information is unlikely to be changed from the default values. The main reason they have been included instead of just defining them directly within Mathcad is for consistency.

The Seed Digester Table defines the composition and kinetic characteristics of the preexisting bpCOD in the digester prior to a change in feed type (Table 10).

Table 10. Seed Digester Table as defined in Excel for the batch feed example



Seed Digester Matrix

Copy and paste into 'digester' matrix

Variable	Value	Units (do not copy into matrix)
k_{hyd_rh0}	2.2	d^{-1}
k_{hyd_sh0}	0.25	d^{-1}
f_{rh_xc0}	0.37	
f_{sh_xc0}	0.39	
f_{sI_xc0}	0.01	
f_{xI_xc0}	0.23	
f_{ch_rh0}	0.26	
f_{pr_rh0}	0.53	
f_{li_rh0}	0.21	

The seed digester information is necessary to differentiate the composition of what is in the digester initially, before a feed with some other composition is introduced. The variables all have the same names as those in the other tables, but are denoted with a ‘naught’ subscript, 0. The seed digester information should always be the same as the values used to simulate the initial conditions of the current simulation. In this case, these values would be plugged into the kinetic rate and COD fraction tables during the preceding steady state simulation. When the new simulation is run, the hydrolysis of X_{rh0} and X_{sh0} will proceed based on the kinetics and composition in the seed digester matrix, instead of using the kinetics and composition of the new feed material.

Defining Operational Characteristics

After the model inputs are provided the final consideration for running the model is to define the feeding strategy of the digester. The flow rate, q, must be defined in the model to correspond to the feeding strategy of the digester. For a continuously fed digester, q can be defined as V_{liq}/SRT. If the digester is batch fed, like our implementation example, then q is equal to the volume of feed COD that must be given to the digester to achieve some desired nominal loading rate (gCOD/L-d). In this example the feed concentration is 230 gCOD/L, and we want to achieve a 12 gCOD/L/day loading rate for our 0.9 m^3 working volume. This means 47 L of food waste will be fed to achieve the equivalent loading rate. As stated in the simulation description, our interval of interest is 1 day. This means q must be defined as function of time over a 1 day period. If the batch feeding were to take place over 1 hour, we can say that q(t) = 0.047 m^3/hr for the first hour, and 0 L/hr for the next 23 hours. Therefore, a composite function for q(t) is written in Mathcad to simulate the batch feeding.

$$q(t) = \begin{cases} 0.047, & 0 \leq t < 1 \\ 0, & \text{Otherwise} \end{cases} \tag{25}$$

Once q is defined, the Mathcad function Odesolve can be called to solve the system:

$$[\text{solutions}] = \text{Odesolve}([\text{vector}], x, b, [\text{intvls}]) \tag{26}$$

where:

[solutions] = vector of solutions for all the function names in [vector]

[vector] = vector of function names for the system of differential equations
x = name of the variable of integration. In the ADM1 this is time, t
b = terminal point of the integration interval
[intvls] (Optional) = integer number of discretization intervals used to interpolate the solution function. The number of solution points is the number of intvls + 1. The default value of intvls is 1000.

The terminal point of the integration interval in this example is 24 hours. The default value of 1000 was used for [intvls]. If the user is interested in a series of batch feeds, the values at the end of the integration interval for the first batch feed simulation are input as the initial conditions of a new simulation for the second feeding. The second simulation can redefine q(t) and the terminal point of the integration interval to describe the new batch feed, and this process can be repeated for any number of feeds.

Outputs

The results from a single simulation using the ADM1 are vast, so the user must decide what information they are trying to get, and how best to organize and utilize this information. By default, running the Odesolve function in Mathcad will not output any information to the user. It is up to the user to query Mathcad for the desired information.

One can divide the outputs from a simulation into two types of results: primary and secondary. The primary results are the values for every dynamic variable contained in the solve block at every instant in the chosen time interval. Secondary information is anything calculated from the primary data, and often times are the most useful simulation outputs. If the user is interested in the total VFA concentration in mg/L, it is more beneficial to predefine a variable for total VFA concentration that is calculated from the primary data (S_{ac}, S_{pro}, S_{bu}, and S_{va}), than to calculate it separately after each simulation.

After the DAE has been solved, Mathcad can be queried for the value of any variable (primary or secondary) at some specific time of interest, or as a table containing many points in time. The user can define output tables containing the information they deem valuable to a simulation. In Mathcad, equations defining secondary variables in terms of the solve block (primary) variables can be written into the file before the simulation has been run. These secondary variables can be presented as graphs or tables, just as the primary results.

Once the user knows what kind of information they want as outputs, they have to format how the information will be displayed by Mathcad. The compatibility between Mathcad and Excel is useful for organizing the results from simulations. For this example, we will assume the user is interested in how the acetate concentration changes in the digester over the one day interval. The user can define a variable for acetate concentration in mg/L, (Ac_{mg_L}), which can be calculated from the primary acetate concentration as gCOD/L. A matrix can then be defined that gives the acetate concentration every fifteen minutes for the 24 hour interval. The first column is the time in hours and the second column is the acetate concentration in mg/L. The following equations in Mathcad will create the table of acetate concentrations.

$$i := 0..24 \times 4 \tag{27}$$

$$Acetate\_Table_{i,1} := \frac{i}{4} \tag{28}$$

$$Acetate\_Table_{i,2} := Ac_{mg\_L}\left(\frac{i}{4}\right) \tag{29}$$

where:

i = range variable of integers from 0 to 24×4, where 24 is the number of hours and 4 is the number of intervals per hour that will be defined in the table (every 15 minutes).

$Acetate\_Table_{i,1}$ = the time value at each interval (i/4) assigned to the ith row of the 1st column. This is simply a vector from 0 to 24 by intervals of 0.25 in the first column of Acetate_Table.

$Acetate\_Table_{i,2}$ = the acetate concentration in mg/L at each interval (i/4) assigned to the ith row of the 2nd column.

This matrix, and any defined in this fashion can be copied directly out of Mathcad and into Excel. The outputs from an ADM1 Mathcad simulation are completely customizable and up to the user. Predesigning output tables for Excel can maximize the value of model simulations by getting the exact information the user needs as quickly and efficiently as possible.

CHAPTER IV: MODEL CALIBRATION

Hydrolysis is the rate limiting step in the conversion of particulate material to methane in anaerobic digestion (Eastman and Ferguson 1981, Pavlostathis and Gossett 1988, Vavilin et al. 1996),in that it initiates the conversion of COD to methane, and under stable digester operating conditions the concentration of degradable particulate COD is higher than the soluble degradable COD and VFA COD. It is therefore a critical step in the prediction of solids destruction and methane production by anaerobic digestion simulation models. Laboratory tests were carried out to provide kinetic information of food wastes hydrolysis for the ADM1 application to food waste digestion.

Five laboratory scale anaerobic digesters maintained in the CDM laboratory and four batch bottle tests were used to estimate the hydrolysis kinetics of selected food waste samples from the USAFA. A number of food waste samples from the USAFA were collected and characterized in terms of Volatile Solids/Total Solids (VS/TS) ratios and protein, carbohydrate, and lipid fractions. Two of these with the greatest differences in protein, carbohydrate, and lipid composition were selected for experimental use (Table 11). The food waste analyses did not determine the inert portion of the COD. Comparison between ultimate degradability studies by Newton (1999) of municipal sludge and laboratory scale food waste digesters was used to estimate the inert fraction of food waste. For 62 day degradability tests of primary and waste activated sludges from South Wastewater Treatment Plant (WWTP) in Renton, WA, Newton found 87% and 61% ultimate degradability respectively. Conversely, 70-90% COD conversion of food waste batch feedings was typical over 2-3 day intervals, suggesting the food wastes were highly degradable. An initial estimate of 10% inert COD in the food waste was made based on the laboratory digester data, but preliminary model fitting and simulations proved this assumption was too high. An inert assumption of 6% provided the best fitting of VS destruction, methane production, %CH_4, ammonia, and alkalinity.

Table 11. Properties of USAFA food wastes used in laboratory digesters and batch bottle tests for hydrolysis kinetics

Waste Name	Composition (% of COD)				VS/TS
	Protein	Carbohydrate	Lipid	Inert	
FW-004	17	51	26	6	0.94
FW-011	24	17	53	6	0.94
FW-MIX	20	35	39	6	0.94

Long-term laboratory anaerobic reactors and shorter term anaerobic reactors used for batch experiments were maintained with one of the three feeds described in Table 11, with and without 10% FOG (fats, oil and grease) as COD, and operated at different average COD loading rates between 4 and 10 g COD/L-d (Table 12). The reactors were 2.0 L bottles with a 0.5 L working volume. The working volume was kept at 0.5 L by withdrawing a volume equal to the following feed volume. The reactors were inoculated with anaerobic digester sludge from South Wastewater Treatment Plant (WWTP) (Renton, WA) and maintained at 37°C. The reactors were batch fed equal volumes three times a week (M, W, and F) with food waste at a constant concentration of 230 g COD/L. The average daily COD loading rate was set by the volume of food waste fed. The long term reactors were operated for 45-55 days and the batch test reactors were fed food waste for 26 days at 4gCOD/L-d, followed by a single batch test feeding at 12.0 gCOD/L. The 4gCOD/L-d loading rate during the 26 day acclimation period of the batch test reactors corresponded to average daily feed volumes that were 1.7% of the working volume (equivalent to a 57.5 day SRT).

Table 12. Laboratory experimental conditions for long-term digesters operation and batch bottle tests (T = 37°C, V = 0.5 L, Inoculated with anaerobic digester sludge from King County South WWTP at Renton, WA)

Reactor Name	Feed	Loading Rate (gCOD/L-d)	Average SRT (d)	Duration of Reactor Operation (d)
Longterm-1	FW-MIX	4	58	45
Longterm-2	FW-MIX	Ramped 4 - 10*	41	44
Longterm-3	FW-MIX + 10% FOG	4	58	47
Longterm-4	FW-MIX + 10% FOG	Ramped 4 - 10*	41	45
Longterm-5	FW-MIX	10	24	55
Batch-1	FW-004	-	-	31
Batch-2	FW-004 + 10% FOG	-	-	31
Batch-3	FW-011	-	-	31
Batch-4	FW-011 + 10% FOG	-	-	31

* Ramping occurred steadily throughout the entire duration of reactor operation

The parameters used to monitor and observe the performance of the laboratory anaerobic reactors are summarized in Table 13. These performance parameters provide the necessary data for model calibration and verification. The methane gas, VFA production, and soluble COD (sCOD) are the primary data used to evaluate hydrolysis kinetics, as they can be used to estimate the change in biodegradable particulate COD (bpCOD) in the reactors. The batch reactors were sampled more frequently in order to better describe the digester response immediately following feedings.

Table 13. Data collection parameters, sample frequency, and analytical methods for anaerobic digesters used for hydrolysis kinetics evaluation

Analyte	Collection Frequency		Method
	Long term	Batch	
Methane gas	continuous	continuous	Respirometry
VFAs	3/week	10 over 56hrs	GC-FID
pH	3/week	10 over 56hrs	pH probe
Alkalinity	~1/week	2 over 56hrs	Titration
Ammonia	-	10 over 56hrs	Colorimetric
%VS, %TS	~1/week	2 over 56hrs	Gravimetric
sCOD	-	10 over 56hrs	Colorimetric

The respirometry system from Columbus Instruments provided biogas accumulation, production rate, and concentration data continuously during testing. Gas was collected in a glass sample collection bottle. Nitrogen was used to circulate the sample gas through sensors to determine gas concentration, temperature, and pressure. Micro-Oxymax software calculated biogas volume, composition, and production rate.

Acetate, propionate, butyrate, iso-butyrate, valerate, and iso-valerate concentrations were measured in reactor samples following Method 5560D (APHA, 2005). The VFA samples were obtained by centrifugation and 0.45µm syringe filtration of 0.5 mL of centrate sample volume. A drop of 5.65 N sulphuric acid was added to each sample in a GC vial to fully protonate the acids. Analysis was performed using a Shimadzu gas chromatograph with flame ionization detection (GC-FID).

The objective was to use the long term and batch reactor data in conjunction with a hydrolysis model that could accurately describe solubilization of bpCOD in order to quantify the hydrolysis kinetics of the USAFA food waste. The first order, dual-hydrolysis model described above was deemed appropriate because of the two distinct regions found in methane production vs. time curves for both long term and batch reactors (Example in Figure 4).

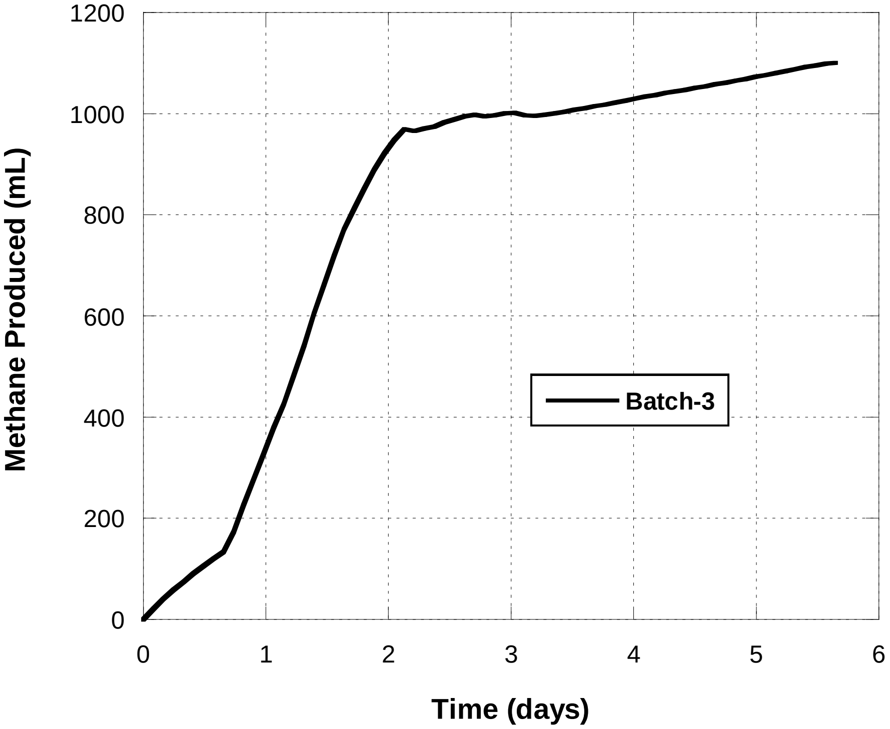


Figure 4. Cumulative methane production (adjusted to standard conditions) vs. time in batch test with Batch-3 reactor at 37^{0}C showing an initial rapid and final slower methane production rate

The dual hydrolysis model considers the reactor bpCOD to have both rapidly and slowly degrading fractions as described in Equations (10) and (11). The solubilization of each of these components is described independently using first order kinetics. By fitting this model to experimentally derived bpCOD data, the kinetic rate coefficients could be determined. The bpCOD remaining in the reactor as a function of time, hydrolysis rate coefficients, and fractions of rapid and slow bpCOD is:

$$X_c(t) = X_{c0}\left[f_{rh,xc}e^{\left(-k_{rh}t\right)} + f_{sh,xc}e^{\left(-k_{sh}t\right)}\right] \qquad (30)$$

where:

$X_c(t)$ = concentration of bpCOD at any time, t (gCOD/L)

t = time (days)

The process for determining the rapid and slow kinetic rate coefficients began with analysis of the batch reactor data. In order to calibrate the dual-hydrolysis model to food waste, experimental bpCOD concentration vs. time curves had to be synthesized from the available data. For the batch tests, the amount of bpCOD hydrolyzed in a given interval was determined by the sum of accumulative methane and VFA production as COD minus the non-VFA sCOD (nvsCOD). The nvsCOD is calculated by subtracting the VFA concentration as COD from the total sCOD concentration. If the VFA and sCOD concentrations were to remain constant during the test, the hydrolysis of bpCOD would simply be calculated using methane production, but because the hydrolysis products change during the test they were accounted for in the calculation.

$$\Delta \mathrm{bpCOD_{hyd}} = \left(\mathrm{CH_{4_{COD,t2}}} - \mathrm{CH_{4_{COD,t1}}}\right) + \left(\mathrm{VFA_{COD,t2}} - \mathrm{VFA_{COD,t1}}\right) + \left(\mathrm{nvsCOD_{t2}} - \mathrm{nvsCOD_{t1}}\right) \quad (31)$$

where:

$\Delta \mathrm{bpCOD_{hyd}}$ = amount of bpCOD hydrolyzed between t_1 and t_2, gCOD

$\mathrm{CH4_{COD}}$ = methane COD, gCOD

$\mathrm{VFA_{COD}}$ = VFA COD, gCOD

nvsCOD = non-VFA soluble COD, gCOD

The hydrolyzed bpCOD is subtracted from the initial bpCOD concentration in the reactor just after feeding to determine the reactor bpCOD concentration. The initial bpCOD concentration was estimated by the g bpCOD fed divided by the batch reactor volume. Preexisting bpCOD concentration in the reactors prior to feeding was unknown and was not included in the calculation. The effect of this simplification is discussed below. The fractions of rapid and slow bpCOD were also needed to calibrate the dual-hydrolysis model. These were estimated using the experimental bpCOD concentration vs. time curves for the batch tests (Figure 5). An exponential trend line was created using the slowly hydrolyzing portion of the bpCOD concentration curve. A significant fraction (0.96) of the rapid bpCOD had been hydrolyzed 45 hours after feeding, so the trend line was generated from the data after 45 hours had elapsed. The value for this trend line at time equal to zero was used to estimate the amount of slow bpCOD. The fraction of slow bpCOD was determined by dividing this value by the bpCOD fed, and the rapid bpCOD fraction was determined by difference.

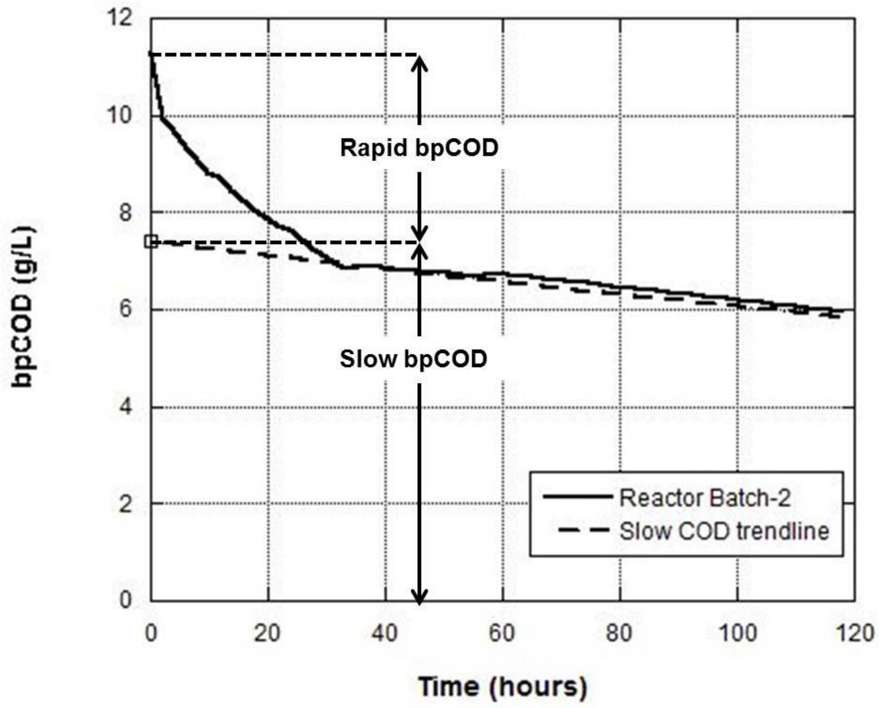


Figure 5. Determination of rapid and slow hydrolyzing bpCOD fractions using an exponential fit to the bpCOD concentration after 45 hours.

The hydrolysis rate coefficients were determined by minimizing the sum of the square error between the experimental bpCOD concentration vs. time curve and the dual-hydrolysis model (Figure 6). This was achieved using Microsoft Excel solver function; the rapid and slow hydrolysis rates were allowed to vary in order to solve for the smallest possible square error between the curves.

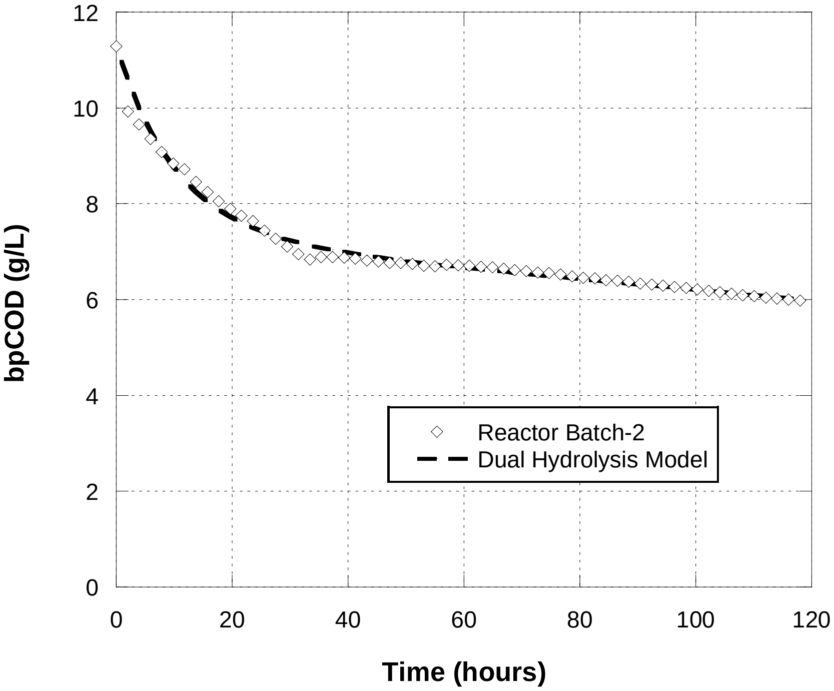


Figure 6. Dual hydrolysis model fitting of Batch-2 bpCOD concentration vs. time

The hydrolysis rates in a first order model are proportional to the concentration of bpCOD in the reactor. In this case, each of the rapid and slow rates is proportional to their respective bpCOD concentrations. Because the preexisting bpCOD in the reactor was not considered in the calculation of the initial concentration, an error was introduced in the determination of the hydrolysis rate coefficients. Any preexisting bpCOD in the reactor prior to feeding was likely slowly hydrolysable, as the rapid bpCOD had enough time to nearly completely hydrolyze between feedings. Therefore, the rapid hydrolysis rate coefficients determined from the dual hydrolysis model fitting will not contain this error (Table 14).

Table 14. Rapid hydrolysis rate coefficients and their given fraction of the bpCOD determined by least squares fitting of dual hydrolysis model to batch test data

Reactor	Rapid Fraction of bpCOD	Rapid Hydrolysis Rate Coefficient (d^{-1})
Batch-1	0.32	1.04
Batch-2	0.26	2.16
Batch-3	0.39	1.50
Batch-4	0.39	1.56
Duplicate of Batch-1	0.24	1.29

The long term reactors were used in the determination of the slow hydrolysis rate coefficients because they minimize the error introduced by unknown preexisting bpCOD concentrations. If the initial bpCOD concentration is assumed to be less than what is actually in the reactor, the hydrolysis rate will be under predicted for a single feeding event. Over many feeds the error will be mitigated by a buildup of bpCOD in the model due to the under predicted hydrolysis rate. This increase in bpCOD will cause the hydrolysis rate to increase until steady conditions are reached. Therefore, the predicted bpCOD concentration by the model will reach the reactor bpCOD concentration regardless of the initial bpCOD.

The long term reactor data was used to synthesize bpCOD concentration vs. time curves that spanned many feedings (Figure 7). Because these reactors were operated at long SRTs and allowed to reach steady operation, they did not demonstrate significant accumulation of hydrolysis products following feedings. The hydrolysis of bpCOD was therefore estimated by methane production only for the long term reactors. Like the batch reactors, the initial bpCOD concentration was determined by dividing the g bpCOD from the first feeding by the reactor volume. For subsequent feedings, the bpCOD concentration was increased by the g bpCOD fed divided by the reactor volume. The dual-hydrolysis model had to be modified so that it could be fit to the synthesized bpCOD curves with multiple feedings. The first feeding was done identically to the batch reactors. When new feedings occurred, and additional bpCOD was added, additional terms were added to account for the new bpCOD, each with a corresponding X_{c0}, f_{rh_xc}, and f_{sh_xc}. The new bpCOD terms were considered to be at time zero just as they were fed, while any remaining bpCOD from previous feeds continued to decay exponentially from their corresponding feeding time. Because the hydrolysis rate is proportional to the bpCOD in the reactor for a first order model, each new feeding can be considered separately and summed together to calculate the bpCOD concentration in the reactor.

The slow hydrolysis rate coefficients were determined by minimizing the square error between the synthesized bpCOD curves and the modified dual hydrolysis model curves. The average rapid hydrolysis rate coefficient (1.51 d^{-1}) and average rapid fraction of bpCOD (0.32) were taken from the batch reactor results, and only the slow hydrolysis rate coefficient was allowed to vary in Microsoft Excel's solver function in order to optimize the fit (Table 15).

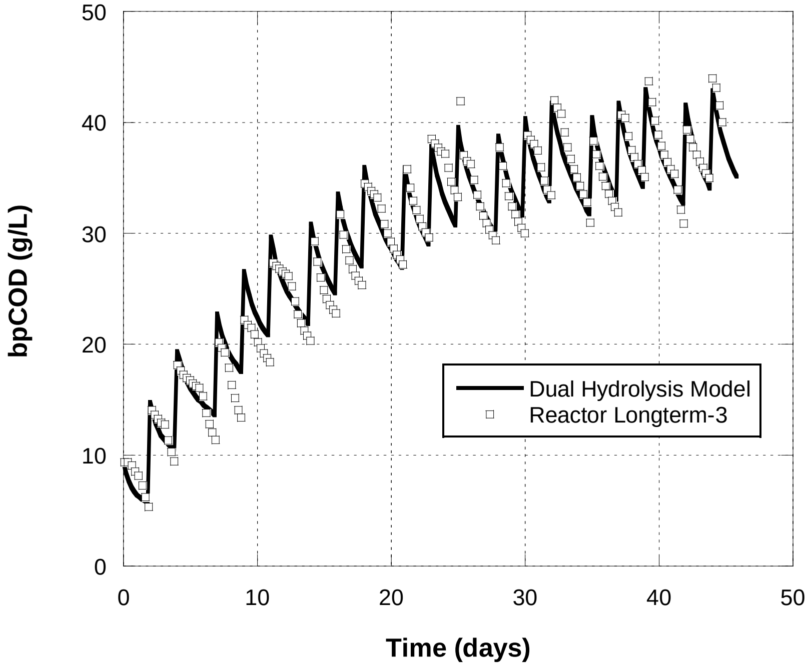


Figure 7. Least squares fit for dual hydrolysis model of the bpCOD concentration in reactor Longterm-3

Table 15. Slow hydrolysis rate coefficients determined from long term reactors. Average batch reactor results were used for rapid COD rate coefficient (1.51 d^{-1}) and rapid fraction of total COD (0.32).

Reactor	Slow Hydrolysis Rate Coefficient (d^{-1})	R^2	Slope
Longterm-1	0.32	0.72	0.74
Longterm-2	0.67	0.32	0.45
Longterm-3	0.07	0.91	0.88
Longterm-4	0.15	0.95	0.88
Longterm-5	0.12	0.92	1.01

Reactor Longterm-2 has a significantly higher rate coefficient than the other reactors. The fit is also by far the poorest and was therefore not considered in the final hydrolysis rate estimations used for simulations. Due to the nature of the synthesis of the bpCOD concentration vs. time curves, traditional fitting parameters like bivariate R^2 and slope don't necessarily provide a definitive representation of the goodness of fit. In a few cases, there was a small lag period between feeding and significant methane production. The model does not account for lag time, as most feedings saw immediate production of methane gas. Therefore, the reactors that had more feedings with lag periods may have poorer R^2 or sum of square error, even if the overall fit was visually better. A holistic approach combining R^2, slope, and visual confirmation was taken to describe goodness of fit (Table 15, Figure 7—Figure 11).

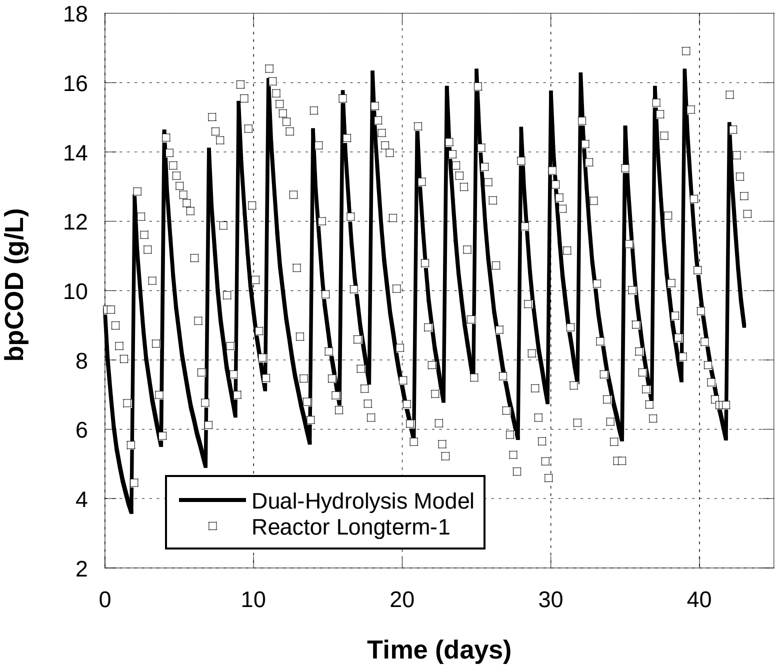


Figure 8. Least squares fit for dual hydrolysis model of the bpCOD concentration in reactor Longterm-1

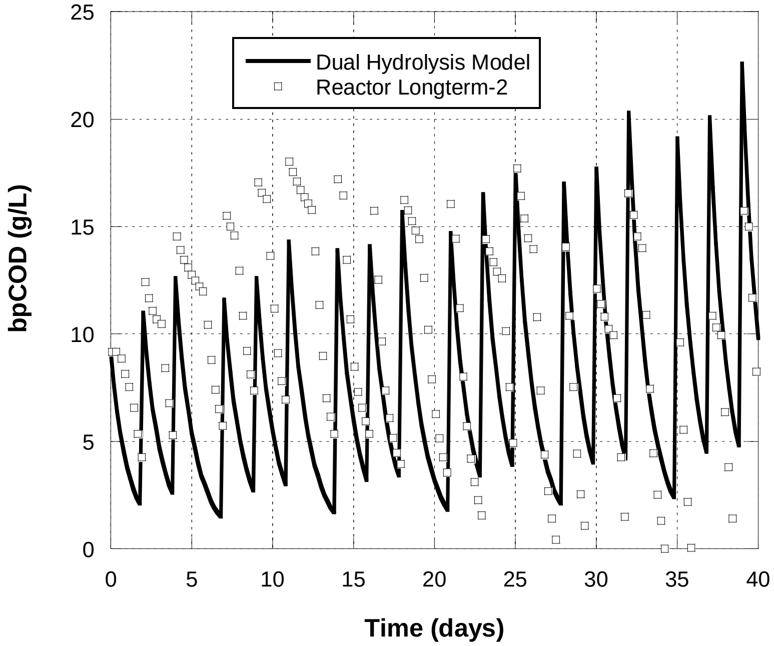


Figure 9. Least squares fit for dual hydrolysis model of the bpCOD concentration in reactor Longterm-2

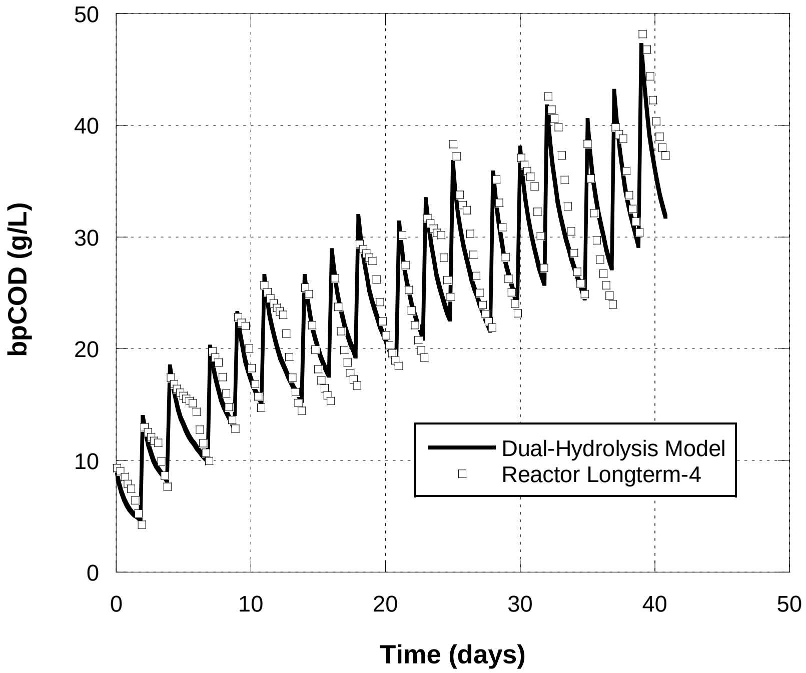


Figure 10. Least squares fit for dual hydrolysis model of the bpCOD concentration in reactor Longterm-4

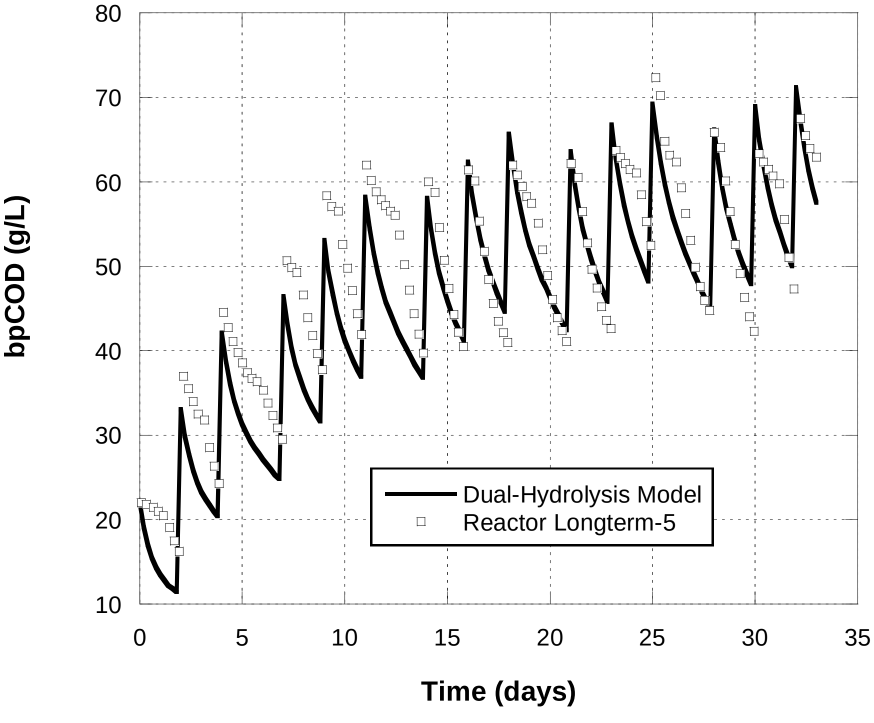


Figure 11. Least squares fit for dual hydrolysis model of the bpCOD concentration in reactor Longterm-5

As the R^2, slope, and visual fit suggest, Longterm-2 was unable to achieve a good fit using the dual-hydrolysis model. The other reactors had R^2 values and slopes from 0.72-0.95 and 0.74-1.01 respectively. These reactors had much better fits, which can be confirmed by Figure 7—Figure 11 . Longterm-1 had a slightly worse fit than 3, 4, or 5, according to R^2, slope, and visual appearance. The relative goodness of fit between reactors 3, 4, and 5 cannot be significantly distinguished by the fitting parameters used in this analysis.

The results from all long term reactors with the exception of Longterm-2 were averaged to estimate the slow hydrolysis rate coefficient. The value, 0.16 d^{-1}, is approximately an order of magnitude less than the 1.5 d^{-1} rapid rate coefficient. These values provided an initial estimate for the hydrolysis kinetics of food waste, which were used for simulations in the modified ADM1.

A secondary goal of the hydrolysis tests were to determine if the presence of FOG, variability in loading rate, or waste composition had an effect on the hydrolysis characteristics of food waste. No significant trends for the rapid or slow hydrolysis rate coefficients with respect to FOG addition, max loading rate, or ramping of the loading rate were found from these tests. These factors may have effects on the hydrolysis kinetics, but additional study, designed specifically to address any impacts, is needed.

CHAPTER V: MODEL SIMULATIONS

The calibrated ADM1 was used in model simulations to evaluate digester performance for planned operating conditions for pilot plant digesters to be installed at the USAFA to process food waste to energy. Two 600 gallon digesters will be filled initially with sludge obtained from an anaerobic digester at the USAFA domestic wastewater treatment facility. The following operational phases anticipated for the pilot plant study include: 1) start up and acclimation to the food waste feed, 2) steady state operation, 3) step-wise loading increases to a maximum level that maintains digester stability and 4) temporary reduced loading rates. Model simulations for various conditions were done to determine the effect of the above expected pilot plant test scenarios on digester performance and stability. The information gained from these simulations will be useful for determining expected performance for the operating conditions presently planned and may be used to guide decisions on pilot plant test conditions.

Table 16 summarizes the digester design liquid and head space volumes and operating temperature and the expected feed concentration for all of the simulations with regard to the pilot plant operation. The pilot plant digesters are expected to be batch fed over a 60 min period three times per week on Monday, Wednesday, and Friday. At the initial target loading of 7.0 gCOD/L-d, the HRT and SRT would be 18.5 days, based on the expected feed concentration of 129.5 gCOD/L. For higher loadings, the volumetric feed rate would be increased, and the SRT would be decreased as the feed concentration is expected to be relatively constant.

Table 16. Pilot plant digester specified design conditions

Parameter	Units	Value
Temperature	°C	36.7
Volume	m^3	1.893
Gas Volume	m^3	0.379
Feed Concentration	gCOD/L	129.5

The food waste composition was estimated by averaging the results from food proximate analyses of 15 USAFA food waste samples. Appendix E contains detailed data for each of the individual wastes. Table 17 summarizes the waste characteristics used in model simulations. The average protein, carbohydrate, lipid, and inert COD fractions are 0.29, 0.31, 0.34, and 0.06, respectively. The fractions of rapid and slowly hydrolysable COD and the hydrolysis characteristics are average values from the model calibrations as described previously.

Table 17. Average USAFA waste characteristics used for ADM1 simulations

Parameter	Units	Value
Protein COD	g/gCOD	0.29
Lipid COD	g/gCOD	0.34
Carbohydrate COD	g/gCOD	0.31
Rapid COD fraciton	g_{rapid}/gCOD	0.3
Slow COD fraction	g_{slow}/gCOD	0.64
Inert COD fraction	g_{inert}/gCOD	0.06
VS/TS	-	0.94

Because the digesters will be charged with anaerobic digester sludge from the USAFA digesters treating sludge from domestic wastewater, it was necessary to simulate that digester treatment first to characterize the pilot plant digester microbial population and undigested solids composition before feeding USAFA food waste. Three months of data from the USAFA wastewater treatment plant, including the daily flowrate, concentration of waste primary and secondary sludge, VS/TS ratio and digester TS were used to calculate the average VS destruction efficiency (Appendix F), which was used along with the digester volume and temperature in modified ADM1 simulations to establish the characteristics of the seed sludge to the digester. Using the conditions described by the USAFA domestic wastewater digester as the starting point, the model simulation plan listed in Table 18 was followed to evaluate the anticipated pilot plant operation.

Table 18. ADM1 simulations plan

Number	Simulation
1	Startup and acclimation
2	Steady state operation
3	Transition to higher loading rate
4	Temporary reduced loading rate
5	Effect of feeding strategy
6	Effect of hydrolysis kinetics coefficients
7	Effect of waste composition
8	Effect of endogenous decay rate

In addition to predicting digester food conversion efficiency and biomethane gas production rates, information on the potential for unstable operation and digester upset was an important aspect of the model simulations. Evaluation of the potential for digester instability required selecting appropriate digester performance or operating parameters that could be tracked and quantified in the model simulations to yield numerical values that would be expected for stable digester operation. Typical indicators of digester health include pH, alkalinity, VFA concentration, VFA/Alkalinity ratio, and relative biomethane and total gas production rates. Due to the highly degradable nature of the food wastes and their composition, the laboratory digesters often produced enough bicarbonate to sustain healthy alkalinity and pH values in spite of VFA concentrations increasing to inhibitory levels with a decline in biomethane production. In many laboratory digesters the pH and alkalinity were > 7.3 and > 9000 mg $CaCO_3$/L respectively, when the total VFA concentrations were up near 5000 mg/L as acetate. Biomethane production was inhibited in most of the laboratory digesters when the total VFA concentration exceeded 3000 mg/L as acetate. Thus, it would not be sufficient to base digester health and potential for upset on only typical parameters such as pH and alkalinity. Near day 32 of operation, the methane production in a laboratory digester loaded at 6gCOD/L-d declined when the total VFA concentration exceeded 2500 mg/L (Figure 12), while the pH was still above 7.6 (Figure 13). Appendix G shows additional laboratory reactors that exhibit similar behavior as Figure 12 and Figure 13.

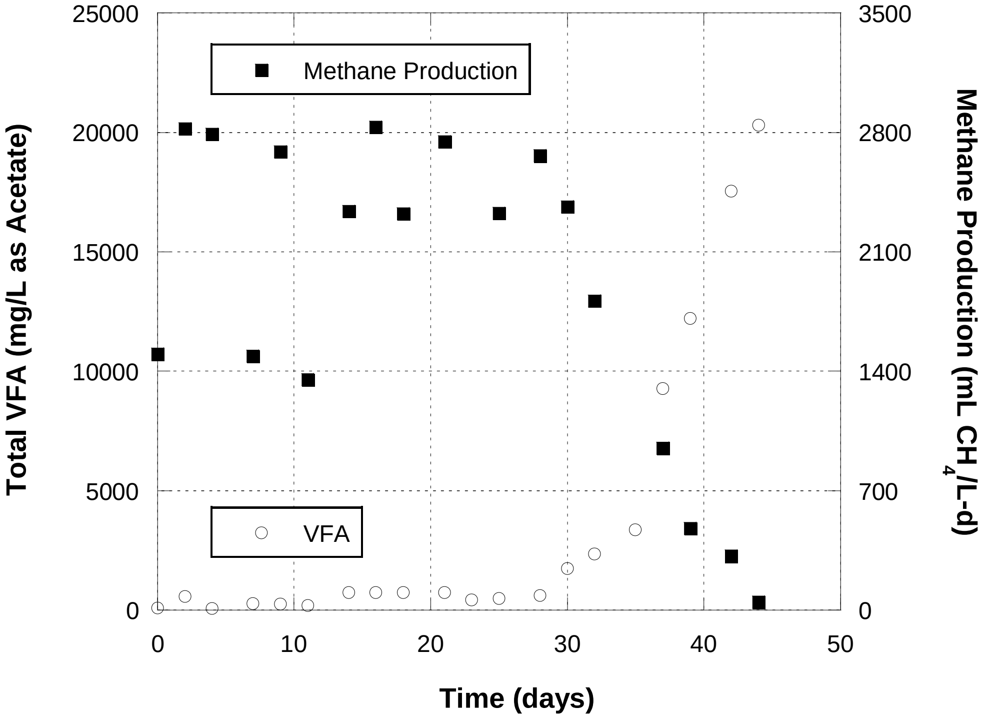


Figure 12. Total VFA concentration and methane production rate vs. time for a laboratory digester with a 6gCOD/L-d average loading rate

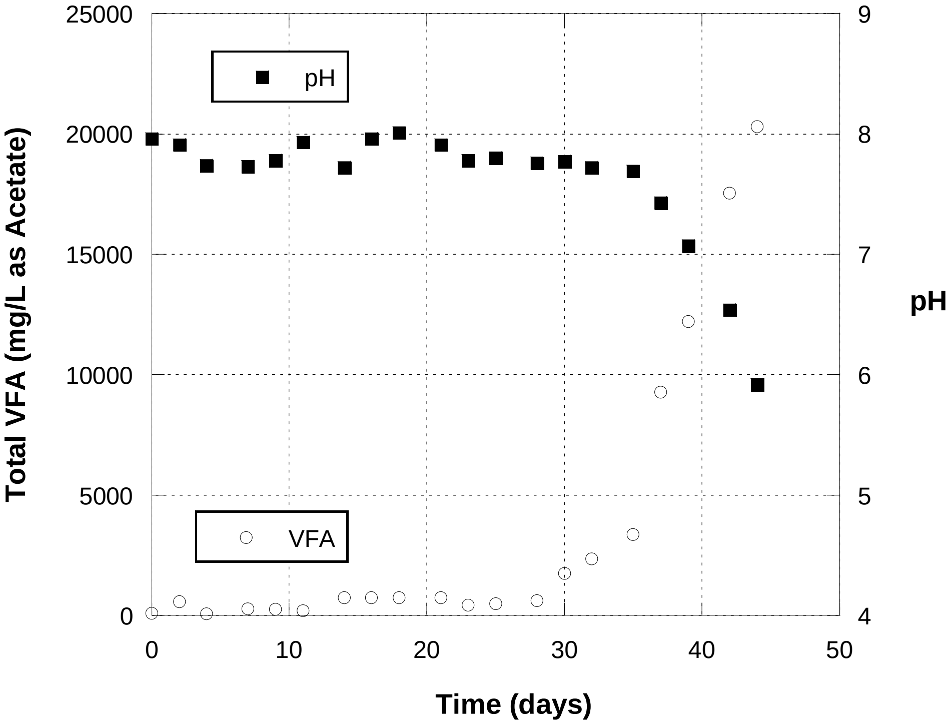


Figure 13. Total VFA concentration and pH vs. time for a laboratory digester with a 6 gCOD/L-d average loading rate

Unionized acetic acid has been shown to be inhibitory to methanogenesis at elevated levels (Fukuzaki et al. 1990, Kus and Wiesmann 1995, Ryhiner et al. 1992). Acetate concentration was used as the main indicator of digester health for the pilot scale food waste simulations because of the inhibitory effects seen in the lab-scale digesters. If the acetate gets fully utilized between feedings without significant accumulation and is not sustained at high concentration for prolonged periods, the digester will be considered under stable operation. In the evaluation of digester potential instability for the model simulations, a high potential for unstable operation was assumed if the acetate concentration exceeded 2500 mg/L. Propionate, another important VFA, typically ranged from 10 to 30% of the acetate concentration in simulations and steady lab digester operation.

During the startup period the digester microbial population and solids composition would change after the seed sludge from the USAFA digester starts receiving food waste. Laboratory digester studies with digester sludge from the King County Renton municipal WWTP showed immediate adaptation to food waste. The initial conditions for the pilot plant seed sludge was determined from simulations of the USAFA anaerobic digester using plant data on the digester temperature and SRT and feed solids concentrations and volatile fraction for waste primary and waste activated sludge.

Steady state operation

An initial loading of 7gCOD/L-d was used for the pilot plant study as laboratory studies showed this to be a safe loading for stable operation. This loading is an "average" daily loading over a 7-day or weekly period as the digesters are expected to be fed three times per week. The initial goal was defined as a “steady state” operation with the 7gCOD/L-d loading, but because the digester is not fed continuously, a true steady state condition in terms of constant gas production rates and constant digester parameter concentrations is not attainable. For the Monday, Wednesday, and Friday batch feeding strategy, a pseudo-steady state was defined by a week-long cycle. When the transient concentrations in the digester were replicated in successive weeks, the digester was considered to be operating at steady state. The steady state operation at the 7gCOD/L-d loading was then used as the initial condition for the remaining simulations in Table 18. Digester performance at 7gCOD/L-d is summarized after the determination of the optimized loading rate below.

Effect of transitioning to a higher loading rate

The digester loading rate was then increased in a stepwise manner to address the optimization and challenge phases of pilot plant operation. The first simulation increased the loading rate from 7gCOD/L-d to 15gCOD/L-d, corresponding to a decrease in SRT from 18.5 to 8.6 days. The acetoclastic biomass, X_{ac}, was compared for a thirty day transition vs. an immediate transition to the new loading rate. As the loading rate is increased incrementally, the amount of biomass that is withdrawn from the reactor for each feed also increases due to the higher flowrate, which causes the biomass concentration to be lowered at the beginning of each cycle after batch feeding (Figure 14). For example just before Day 40, when the 15gCOD/L-d loading is reached, the X_{ac} concentration is about 1.8 gCOD/L versus about 2.0 g COD/L at the start of the transient loading period. When the transition is made immediately from 7 to 15gCOD/L-d the population of X_{ac} is even lower at the same time (Figure 15).

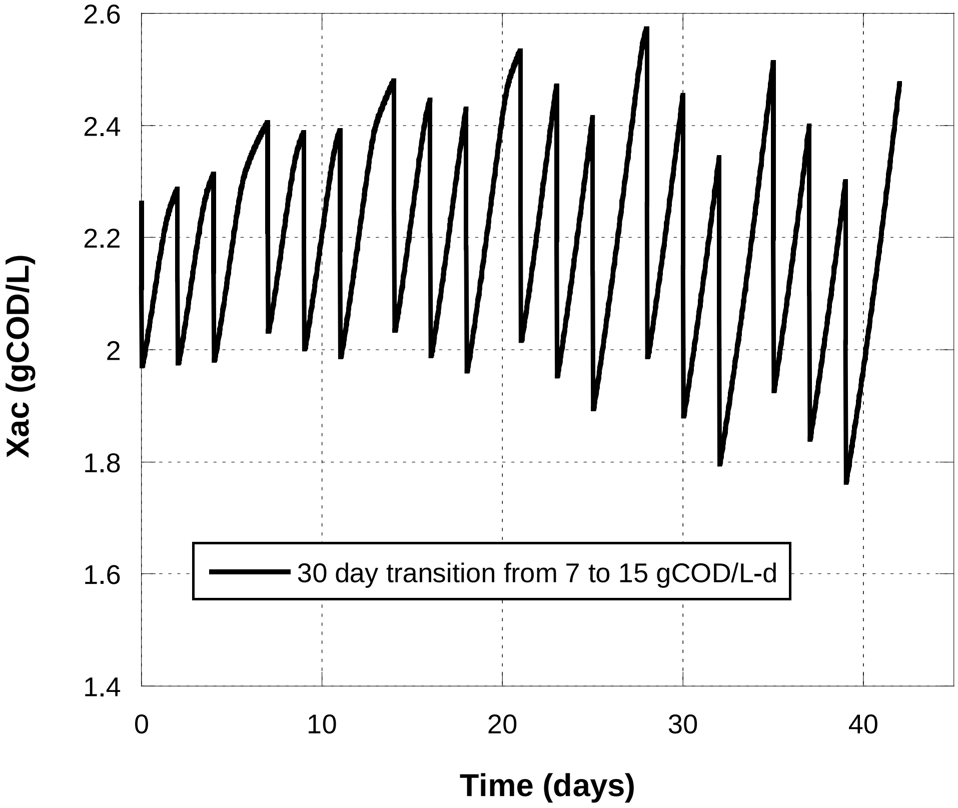


Figure 14. Simulated acetoclastic methanogen population vs. time for a 30 day transition from 7 to 15 gCOD/L-d by step wise increase in feed volume, equivalent to a decrease in SRT from 18.5 to 8.6 days

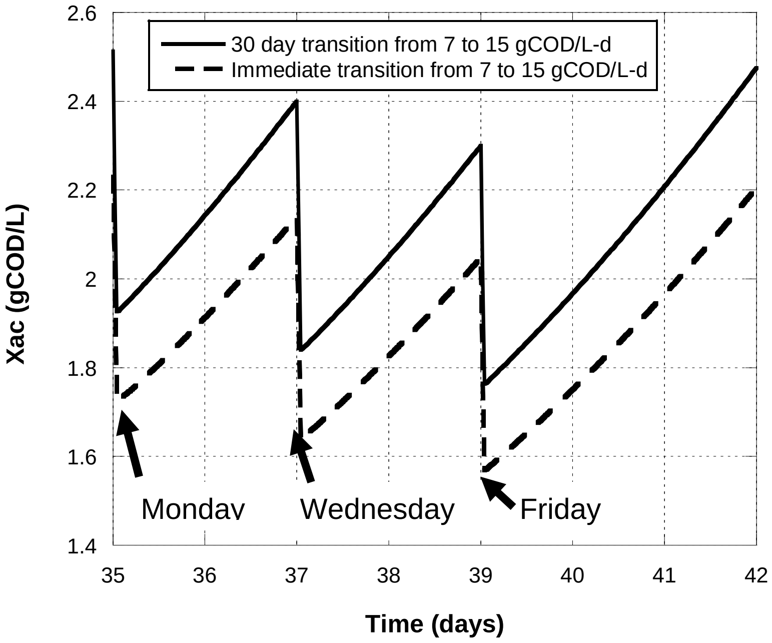


Figure 15. Simulated acetoclastic methanogen population vs. time for both immediate, and 30 day transitions from 7 to 15 gCOD/L-d by step wise increase in feed volume, equivalent to a decrease in SRT from 18.5 to 8.6 days. Day 35 corresponds to the first day of 15gCOD/L-d loading (Arrows indicate feed additions).

A digester that withdraws 11.5% of its volume each day of the week can be considered to have an SRT of 8.6 days. However, for three batch feed events (MWF) per week at the same average weekly SRT, 27% of the digester volume is withdrawn for each feeding. The withdrawal is much more dramatic for three feeds per week, which affects biomass wasting and growth potential in the digester. Biomass increases after each feeding event, and has three days to increase after Friday's feed, as opposed to two days after Monday and Wednesday (Figure 15). The decline in the acetoclasts concentration with time due to the high fraction of digester volume withdrawn at 15gCOD/L-d loading causes the acetate concentration to increase with time to accumulate to unstable levels (Figure 16).

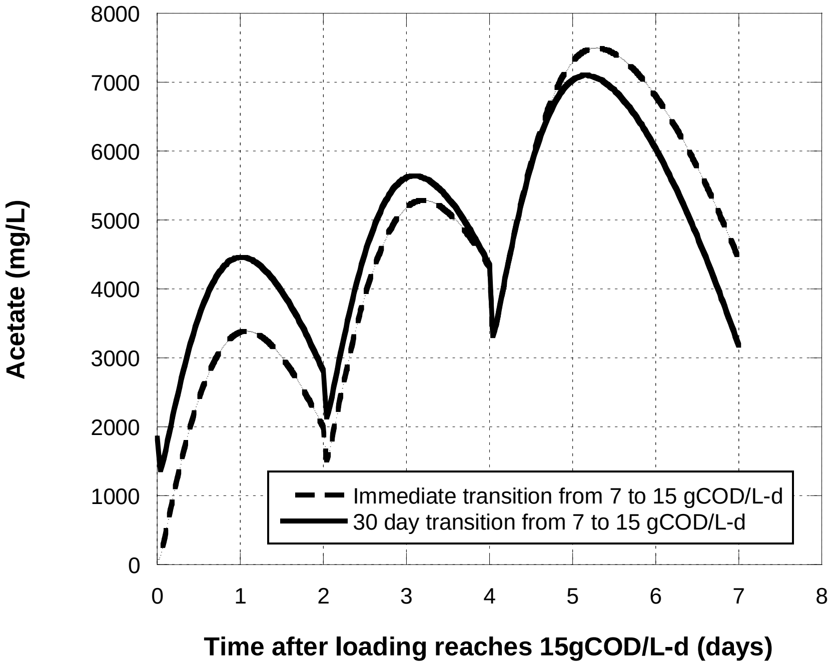


Figure 16. Simulated acetate concentration vs. time after the loading rate reaches 15gCOD/L-d for both immediate, and 30 day transitions from 7 to 15 gCOD/L-d by step wise increase in feed volume, equivalent to a decrease in SRT from 18.5 to 8.6 days.

The transient acetate peaks do not increase as rapidly after the loading reaches 15gCOD/L-d for the 30 day transition, leading to a lower peak acetate concentration by the third batch feed at 15gCOD/L-d. This is an effect of the increased X_{ac} population in the 30 day transition scenario.

Simulations for increasing the loading rate to 15gCOD/L-d when feeding three times a week proved to be unstable. A new target loading rate of 12gCOD/L-d (10.8 d SRT) was selected with the same operating conditions to see if stable operation could be reached. Acetate concentration and acetoclastic methanogen population were simulated for immediate transition; and 10, 20, and 30 day transitions from 7 to 12 gCOD/L-d (Figure 17 and Figure 18).

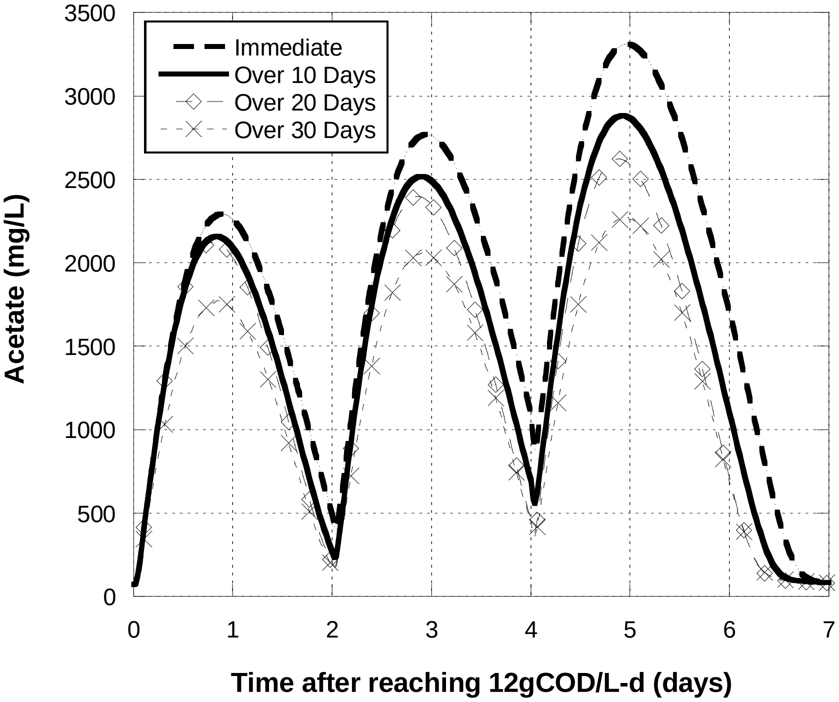


Figure 17. Simulated acetate concentration vs. time after reaching 12gCOD/L-d loading rate for immediate, 10 day, 20 day, and 30 day transitions from 7 to 12 gCOD/L-d by step wise increase in feed volume, equivalent to a decrease in SRT from 18.5 to 10.8 days.

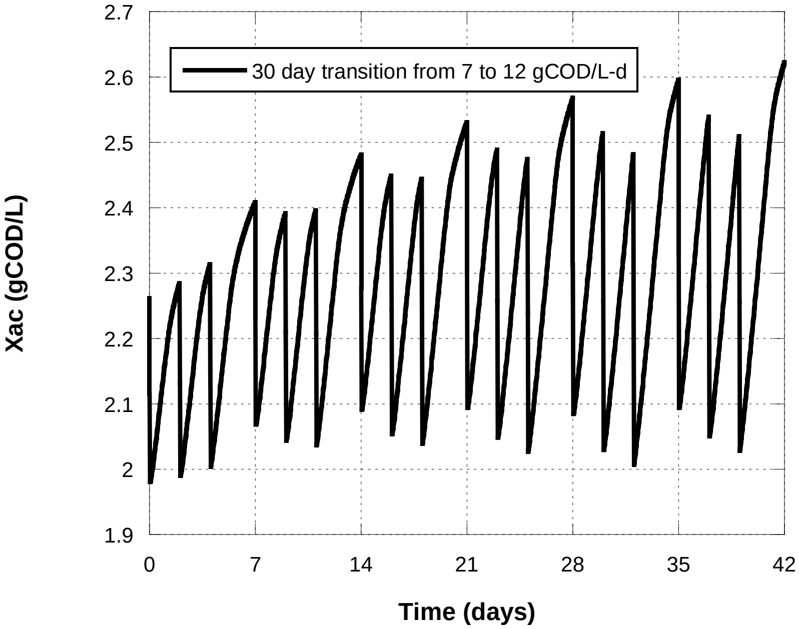


Figure 18. Simulated acetoclastic methanogen population vs. time for a 30 day transitions from 7 to 12 gCOD/L-d by step wise increase in feed volume, equivalent to a decrease in SRT from 18.5 to 10.8 days.

The effect of the length of the transition period for increasing the loading rate is much more apparent in the 12gCOD/L-d target loading simulations. The 12gCOD/L-d loading does not withdraw biomass at a rate that causes instability, as occurred for the 15gCOD/L-d scenarios. Figure 18 shows that for weekly intervals, the net acetoclastic methanogen population increases over the entire 30 day transitional period. The steady increase in biomass allows the digester to consume more acetate at higher loading rates than a digester that transitions immediately. Figure 17 demonstrates that the longer the transitional period, the smaller the transient acetate concentration will be when the target loading is reached. There is a limit to this effect. At a certain transitional length, the change in loading will be so small that biomass population will already be at the pseudo-steady state conditions described previously. The digester acetate concentration will be the same for any transitional period that approaches this limit. The 30 day transitional period is very close to this limit, as continued simulation at 12gCOD/L-d shows the pseudo-steady state conditions are met. Therefore, the peak acetate concentrations will never get significantly lower than those simulated for the 30 day transitional period in Figure 17.

When the loading was increased over a 30 day period, the transient acetate concentration remained under the acceptable limit of 2500 mg/L acetate. 12gCOD/L-d appeared to be approaching the maximum loading rate that keeps acetate under 2500 mg/L for three feeds per week operation. The digester performance of 7gCOD/L-d and 12gCOD/L-d loadings was summarized to compare the effects of operating at a higher loading rate (Table 19). The simulations were run until the pilot digester achieved pseudo-steady state operation at each loading rate. As expected, at the higher loading rate and lower SRT, the solids destruction efficiency is lower and the biomethane production rate per unit digester volume is higher.

Table 19. Simulated digester performance data for 7 and 12 gCOD/L-d average loadings operated at pseudo-steady state for three batch feeds (MWF) a week. SRTs are 18.5 and 10.8 days respectively. Methane production rates are at the 36.7 °C digester temperature.

Parameter	Units	7gCOD/L-d	12gCOD/L-d
Effective SRT	days	18.5	10.8
COD Conversion Efficiency	%	67	58
VS Destruction Efficiency	%	72	67
Methane Production Rate*	mL CH_4/L-d	1,860	2,780
Effluent VS concentration**	%	2.5	3.0
Effluent TS concentration**	%	3.1	3.6
Effluent Acetate concentration	mg/L	60	190
Effluent Alkalinity	mg/L as $CaCO_3$	11,620	10,480
Effluent pH	-	7.6	7.6
Effluent NH_4-N concentration	mg/L	3,250	2,983

*based on digester volume, ** based on sludge at specific gravity of 1.03

The final solids concentration in the digester is also an important factor which is related to the digester mixing requirements. As shown in Table 19, as the average loading was increased from 7.0 to 12.0 gCOD/L-d the model predicted that the digester volatile and total solids concentration would increase from 2.5 to 3.0% and 3.1 to 3.6%, respectively. At higher loadings the digester would have higher solids concentrations, which would impact the mixing requirements of the digester.

Effect of changing digester load by feed concentration or feed flow rate

With the limitation that the food waste feed concentration is constant, any the loading rate increases could only be done by increasing the volume fed to the digester. As seen in the simulations for transitioning to 15 gCOD/L-d, the instantaneous SRT was too low to allow for stable digester operation with the MWF batch feeds per week. To further demonstrate the impact of SRT during high loading rates the simulation for ramping from 7 to 15 gCOD/L-d was repeated, but instead the feed concentration was increased from 129.5 to 277.5 gCOD/L while keeping the SRT constant at 18.5 days. The fraction of acetoclastic methanogen population that is wasted during feeding periods is much less when the loading rate is increased by raising the feed concentration instead of the flowrate (Figure 19). For an SRT of 18.5 days only 12.6% of the biomass is wasted for each feeding, whereas an SRT of 8.6 days corresponds to 27% loss. As a result, the simulated acetoclast biomass is 38% higher for the feed concentration increase than for the flowrate increase after a week of feeding at 15gCOD/L-d. A greater population of biomass allows the digester to utilize acetate more rapidly. As expected from the increase in biomass, the model predicts lower acetate concentrations for higher loading by increasing the feed concentration instead of decreasing the SRT (Figure 20). The peak transient acetate concentrations during a week of feeding are less than 50% of those due to the same load increase associated with increased flowrate. The peak acetate concentrations are still over 2500 mg/L, meaning that a sudden increase to 15gCOD/L-d is still not advised under these operating conditions.

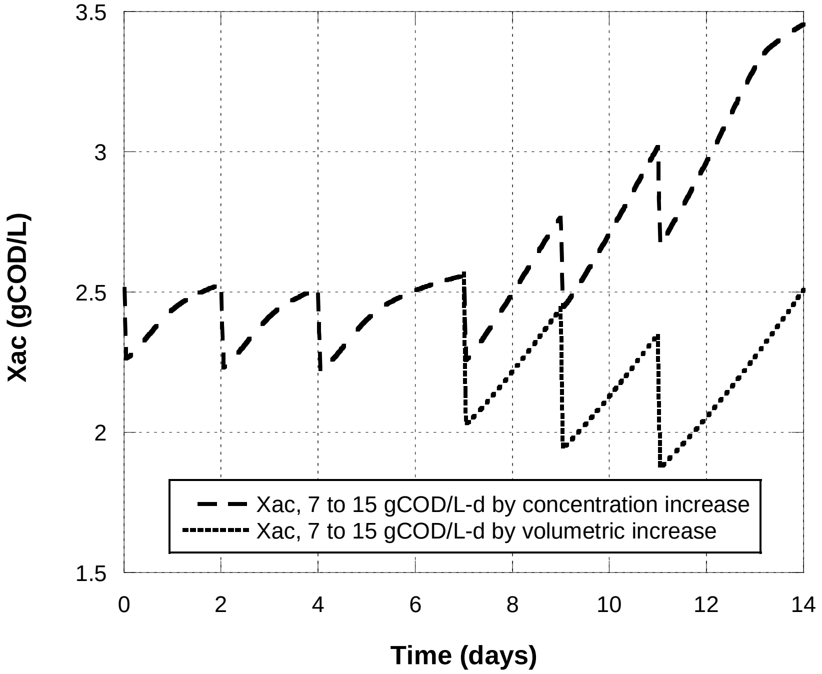


Figure 19. Comparison of simulated Xac concentration vs. time for increasing the loading rate from 7 to 15 gCOD/L-d by increasing the feed COD concentration (129.5 to 277.5 gCOD/L) versus increasing the feed volume. The loading rate is 7 gCOD/L-d for days 0-7 and 15gCOD/L-d for days 7-14.

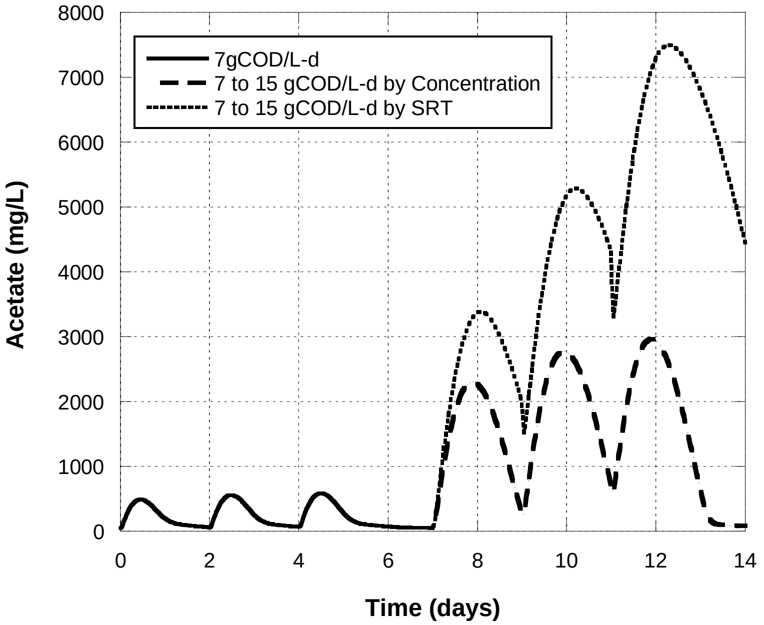


Figure 20. Comparison of simulated transient acetate concentration vs. time for increasing the loading rate from 7 to 15 gCOD/L-d by increasing the feed COD concentration (129.5 to 277.5 gCOD/L) versus increasing the feed volume. The loading rate is 7 gCOD/L-d for days 0-7 and 15gCOD/L-d for days 7-14.

These simulations show that for the same load increase in gCOD/L-d, the acetoclast population can increase faster and better respond to the loading change if the effluent flowrate is lower, which could occur if the loading rate is increased by raising the feed concentration instead of the flowrate. Thickening the feed to achieve a higher COD concentration may not be practical for digester operation, but there may be some control over the feed concentration. The model has demonstrated the effect of loading change due to increasing flow or concentration on acetate accumulation under transient conditions.

Effect of temporary reduced loading rate

We assume that with cadet activities changes at the USAFA, the resident population and amount of food waste available for digester feeding may change throughout the year. During the summer months not all the cadets are on campus. Model simulations were done by assuming the COD loading rate was decreased to 1/3 the typical load for a two month period during the summer. The population was then assumed to return to normal after these two months, and the digester response was evaluated when the loading rate was returned to normal. The original loading rate of 7gCOD/L-d (18.5 d SRT) was reduced threefold to 2.33gCOD/L-d (55.5 d SRT). The effect of the lower loading was seen through decreases in the digester VFA (Figure 21) and biomass concentrations (Figure 22) over the decreased loading period. Methane production rates decreased significantly during this period, producing an average of 50% less biomethane per feeding.

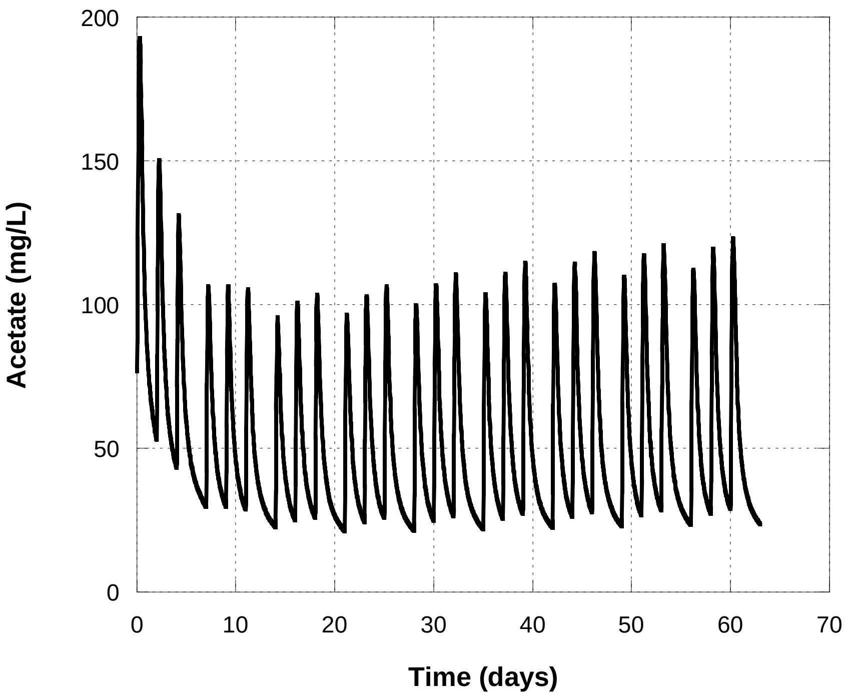


Figure 21. Simulated acetate concentration during a two month period with the load reduced to 2.33 gCOD/L-d (55.5 d SRT) from 7gCOD/L-d (18.5 d SRT)

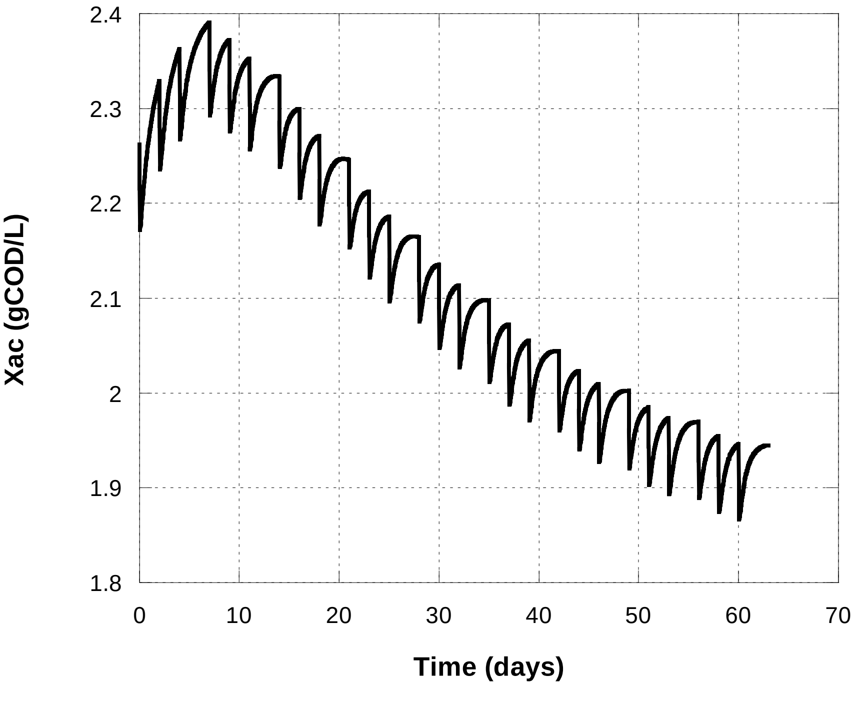


Figure 22. Simulated acetoclastic methanogen biomass with the load reduced to 2.33 gCOD/L-d (55.5 day SRT) from 7gCOD/L-d (18.5 d SRT)

The simulated increase in acetoclast concentration over the first week is a result of the sudden increase in SRT providing more time to consume residual bpCOD from the lower SRT operation. When the loading rate is reduced and the SRT increases to 55.5 days, a higher amount of the slowly hydrolysable bpCOD fed previously gets solubilized. The hydrolysis of the preexisting bpCOD causes the population to increase initially, but as it gets used up the population decreases due to the reduced loading rate.

An important issue for the pilot digester operation is whether stable digester operation is possible after returning to the previous 7gCOD/L-d loading. The biomass concentrations are lower following the reduced loading period, and thus the digester has lower substrate utilization rates. Model simulations showed that the digester could be returned to the 7gCOD/L-d loading without instability problems (Figure 23). When the digester resumes to a loading that still has a relatively long SRT, biomass loss in the effluent is low enough to allow the digester to accommodate the higher loading without instability. To demonstrate the potential instability effects of instead feeding at a higher loading rate, the simulation was also done with a 12gCOD/L-d loading (10.8 d SRT), which may also be used during pilot digester operation. In this case, acetate buildup and prolonged periods of high acetate concentration occurred (Figure 23).

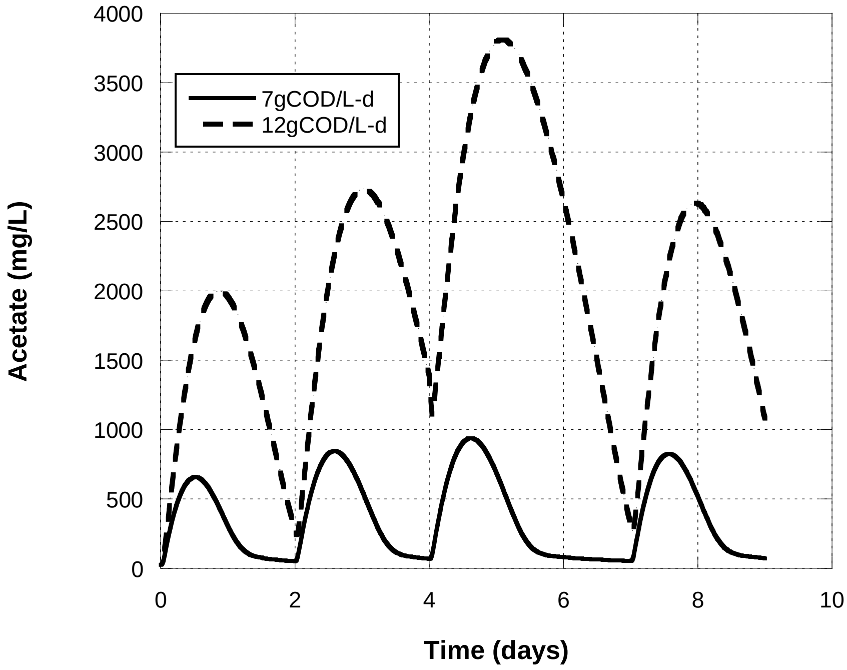


Figure 23. Simulated acetate concentration for resumption to 7gCOD/L-d (18.5 d SRT) or transition to 12gCOD/L-d (10.8 day SRT) following 2 months at 2.33 gCOD/L-d (55.5 d SRT)

Although the simulations for resumption at 7gCOD/L-d did not predict signs of instability, if the digester is operated at higher loading rates (lower SRTs) there may be more noticeable effects on digester stability. The decrease in digester biomass resulting from a reduced loading rate makes the digester more vulnerable to increases in loading rate.

Model Sensitivity Simulations

Model simulations were performed to examine the effect of various model parameters on predicted digester performance. The parameters that were hypothesized to have implications for the pilot plant study were feeding strategy, hydrolysis rate coefficients, food waste composition, and the acetoclast's endogenous decay rate.

Effect of feeding strategy

The digester feeding strategy has a major effect on the digester VFA concentration changes with time. The USAFA pilot digester is expected to be fed three times a week. Fewer feeding events per week result in larger instantaneous COD loadings to the digester. To demonstrate the effect of feeding frequency, digester acetate concentrations were observed in model simulations of daily and three feedings a week for the same average daily loading rate of 12gCOD/L-d (10.8 d SRT). The peak acetate concentration for daily feeding was approximately 850 mg/L, but was 1700-2200 mg/L for feeding at three times per week (Figure 24).

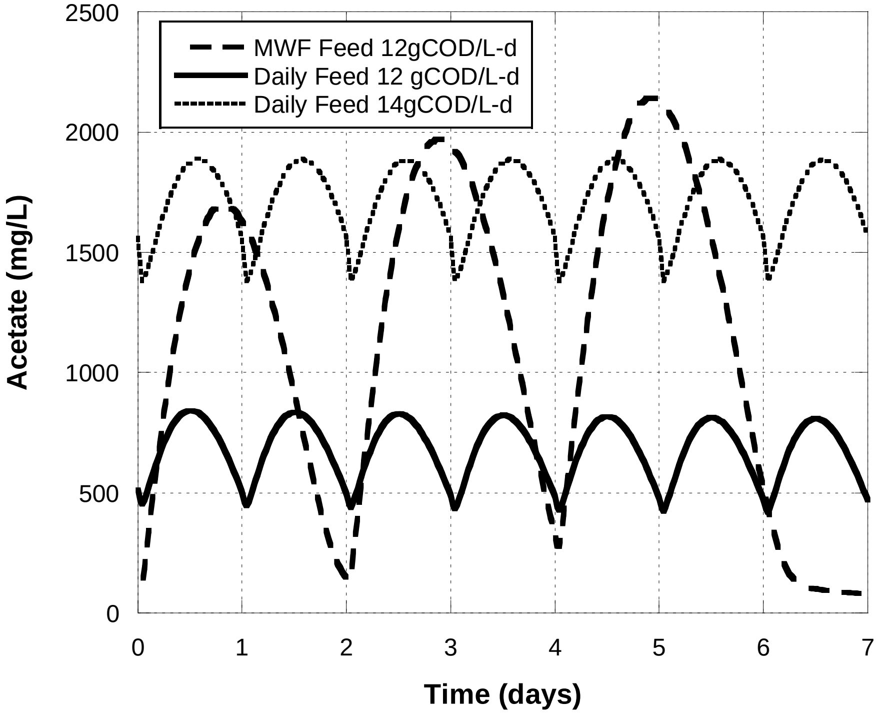


Figure 24. Simulated digester acetate concentration vs. time for daily and three batch feeds (MWF) per week at an average load of 12gCOD/L-d (10.8 d SRT) and daily batch feeds at an average load of 14gCOD/L-d (9.2 d SRT)

In addition to the 12gCOD/L-d loading rate feed frequency simulations, 14 and 15 gCOD/L-d average loading rates were simulated with daily batch feedings. For daily feeding with an average loading rate of 14gCOD/L-d, stable operation was simulated with acetate concentration under 2000 mg/L (Figure 24). Model simulations of daily batch feeds for a 15gCOD/L-d average loading rate resulted in extreme acetate concentration greater than 5000 mg/L at all times in the digester.

A number of advantages in operation and digester capacity result from more frequent feeding. Acetate concentration is lower at the same average loading rate resulting in more stable operation, as evidenced by Figure 24. A continuosly fed digester with a loading rate of

12gCOD/L-d (10.8 d SRT) has a simulated acetate concentration of 610 mg/L, demonstrating the trend of decreasing peak acetate concentration with increased feed frequency. Higher average loading rates are possible when the digester is operated with more frequent feeding, which increases biomethane production in the digester. Performance parameters such as volatile solids destruction and methane production are almost identical, all within 5%, for continuous, daily, or 3 feeds per week for the same average weekly loading. Reduced feeding frequency results in higher initial acetate concentrations and higher initial gas production rates, which raise concern about a greater potential for digester foaming.

Effect of hydrolysis rate

Solids hydrolysis rate is affected by the available surface area of the feed particles (Hobson 1987, Mshandete et al. 2006). The lab digesters were fed a milkshake-like slurry, while the pilot digesters are expected to be fed a more granular material. The dual hydrolysis model does not directly account for particle size and no particle size distribution tests were performed to compare the feeds. Thus simulations were done with reduced hydrolysis rate coefficient values from those determined from the laboratory digester studies to simulate the potential effect of increased particle size distribution in the USAFA pilot digester feed.

For the hydrolyis rate evaluation, consideration was given to the ease of applying the model and observing the results, such that the feed was assumed to be added at a constant rate and steady state conditions on digester performance could be observed and compared. Model simulations were done with the previously used rapid and slow hydrolysis rate coefficients reduced by 50%, from 1.51 and 0.16 d^{-1} to 0.76 and 0.08 d^{-1}, respectively. The loading rate and SRT for the comparison were 7gCOD/L-d and 20 days respectively with a feed concentration of 140 gCOD/L. The simulation showed that the reduced rate coeffiecents cause a decrease in volatile solids destruction efficiency, and ammonia production, which led to decreased methane and alkalinity production (Table 20). For an SRT of 20 days, a reduction of 50% to the hydrolysis rate coefficients resulted in a 13% reduction in volatile solids reduction. The effect of changes in hydrolysis rate coeffients will be more pronounced in shorter SRT systems.

Table 20. Effect of hydrolysis rate coefficients on digester performance through continuously fed steady state simulations at a 7gCOD/L-d loading and 20 day SRT. Composition of food waste is from average of food proximate analyses. Methane production rates are at the 36.7 °C digester temperature

Parameter	Units	Original Hydrolysis Rate Coefficients	50% of Original Rate Coefficients
VS Destruction Efficiency	%	69	60
Alkalinity concentration	mg/L as $CaCO_3$	11,880	10,300
Acetate concentration	mg/L	144	144
pH	-	7.7	7.6
Specific Methane Production Rate*	mL CH_4/L-d	1,900	1,660
%CH_4 in biogas	%	61	61
Effluent VS concentration**	%	3.0	3.9
NH_4-N concentration	mg /L	3,410	2,960

*based on digester volume ** based on sludge at specific gravity of 1.03

A dynamic simulation was also performed with the same reduced hydrolysis rate coefficients for the previous loading rate transition of 7 to 12 gCOD/L-d, corresponding to an SRT decrease from 18.5 to 10.8 days. The simulation results with the lower hydrolysis rate coefficients showed decreased transient acetate concentrations compared to that with the original hydrolysis coefficient values (Figure 25).

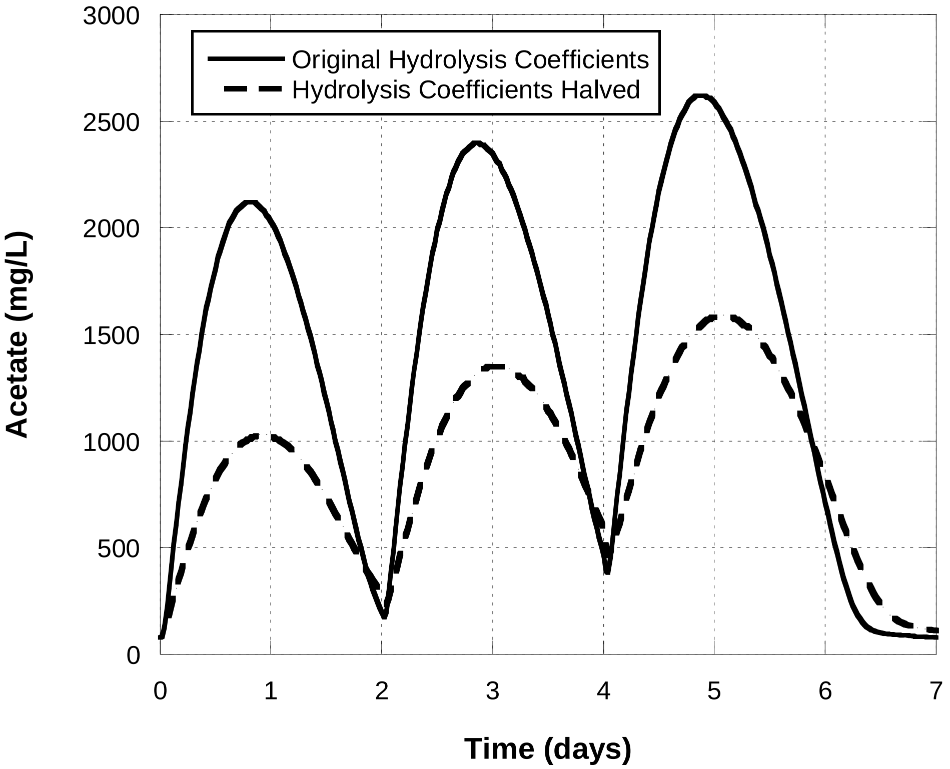


Figure 25. Simulated digester acetate concentration for ramping simulations from 7 to 12 gCOD/L-d at 5% increase/day for original hydrolysis rate coefficients (k_{rh} = 1.51 d^{-1} and k_{sh} = 0.16 d^{-1}) and halved hydrolysis rate coefficients (k_{rh} = 0.76 d^{-1} and k_{sh} = 0.08 d^{-1}).

The model predicts 82% as much biomethane will be produced over the week long interval with the lower hydrolysis coefficients. Overestimating the hydrolysis rate coefficients is a more conservative approach for evaluating digester stability because higher acetate concentrations will result from overestimated volatile solids reduction. The biomethane production will also be overestimated when the hydrolysis rate coefficients are assumed too high. For longer SRT designs, the overprediction of hydrolysis rate coefficents will have a smaller error on the volatile solids destruction and biomethane production values than for shorter SRT designs.

Effect of food waste composition

Food waste composition has a high degree of variability. The average values from food proximate analyses provided a balanced composition of protein, carbohydrate, and lipid for pilot scale simulations. To demonstrate the effect of food waste composition, continuously fed steady state simulations were developed with food wastes with a higher carbohydrate and higher lipid fraction than the average composition used in the pilot plant simulations (Table 21).

Table 21. Effect of food waste composition on digester performance for continuously fed steady state simulations at 7gCOD/L-d loading rate, 20 day SRT, and 140 gCOD/L feed concentration. Methane production rates are at the 36.7 °C digester temperature

Parameter	Units	Average of food proximate analyses (balanced)	FW-011 (lipid rich)	FW-004 (carb rich)
Protein COD Content	%	29	24	17
Carbohydrate COD Content	%	31	17	51
Lipid COD Content	%	34	53	26
Inert COD Content	%	6	6	6
VS Destruction Efficiency	%	69	67	70
Alkalinity	mg/L as $CaCO_3$	11,880	8,660	4,460
Acetate	mg/L	144	144	144
pH	-	7.7	7.6	7.2
Methane Production Rate	mL CH_4/L-d	1,900	1,910	1,890
%CH_4 in biogas	%	61	64	56
Ammonia	mg NH_4-N/L	3,410	2,510	1,330

The most noticeable differences in digester parameters are alkalinity, pH, and ammonia concentration. These are all a direct result of the protein fraction of the feed. The balanced composition has 29% protein content, whereas FW-004 and FW-011 have 17% and 24% respectively. For the reduced protein content, model simulations predicted decreased ammonia production, leading to a lower digester alkalinity concentration and pH (7.2 versus 7.6). The other significant effect that can be seen is the %CH_4 in the biogas. The lipid rich food wastes produced a higher fraction of CH_4, resulting in an increased methane production rate.

For a food waste digester receiving a variety of wastes during operation, it would be unlikely to see the effect of extremes in protein, lipid, and carb fractions as shown by these continuously fed simulations. It is still important to know the effect of waste composition for less frequent occasions of prolonged exposure to an extreme composition. The protein content in particular is critical for maintaining sufficient digester alkalinity, so extended periods of protein deficient feed could be cause for concern.

Effect of endogenous decay rate

The default ADM1 provides a first order decay rate constant to be applied to all biomass terms as an initial estimate. Batstone et al. (2002) acknowledge that in many cases the decay rate, particularly for acetoclastic methanogens, may be as much as double this default value. Starvation simulations were performed to examine the effect of decay rate on digester response to a period of no feeding, followed by a return to regular feeding.

A two week long period of starvation was simulated at the original decay rate for acetoclastic methanogens (0.02 d^{-1}), and twice the decay rate (0.04 d^{-1}). These were followed by a return to the three times per week feeding at 12gCOD/L-d (10.8 d SRT). The concentration of acetoclastic methanogens was approximately 22% lower after the two week starvation period when the decay rate was doubled (Figure 26). The rate at which the digester could utilize acetate was therefore reduced, and when the loading rate was returned to 12gCOD/L-d (10.8 d SRT) the digester acetate concentration reached much higher transient concentrations at levels of concern for stable operation (Figure 27).

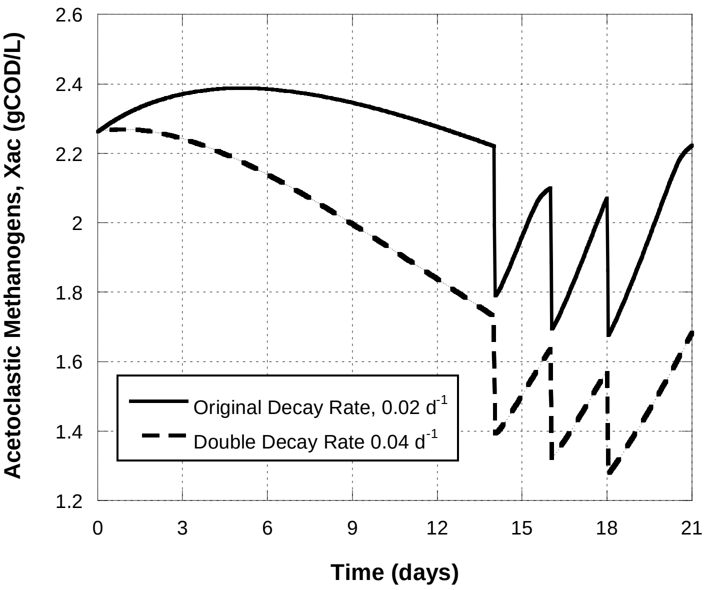


Figure 26. Simulated digester acetoclastic methanogen population vs. time with default and doubled first order decay rates for Xac over a two week starvation period and one week of 12gCOD/L-d (10.8 d SRT) at three feed events per week.

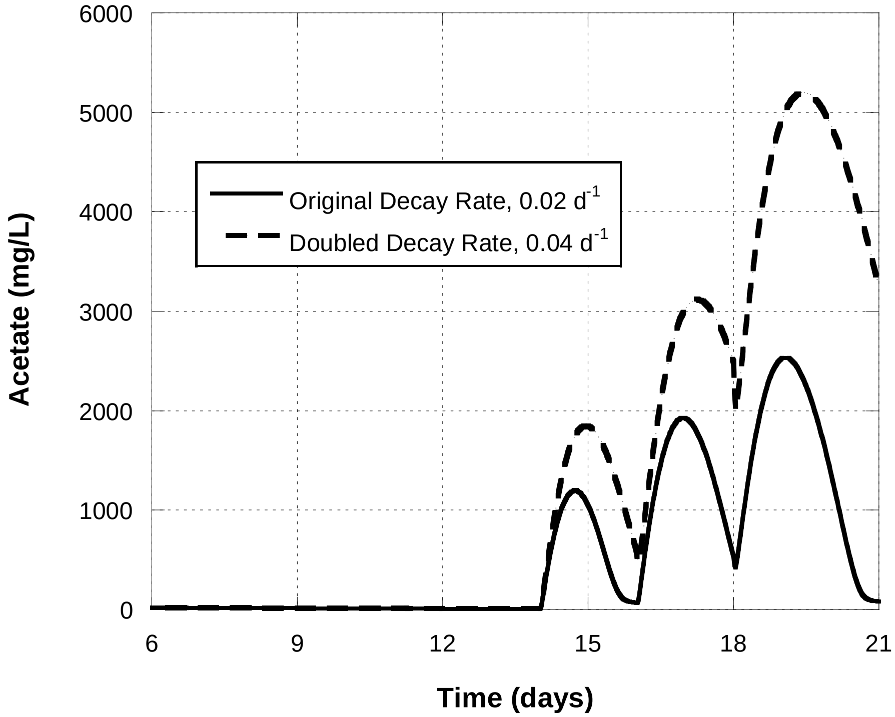


Figure 27. Simulated digester acetate concentration vs. time with default and doubled first order decay rates for Xac over a two week starvation period and one week of 12gCOD/L-d (10.8 d SRT) at three feed events per week.

The original decay rate of 0.02 d^{-1} fit the methane production data from lab-scale digesters, so there is no apparent reason to assume a higher decay rate. It is possible though that the fitting could be achieved with a greater decay rate in conjunction with a greater substrate utilization rate. Conklin et al. (2006) found a k_d of 0.006 ± 0.003 d^{-1} for a *Methanosaeta* enriched reactor, suggesting the decay rate is not likely higher than the default value of 0.02 d^{-1}. Therefore, the model results with the default ADM1 decay rates were assumed to adequately predict the effects of lower loadings or starvation. The effect of decay rate is clearly significant when recovering from periods of starvation. Additional data from starvation testing on the pilot digester will help to discern the decay rate of the acetoclastic methanogen population.

Comparison of Model Predictions for Food Waste Digestion to Municipal Sludge Digestion

Lastly, simulations were performed to compare anaerobic digestion performance for food waste and municipal wastewater sludge treatment. A digester SRT of 20 days and a daily loading rate of 7gCOD/L-d were used. The assumed TS and COD concentrations of the food waste and municipal sludge for these simulations are 9 % and 140 gCOD/L and 6.4% and 80.4 gCOD/L, respectively. The average loading rate for the municipal digester was 4 gCOD/L-d. The dual hydrolysis model has been previously incorporated into the ADM1 by Straub (2008) for municipal sludge digestion. The sludge composition and hydrolysis rate coefficients from Straub were used to simulate a continuously fed municipal digester (Table 22).

Table 22. ADM1 composition and kinetic parameters used to simulate municipal sludge digestion from Straub (2008)

Parameter	Value	Units
$f_{sI,xc}$	0.01	gS_I/gX_c
$f_{xI,xc}$	0.23	gX_I/gX_c
$f_{ch,xc}$	0.20	gX_{ch}/gX_c
$f_{pr,xc}$	0.40	gX_{pr}/gX_c
$f_{li,xc}$	0.16	gX_{li}/gX_c
$f_{rh,xc}$	0.33	gX_{rh}/gX_c
$f_{sh,xc}$	0.43	gX_{sh}/gX_c
$k_{hyd,rh}$	2.2	d^{-1}
$k_{hyd,sh}$	0.25	d^{-1}

The hydrolysis rate coefficients for rapid and slowly hydrolysable municipal waste found by Straub are approximately 30% greater than the food waste hydrolysis coefficients. However, the inert fraction is higher for municipal sludge compared to food waste. For a continuously fed simulation, volatile solids destruction, methane production rate and % CH_4 are all higher for food waste than municipal sludge at the same SRT (Table 23).

Table 23. Comparison of food waste digestion to municipal sludge digestion by continuously fed steady state simulation at 7gCOD/L-d and a 20 day SRT. Composition of food waste is from average of food proximate analyses. Methane production rates are at the 36.7 °C digester temperature

Parameter	Units	Food Waste Digester	Municipal Sludge Digester
VS Destruction Efficiency	%	69	60
Alkalinity	mg/L as $CaCO_3$	11,880	7,600
Acetate	mg/L	144	144
pH	-	7.7	7.4
Methane Production Rate*	mL CH_4/L-d	1,900	940
Digester VS concentration**	%	3.0	2.1
Digester TS concentration**	%	3.7	3.0
%CH_4 in biogas	%	61	59
Ammonia	mg NH_4-N/L	3,410	2,210

*based on digester volume ** based on sludge at specific gravity of 1.03

The low inert fraction of the food wastes results in higher volatile solids destruction efficiency for the same SRT, and therefore greater biomethane production per unit of COD fed. Differences in digester alkalinity, pH, and ammonia are derived from the difference in composition.

A higher volatile solids destruction efficiency was also found for food waste vs. municipal sludge in a study done at the East Bay Utility District (USEPA 2008). Results for mesophilic digestion of food waste at a 15 day SRT were compared to mesophilic municipal wastewater solids digestion with a 15 day SRT. For the 15 day SRT, 74% volatile solids destruction efficiency was found for food waste vs. 57% for municipal sludge (Table 24).

Table 24. Comparison of mesophilic food waste digestion and municipal wastewater solids digestion data at a 15 day SRT from USEPA (2008).

Parameter	Units	Food Waste Digestion	Municipal Sludge Digestion
SRT	days	15	15
VS Destruction Efficiency	%	74	57
COD Loading, Feed	gCOD/L-d	6.7	3.1
%CH_4 in biogas	%	64	63
Methane Production Rate*	mL CH_4/L-d	2,300	940

*based on digester volume

Summary of findings from calibrated ADM1 simulations

The pilot plant simulations performed using the calibrated ADM1 have been used to evaluate numerous operating conditions and model parameters. The model has shown that the pilot digester can operate under stable conditions when fed three times per week at 7 and 12 gCOD/L-d average loading rates. Model simulations to investigate loading transition scenarios indicated that for a constant feed concentration, the time it took to reach the new load and the magnitude of the new load were important. The effect of feeding frequency was found to be a very important parameter effecting digester loading capacity and stability. Comparison on simulations with daily vs. three batch feedings per week showed that more frequent feeding increases digester stability for the same average daily loading rate, which may allow for stable operation at higher average daily loading rates. Though not a topic within the capability of the modeling, the less frequent feeding with higher instantaneous COD loadings could have a greater potential for digester foaming than with more frequent feeding. The modified ADM1 model could account for the effect of hydrolysis rate coefficients and food waste composition on digester performance when these parameters were varied.

The results from the model simulations have created a basis for guiding pilot plant operation during the optimization and challenge phases. When being fed three times per week, the pilot digesters should not be fed higher than 12gCOD/L-d (10.8 d SRT). If the feeding strategy is changed to daily feeding, or the concentration of the feed is increased, a higher loading rate can be achieved during the optimization phase. When attempting to determine the maximum loading rate during the optimization phase it is recommended that daily feeding is employed. This will allow stable operation at higher loading rates than feeding three times per week, and will therefore maximize biomethane gas production. Model simulations show that the pilot plant can withstand a two month reduced loading period, and the ability to do so is favored more for operation at longer SRTs.

During the early portion of the pilot plant study the model will require further calibration. The main variables that will need to be investigated are the hydrolysis rate coefficients, as the feed particle size will be different for the pilot plant than for the lab digesters used for the original calibration. Some data collection is expected during the pilot study to account for the feed composition, which can be used for additional calibration.

SUMMARY and CONCLUSIONS

ADM1 was modified and applied for simulating anaerobic digestion performance when treating food waste from a military installation. The model was incorporated for use in Mathcad15, a commonly available and user friendly software package. Model changes specific to the food waste application were the incorporation of a dual hydrolysis kinetic model and the adjustment of the carbon and nitrogen content of the amino acid component from protein hydrolysis. Additional changes to the default ADM 1, which provided stable model runs under transient conditions were the incorporation of a continuous pH inhibition model and the use of ammonia production from amino acid degradation to predict the bicarbonate alkalinity concentration for use in the pH calculation. Successful model calibration to food waste anaerobic degradation was achieved using long term laboratory digesters and batch bottle tests. Hydrolysis kinetic rate coefficients were determine for readily and slowly biodegradable particulate COD in the food waste.

Model simulations with the calibrated ADM1 were used to indicate operating conditions that can lead to digester instability and evaluate digester performance. The model can be used to evaluate a wide range of transient feeding conditions to provide information on changes in digester VFA concentrations, pH, biomethane production rates, and COD conversion rates to biomethane energy. The calibrated model has been shown to have value as a predictive tool for evaluating pilot plant operational conditions. The following conclusions were drawn from the calibrated ADM1 simulations that have implications for the pilot plant study:

1. Stable operation is possible at average loading rates of 7 and 12 gCOD/L-d for three batch feeds (MWF) per week.
2. Daily batch feeding is more stable than three batch feeds per week, and a higher average COD loading rate can be used.
3. Transition of loading from 7 to 12 gCOD/L-d required a 30 day time period for stable operation with daily incremental increases.
4. The hydrolysis rate is a critical parameter for evaluating digester volatile solids reduction, total methane production, and transient loading VFA concentrations. Assuming higher hydrolysis rates provides a more conservative approach to evaluating digester stability.

5. The relative quantities of lipids and proteins in the food waste composition have a noticeable effect on digester performance and stability with regard to methane production and alkalinity and ammonia production, respectively.
6. At the same SRT, the volatile solids reduction efficiency for food waste digestion is higher than that for municipal waste sludge digestion.

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APPENDIX A: PETERSEN MATRICES FOR DEFAULT ADM1

The following two tables are presented on the next pages:

Table A-1. Petersen matrix for the soluble variables in the default ADM1

Table A-2. Petersen matrix for the particulate variables in the default ADM1

Component →	**i**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Rate (ρ_j, g COD L^{-1} d^{-1})**
j	**Process ↓**	S_{su}	S_{aa}	S_{fa}	S_{va}	S_{bu}	S_{pro}	S_{ac}	S_{h2}	S_{ch4}	S_{IC}	S_{IN}	S_I	
1	Disintegration												$f_{sI,xc}$	$k_{dis}X_c$
2	Hydrolysis Carbohydrates	1												$k_{hyd,ch}X_{ch}$
3	Hydrolysis of Proteins		1											$k_{hyd,pr}X_{pr}$
4	Hydrolysis of Lipids	$1-f_{fa,li}$		$f_{fa,li}$										$k_{hyd,li}X_{li}$
5	Uptake of Sugars	-1				$(1-Y_{su})\ f_{bu,su}$	$(1-Y_{su})\ f_{pro,su}$	$(1-Y_{su})\ f_{ac,su}$	$(1-Y_{su})\ f_{h2,su}$		$-\sum_{i=1-9,11-24} C_i\, v_{i,5}$	$-(Y_{su})\ N_{bac}$		$k_{m,su}\frac{S_{su}}{K_S+S_{su}}X_{su}I_1$
6	Uptake of Amino Acids		-1		$(1-Y_{aa})\ f_{va,aa}$	$(1-Y_{aa})\ f_{bu,aa}$	$(1-Y_{aa})\ f_{pro,aa}$	$(1-Y_{aa})\ f_{ac,aa}$	$(1-Y_{aa})\ f_{h2,aa}$		$-\sum_{i=1-9,11-24} C_i\, v_{i,6}$	$N_{aa}-(Y_{aa})\ N_{bac}$		$k_{m,aa}\frac{S_{aa}}{K_S+S_{aa}}X_{aa}I_1$
7	Uptake of LCFA			-1				$(1-Y_{fa})\ 0.7$	$(1-Y_{fa})\ 0.3$			$-(Y_{fa})\ N_{bac}$		$k_{m,fa}\frac{S_{fa}}{K_S+S_{fa}}X_{fa}I_2$
8	Uptake of Valerate				-1		$(1-Y_{c4})\ 0.54$	$(1-Y_{c4})\ 0.31$	$(1-Y_{c4})\ 0.15$			$-(Y_{c4})\ N_{bac}$		$k_{m,c4}\frac{S_{va}}{K_S+S_{va}}X_{c4}\frac{1}{1+S_{bu}/S_{va}}I_2$
9	Uptake of Butyrate					-1		$(1-Y_{c4})\ 0.8$	$(1-Y_{c4})\ 0.2$			$-(Y_{c4})\ N_{bac}$		$k_{m,c4}\frac{S_{bu}}{K_S+S_{bu}}X_{c4}\frac{1}{1+S_{va}/S_{bu}}I_2$
10	Uptake of Propionate						-1	$(1-Y_{pro})\ 0.57$	$(1-Y_{pro})\ 0.43$		$-\sum_{i=1-9,11-24} C_i\, v_{i,10}$	$-(Y_{pro})\ N_{bac}$		$k_{m,pro}\frac{S_{pro}}{K_S+S_{pro}}X_{pro}I_2$
11	Uptake of Acetate							-1		$(1-Y_{ac})$	$-\sum_{i=1-9,11-24} C_i\, v_{i,11}$	$-(Y_{ac})\ N_{bac}$		$k_{m,ac}\frac{S_{ac}}{K_S+S_{ac}}X_{ac}I_3$
12	Uptake of Hydrogen								-1	$(1-Y_{h2})$	$-\sum_{i=1-9,11-24} C_i\, v_{i,12}$	$-(Y_{h2})\ N_{bac}$		$k_{m,h2}\frac{S_{h2}}{K_S+S_{h2}}X_{h2}I_1$
13	Decay of X_{su}													$k_{dec,xsu}X_{su}$
14	Decay of X_{aa}													$k_{dec,xaa}X_{aa}$
15	Decay of X_{fa}													$k_{dec,xfa}X_{fa}$
16	Decay of X_{c4}													$k_{dec,xc4}X_{c4}$
17	Decay of X_{pro}													$k_{dec,xpro}X_{pro}$
18	Decay of X_{ac}													$k_{dec,xac}X_{ac}$
19	Decay of X_{h2}													$k_{dec,xh2}X_{h2}$
		Monosaccharides (g COD L^{-1})	Amino Acids (g COD L^{-1})	Long Chain Fatty Acids (g COD L^{-1})	Total Valerate (g COD L^{-1})	Total Butyrate (g COD L^{-1})	Total Propionate (g COD L^{-1})	Total Acetate (g COD L^{-1})	Hydrogen Gas (g COD L^{-1})	Methane Gas (g COD L^{-1})	Inorganic Carbon (mol L^{-1})	Inorganic Nitrogen (mol L^{-1})	Soluble Inerts (g COD L^{-1})	Inhibition Factors: $I_1 = I_{pH}I_{IN,lim}$ $I_2 = I_{pH}I_{IN,lim}I_{h2}$ $I_3 = I_{pH}I_{IN,lim}I_{NH3,Xac}$

Component →	i	13	14	15	16	17	18	19	20	21	22	23	24	Rate (ρ_j, g COD L^{-1} d^{-1})
j	**Process ↓**	X_c	X_{ch}	X_{pr}	X_{li}	X_{su}	X_{aa}	X_{fa}	X_{c4}	X_{pro}	X_{ac}	X_{h2}	X_I	
1	Disintegration	-1	$f_{ch,xc}$	$f_{pr,xc}$	$f_{li,xc}$								$f_{xi,xc}$	$k_{dis}X_c$
2	Hydrolysis Carbohydrates		-1											$k_{hyd,ch}X_{ch}$
3	Hydrolysis of Proteins			-1										$k_{hyd,pr}X_{pr}$
4	Hydrolysis of Lipids				-1									$k_{hyd,li}X_{li}$
5	Uptake of Sugars					Y_{su}								$k_{m,su}\frac{S_{su}}{K_S+S_{su}}X_{su}I_1$
6	Uptake of Amino Acids						Y_{aa}							$k_{m,aa}\frac{S_{aa}}{K_S+S_{aa}}X_{aa}I_1$
7	Uptake of LCFA							Y_{fa}						$k_{m,fa}\frac{S_{fa}}{K_S+S_{fa}}X_{fa}I_2$
8	Uptake of Valerate								Y_{c4}					$k_{m,c4}\frac{S_{va}}{K_S+S_{va}}X_{c4}\frac{1}{1+S_{bu}/S_{va}}I_2$
9	Uptake of Butyrate								Y_{c4}					$k_{m,c4}\frac{S_{bu}}{K_S+S_{bu}}X_{c4}\frac{1}{1+S_{va}/S_{bu}}I_2$
10	Uptake of Propionate									Y_{pro}				$k_{m,pro}\frac{S_{pro}}{K_S+S_{pro}}X_{pro}I_2$
11	Uptake of Acetate										Y_{ac}			$k_{m,ac}\frac{S_{ac}}{K_S+S_{ac}}X_{ac}I_3$
12	Uptake of Hydrogen											Y_{h2}		$k_{m,h2}\frac{S_{h2}}{K_S+S_{h2}}X_{h2}I_1$
13	Decay of X_{su}	1				-1								$k_{dec,xsu}X_{su}$
14	Decay of X_{aa}	1					-1							$k_{dec,xaa}X_{aa}$
15	Decay of X_{fa}	1						-1						$k_{dec,xfa}X_{fa}$
16	Decay of X_{c4}	1							-1					$k_{dec,xc4}X_{c4}$
17	Decay of X_{pro}	1								-1				$k_{dec,xpro}X_{pro}$
18	Decay of X_{ac}	1									-1			$k_{dec,xac}X_{ac}$
19	Decay of X_{h2}	1										-1		$k_{dec,xh2}X_{h2}$
		Composites (g COD L^{-1})	Carbohydrates (g COD L^{-1})	Proteins (g COD L^{-1})	Lipids (g COD L^{-1})	Sugar Degraders (g COD L^{-1})	Amino Acid Degraders (g COD L^{-1})	LCFA Degraders (g COD L^{-1})	Valerate and Butyrate Degraders (g COD L^{-1})	Propionate Degraders (g COD L^{-1})	Acetate Degraders (g COD L^{-1})	Hydrogen Degraders (g COD L^{-1})	Particulate Inerts (g COD L^{-1})	Inhibition Factors: $I_1 = I_{pH}I_{IN,lim}$ $I_2 = I_{pH}I_{IN,lim}I_{h2}$ $I_3 = I_{pH}I_{IN,lim}I_{NH3,Xac}$

APPENDIX B: ADM1 SUGGESTED MODEL PARAMETERS

Table B-1. ADM1 suggested kinetic parameter values

Kinetic Parameter	Value at 35°C	Units
k_{dec_all}	0.02	d^{-1}
k_{m_su}	30	d^{-1}
K_{S_su}	0.5	gCOD/L
Y_{su}	0.1	$gCOD_X/gCOD_S$
k_{m_aa}	50	d^{-1}
K_{S_aa}	0.3	gCOD/L
Y_{aa}	0.08	$gCOD_X/gCOD_S$
k_{m_fa}	6	d^{-1}
K_{S_fa}	0.4	gCOD/L
Y_{fa}	0.06	$gCOD_X/gCOD_S$
k_{m_c4}	20	d^{-1}
K_{S_c4}	0.2	gCOD/L
Y_{c4}	0.06	$gCOD_X/gCOD_S$
k_{m_pro}	13	d^{-1}
K_{S_pro}	0.1	gCOD/L
Y_{pro}	0.04	$gCOD_X/gCOD_S$
k_{m_ac}	8	d^{-1}
K_{S_ac}	0.15	gCOD/L
Y_{ac}	0.05	$gCOD_X/gCOD_S$
k_{m_h2}	35	d^{-1}
K_{S_h2}	7.00E-06	gCOD/L
Y_{h2}	0.06	$gCOD_X/gCOD_S$

Table B-2. ADM1 suggested values for carbon and nitrogen content of model variables

C_i or N_i	C or N Content (mole C or N/gCOD$_i$)
C_{ch}	0.0313
C_{li}	0.022
C_{su}	0.0313
C_{fa}	0.0217
C_{va}	0.024
C_{bu}	0.025
C_{pro}	0.0268
C_{ac}	0.0313
C_{h2}	0
C_{ch4}	0.0156
C_{IC}	1
C_{IN}	0
C_{biom}	0.0313
N_{bac}	0.00625
N_{aa}	0.007

Table B-3. ADM1 suggested stoichiometric parameters

Variable	Fraction i from j
f_{fa_li}	0.95
f_{h2_su}	0.19
f_{bu_su}	0.13
f_{pro_su}	0.27
f_{ac_su}	0.41
f_{h2_aa}	0.06
f_{va_aa}	0.23
f_{bu_aa}	0.26
f_{pro_aa}	0.05
f_{ac_aa}	0.4

APPENDIX C: ADM1 LIQUID/GAS EQUATIONS

Gas transfer rate equations:

$$\rho_{T,H_2} = k_L a\left(S_{liq,H_2} - 16K_{H,H_2} p_{gas,H_2}\right) \tag{32}$$

$$\rho_{T,CH_4} = k_L a\left(S_{liq,CH_4} - 64K_{H,CH_4} p_{gas,CH_4}\right) \tag{33}$$

$$\rho_{T,CO_2} = k_L a\left(S_{liq,CO_2} - K_{H,CO_2} p_{gas,CO_2}\right) \tag{34}$$

where:

$\rho_{T,i}$ = transfer rate of gas I (g COD L^{-1} d^{-1} for H_2 and CH_4 and mol L^{-1} d^{-1} for CO_2)

k_La = overall mass transfer coefficient (d^{-1})

$S_{liq,i}$ = the liquid concentration of i (gCOD L^{-1} for H_2 and CH_4 and mol L^{-1} for CO_2)

$K_{H,i}$ = Henry's constant for gas i (M_{liq} bar_{gas}^{-1})

$p_{gas,i}$ = partial pressure of gas i (bar)

$$p_{gas,H_2} = S_{gas,H_2}\, RT/16 \tag{35}$$

$$p_{gas,CH_4} = S_{gas,CH_4}\, RT/64 \tag{36}$$

$$p_{gas,CO_2} = S_{gas,CO_2} RT \tag{37}$$

where:

$S_{gas,i}$ = gas i concentration (g COD L^{-1} for H_2 and CH_4 and M for CO_2)

R = universal gas constant (L bar mol^{-1} K^{-1})

T = temperature (K)

$$\frac{dS_{gas,i}}{dt} = -\frac{S_{gas,i} q_{gas}}{V_{gas}} + \rho_{T,i}\frac{V_{liq}}{V_{gas}} \tag{38}$$

where:

q_{gas} = the gas flow rate, L_{gas}/d, and is defined by the following equation:

$$q_{gas} = \frac{RT}{\sum_i p_{gas,i}} V_{liq}\left(\frac{\rho_{T,H_2}}{16} + \frac{\rho_{T,CH_4}}{64} + \rho_{T,CO_2}\right) \tag{39}$$

APPENDIX D: PETERSEN MATRICES FOR MODIFIED ADM1

The following two tables are presented on the next pages:

Table D-1. Petersen matrix for the soluble variables in the modified ADM1*

Table D-2. Petersen matrix for the particulate variables in the modified ADM1*

*Differences between modified and default ADM1 Petersen Matrices are highlighted in gray.

Component →	i	1	2	3	4	5	6	7	8	9	10	11	12	Rate (ρ_j, g COD L^{-1} d^{-1})
j	Process ↓	S_{su}	S_{aa}	S_{fa}	S_{va}	S_{bu}	S_{pro}	S_{ac}	S_{h2}	S_{ch4}	S_{IC}	S_{IN}	S_I	
1	Partitioning of Composite												$f_{sI,xc}$	k_{inst}
2	Preexisitng Rapid Hydrolysis	$f_{ch,rh0}$	$f_{pr,rh0}$	$f_{li,rh0}$										$k_{hyd,rh0}X_{rh0}$
3	Preexisitng Slow Hydrolysis	$f_{ch,sh0}$	$f_{pr,sh0}$	$f_{li,sh0}$										$k_{hyd,sh0}X_{sh0}$
4	Rapid Hydrolysis	$f_{ch,rh}$	$f_{pr,rh}$	$f_{li,rh}$										$k_{hyd,rh}X_{rh}$
5	Slow Hydrolysis	$f_{ch,sh}$	$f_{pr,sh}$	$f_{li,sh}$										$k_{hyd,sh}X_{sh}$
6	Recycling Biomass Decay	$f_{ch,ed}$	$f_{pr,ed}$	$f_{pr,ed}$										$k_{inst}X_{ed}$
7	Uptake of Sugars	-1				$(1-Y_{su})\ f_{bu,su}$	$(1-Y_{su})\ f_{pro,su}$	$(1-Y_{su})\ f_{ac,su}$	$(1-Y_{su})\ f_{h2,su}$		$-\sum_{i=1-9,11-26} C_i\, v_{i,5}$	$-(Y_{su})\ N_{bac}$		$k_{m,su}\frac{S_{su}}{K_S+S_{su}}X_{su}$
8	Uptake of Amino Acids		-1		$(1-Y_{aa})\ f_{va,aa}$	$(1-Y_{aa})\ f_{bu,aa}$	$(1-Y_{aa})\ f_{pro,aa}$	$(1-Y_{aa})\ f_{ac,aa}$	$(1-Y_{aa})\ f_{h2,aa}$		$-\sum_{i=1-9,11-26} C_i\, v_{i,6}$	$N_{aa} - (Y_{aa})\ N_{bac}$		$k_{m,aa}\frac{S_{aa}}{K_S+S_{aa}}X_{aa}$
9	Uptake of LCFA			-1				$(1-Y_{fa})$ 0.7	$(1-Y_{fa})$ 0.3			$-(Y_{fa})\ N_{bac}$		$k_{m,fa}\frac{S_{fa}}{K_S+S_{fa}}X_{fa}$
10	Uptake of Valerate				-1		$(1-Y_{c4})$ 0.54	$(1-Y_{c4})$ 0.31	$(1-Y_{c4})$ 0.15			$-(Y_{c4})\ N_{bac}$		$k_{m,c4}\frac{S_{va}}{K_S+S_{va}}X_{c4}\frac{1}{1+S_{bu}/S_{va}}$
11	Uptake of Butyrate					-1		$(1-Y_{c4})$ 0.8	$(1-Y_{c4})$ 0.2			$-(Y_{c4})\ N_{bac}$		$k_{m,c4}\frac{S_{bu}}{K_S+S_{bu}}X_{c4}\frac{1}{1+S_{va}/S_{bu}}$
12	Uptake of Propionate						-1	$(1-Y_{pro})$ 0.57	$(1-Y_{pro})$ 0.43		$-\sum_{i=1-9,11-26} C_i\, v_{i,10}$	$-(Y_{pro})\ N_{bac}$		$k_{m,pro}\frac{S_{pro}}{K_S+S_{pro}}X_{pro}$
13	Uptake of Acetate							-1		$(1-Y_{ac})$	$-\sum_{i=1-9,11-26} C_i\, v_{i,11}$	$-(Y_{ac})\ N_{bac}$		$k_{m,ac}\frac{S_{ac}}{K_S+S_{ac}}X_{ac}I_{pH}$
14	Uptake of Hydrogen								-1	$(1-Y_{h2})$	$-\sum_{i=1-9,11-26} C_i\, v_{i,12}$	$-(Y_{h2})\ N_{bac}$		$k_{m,h2}\frac{S_{h2}}{K_S+S_{h2}}X_{h2}$
15	Decay of X_{su}													$k_{dec,xsu}X_{su}$
16	Decay of X_{aa}													$k_{dec,xaa}X_{aa}$
17	Decay of X_{fa}													$k_{dec,xfa}X_{fa}$
18	Decay of X_{c4}													$k_{dec,xc4}X_{c4}$
19	Decay of X_{pro}													$k_{dec,xpro}X_{pro}$
20	Decay of X_{ac}													$k_{dec,xac}X_{ac}$
21	Decay of X_{h2}													$k_{dec,xh2}X_{h2}$
		Monosaccharides (g COD L^{-1})	Amino Acids (g COD L^{-1})	Long Chain Fatty Acids (g COD L^{-1})	Total Valerate (g COD L^{-1})	Total Butyrate (g COD L^{-1})	Total Propionate (g COD L^{-1})	Total Acetate (g COD L^{-1})	Hydrogen Gas (g COD L^{-1})	Methane Gas (g COD L^{-1})	Inorganic Carbon (mol L^{-1})	Inorganic Nitrogen (mol L^{-1})	Soluble Inerts (g COD L^{-1})	Inhibition Factors: I_{pH}: For acetoclastic methanogens only

Component →	i	13	14	15	16	17	17	19	20	21	22	23	24	25	26	Rate (ρ_j, g COD L^{-1} d^{-1})
j	**Process ↓**	X_c	X_{ed}	X_{rh0}	X_{sh0}	X_{rh}	X_{sh}	X_{su}	X_{aa}	X_{fa}	X_{c4}	X_{pro}	X_{ac}	X_{h2}	X_I	
1	Partitioning of Composite	-1				$f_{rh,xc}$	$f_{sh,xc}$								$f_{xI,xc}$	k_{inst}
2	Preexisitng Rapid Hydrolysis			-1												$k_{hyd,rh0}X_{rh0}$
3	Preexisitng Slow Hydrolysis				-1											$k_{hyd,sh0}X_{sh0}$
4	Rapid Hydrolysis					-1										$k_{hyd,rh}X_{rh}$
5	Slow Hydrolysis						-1									$k_{hyd,sh}X_{sh}$
6	Recycling Biomass Decay		-1												$f_{xI,ed}$	$k_{inst}X_{ed}$
7	Uptake of Sugars							Y_{su}								$k_{m,su}\frac{S_{su}}{K_S+S_{su}}X_{su}$
8	Uptake of Amino Acids								Y_{aa}							$k_{m,aa}\frac{S_{aa}}{K_S+S_{aa}}X_{aa}$
9	Uptake of LCFA									Y_{fa}						$k_{m,fa}\frac{S_{fa}}{K_S+S_{fa}}X_{fa}$
10	Uptake of Valerate										Y_{c4}					$k_{m,c4}\frac{S_{va}}{K_S+S_{va}}X_{c4}\frac{1}{1+S_{bu}/S_{va}}$
11	Uptake of Butyrate										Y_{c4}					$k_{m,c4}\frac{S_{bu}}{K_S+S_{bu}}X_{c4}\frac{1}{1+S_{va}/S_{bu}}$
12	Uptake of Propionate											Y_{pro}				$k_{m,pro}\frac{S_{pro}}{K_S+S_{pro}}X_{pro}$
13	Uptake of Acetate												Y_{ac}			$k_{m,ac}\frac{S_{ac}}{K_S+S_{ac}}X_{ac}I_{pH}$
14	Uptake of Hydrogen													Y_{h2}		$k_{m,h2}\frac{S_{h2}}{K_S+S_{h2}}X_{h2}$
15	Decay of X_{su}		1					-1								$k_{dec,xsu}X_{su}$
16	Decay of X_{aa}		1						-1							$k_{dec,xaa}X_{aa}$
17	Decay of X_{fa}		1							-1						$k_{dec,xfa}X_{fa}$
18	Decay of X_{c4}		1								-1					$k_{dec,xc4}X_{c4}$
19	Decay of X_{pro}		1									-1				$k_{dec,xpro}X_{pro}$
20	Decay of X_{ac}		1										-1			$k_{dec,xac}X_{ac}$
21	Decay of X_{h2}		1											-1		$k_{dec,xh2}X_{h2}$
		Composites (g COD L^{-1})	Endogenous Decay (g COD L^{-1})	Preexisting Rapidly Hydrolyzable Composite (g COD L^{-1})	Preexisting Slowly Hydrolyzable Composite (g COD L^{-1})	Rapidly Hydrolyzable Composite (g COD L^{-1})	Slowly Hydrolyzable Composite (g COD L^{-1})	Sugar Degraders (g COD L^{-1})	Amino Acid Degraders (g COD L^{-1})	LCFA Degraders (g COD L^{-1})	Valerate and Butyrate Degraders (g COD L^{-1})	Propionate Degraders (g COD L^{-1})	Acetate Degraders (g COD L^{-1})	Hydrogen Degraders (g COD L^{-1})	Particulate Inerts (g COD L^{-1})	Inhibition Factors: I_{pH}: For acetoclastic methanogens only

APPENDIX E: FOOD PROXIMATE ANALYSES FOR USAFA FOOD WASTES

The following two tables are presented on the next pages:

Table E-1. Raw food proximate analyses for USAFA food wastes

Table E-2. USAFA food waste description on dry weight and COD basis

Sample #	Meal	Description	Calories (per 100g)	VS (%)	TS (%)	VS/TS	TP (mg/100g)	TKN (% of wet weight)	Moisture (%)	Protein (% of wet weight)	Fat (% of wet weight)	Ash (% of wet weight)	Carbs (% of wet weight)
FW-001	Breakfast	Vegetable matter (greens and orange), possibly eggs, starches	111	22.6	24	0.94	256	1.67	76.00	10.40	4.1	1.4	8.1
FW-002	Lunch	Cheese, bits of paper, black peels from beans or grapes, yellow clumps, meat	117	23.9	25.7	0.93	80.3	0.95	74.30	5.90	3.6	1	15.2
FW-003	Dinner	Rice, meat, vegetable matter	106	30.2	30.7	0.98	58.8	0.85	69.30	5.30	1.9	0.7	17
FW-004	Breakfast	Vegetable matter, meat, dairy and possibly eggs, strings of plastic	90	18.8	19.9	0.94	31.5	0.50	80.10	3.10	2.5	0.6	13.7
FW-005	Lunch	Yellow and white matter (appears to be starch or dairy) with pieces of meat, low moisture content	312	34.1	62.3	0.55	188	2.32	37.70	14.50	13.4	1.1	33.3
FW-006	Dinner	High moisture content, vegetable matter (green, orange and red), small pieces of meat	96	14.2	22.5	0.63	40	0.55	77.50	3.40	1.5	0.5	17.1
FW-007	Breakfast	Mostly meat, low moisture content, strips of plastic, orange peel, eggs or starches	286	32	59.7	0.54	108	3.26	40.30	20.40	10	0.7	28.6
FW-008	Lunch	Mostly yellow starchy material (low moisture) with bits of meat, yellow and black vegetable matter	277	30.3	55.7	0.54	130	2.40	44.30	15.00	11.6	1	28.1
FW-009	Dinner	Meat, vegetable matter (yellow, orange green and black), citrus peel, strips of plastic	158	30.8	31.3	0.98	62.7	1.25	68.70	7.80	7.1	0.7	15.7
FW-010	Breakfast	Mostly meat, medium moisture content, vegetable matter (red, green, yellow and white), strips of plastic	65	15.6	16.1	0.97	30	0.35	83.90	2.20	0.6	0.6	12.7
FW-011	Lunch	Yellow starch or dairy, medium moisture content, vegetable matter (green, red, orange and black), bits of paper, possible grape peel material	137	23.2	24.7	0.94	80	1.15	75.3	7.2	8.6	1.1	7.8
FW-012	Dinner	Mostly white meat, low moisture content, Vegetal matter (green, yellow, orange and white)	122	23	23.4	0.98	76.5	2	76.6	12.7	6.1	0.6	4
FW-013	Breakfast	Wet brown material with pieces of pink meat, Vegetable matter (red, green and white), possible grape peel material, some of the material has a blue-green discoloration	159	30.1	31.9	0.94	87.4	2.96	68.1	18.5	7.8	2	3.6
FW-014	Lunch	High moisture content, pink meat, nuts, peel material, vegetable matter (red, yellow, white, green and black)	125	26.4	26.8	0.99	97.5	2.52	73.2	15.8	4.6	1.2	5.2
FW-015	Dinner	Dark meat, grains (rice or barley), high moisture content, vegetable matter (green, orange yellow and white)	164	33	40.1	0.82	106	1.69	59.9	10.6	7.6	1.2	13.2
FG-051410-B	Cooking Oil	Solid at room temperature, some water, small bits of food	576	66.5	67.6	0.98	30	0.04	32.4	0.2	61.3	0.2	5.9
FW-016 (FW-011 Duplicate)	Lunch	Yellow starch or dairy, medium moisture content, vegetable matter (green, red, orange and black), bits of paper, possible grape peel material	145	25.6	27.1	0.94	79.5	1.28	72.9	8	8.4	1.3	9.4

Sample #	Moisture (%)	Protein (% of wet weight)	Fat (% of wet weight)	Ash (% of wet weight)	Carbs (% of wet weight)	Dry weight Protein (g/gVS)	Dry weight Lipids (g/gVS)	Dry weight Carb (g/gVS)	Protein COD (g/g COD)	Lipid COD (g/g COD)	Carb COD (g/g COD)
FW-001	76.00	10.40	4.1	1.4	8.1	0.46	0.18	0.36	0.43	0.33	0.24
FW-002	74.30	5.90	3.6	1	15.2	0.24	0.15	0.62	0.25	0.29	0.46
FW-003	69.30	5.30	1.9	0.7	17	0.22	0.08	0.70	0.25	0.17	0.58
FW-004	80.10	3.10	2.5	0.6	13.7	0.16	0.13	0.71	0.17	0.27	0.55
FW-005	37.70	14.50	13.4	1.1	33.3	0.24	0.22	0.54	0.22	0.40	0.37
FW-006	77.50	3.40	1.5	0.5	17.1	0.15	0.07	0.78	0.18	0.16	0.66
FW-007	40.30	20.40	10	0.7	28.6	0.35	0.17	0.48	0.34	0.32	0.34
FW-008	44.30	15.00	11.6	1	28.1	0.27	0.21	0.51	0.26	0.39	0.35
FW-009	68.70	7.80	7.1	0.7	15.7	0.25	0.23	0.51	0.24	0.42	0.34
FW-010	83.90	2.20	0.6	0.6	12.7	0.14	0.04	0.82	0.17	0.09	0.73
FW-011	75.3	7.2	8.6	1.1	7.8	0.31	0.36	0.33	0.24	0.57	0.19
FW-012	76.6	12.7	6.1	0.6	4	0.56	0.27	0.18	0.46	0.43	0.11
FW-013	68.1	18.5	7.8	2	3.6	0.62	0.26	0.12	0.51	0.42	0.07
FW-014	73.2	15.8	4.6	1.2	5.2	0.62	0.18	0.20	0.55	0.32	0.13
FW-015	59.9	10.6	7.6	1.2	13.2	0.34	0.24	0.42	0.30	0.42	0.27
FG-051410-B	32.4	0.2	61.3	0.2	5.9	0.003	0.91	0.09	0.00	0.96	0.03
FW-016 (FW-011 Duplicate)	72.9	8	8.4	1.3	9.4	0.31	0.33	0.36	0.26	0.53	0.22

APPENDIX F: USAFA ANAEROBIC DIGESTER VOLATILE SOLIDS DESTRUCTION EFFICIENCY

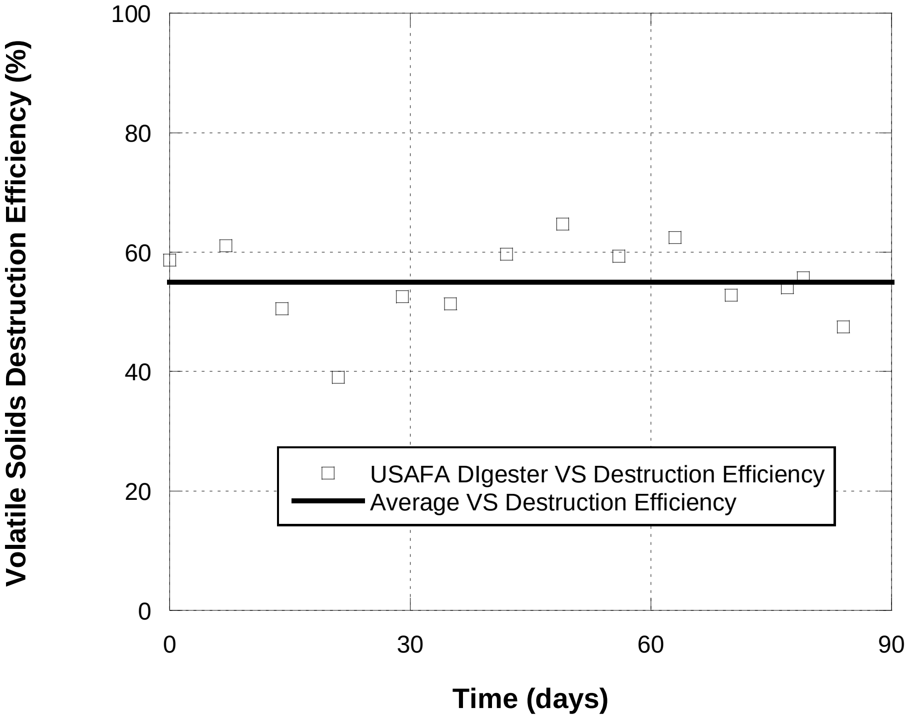

Figure F-1. USAFA wastewater treatment plant anaerobic digester volatile solids destruction efficiency vs. time for a relatively steady three month period. Average VS Destruction Efficiency is 55.0%.

APPENDIX G: EFFECT OF VFA CONCENTRATION ON METHANE PRODUCTION

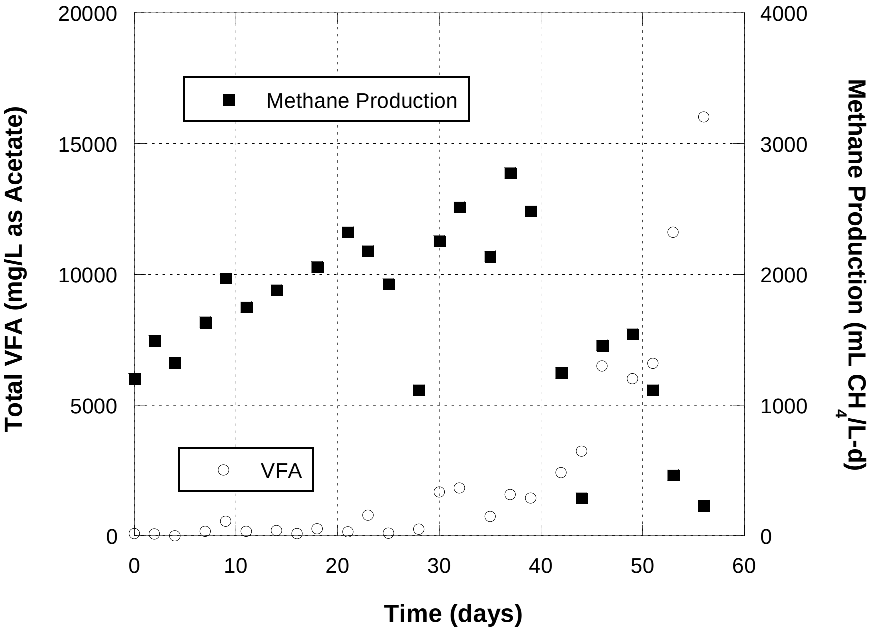

Figure G-1. Total VFA concentration and methane production rate vs. time for a laboratory digester with loading rate transitioned from 5 to 10 gCOD/L-d over 50 days

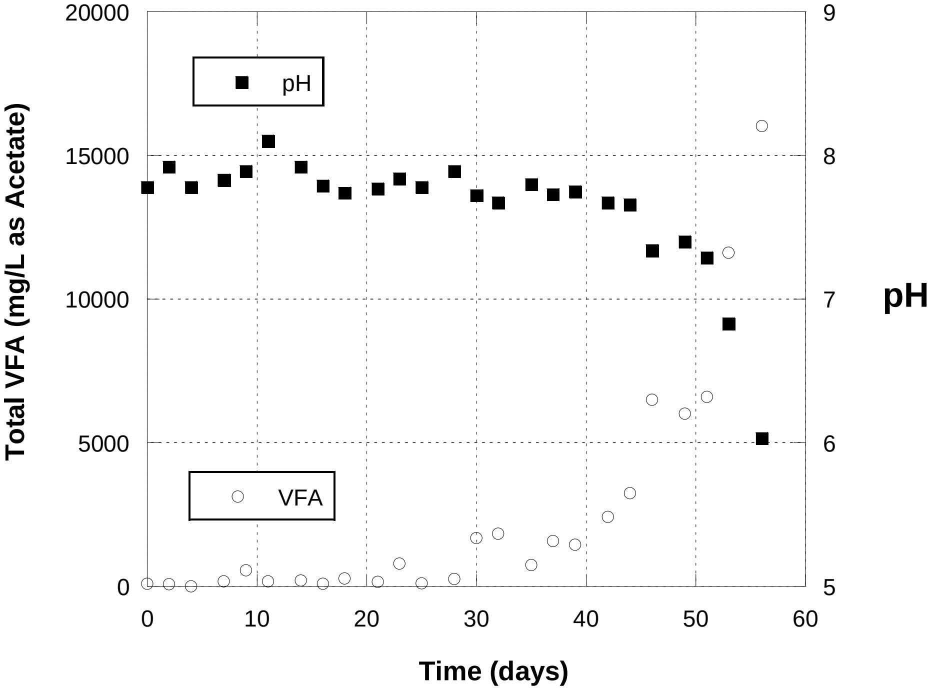

Figure G-2. Total VFA concentration and pH vs. time for a laboratory digester with loading rate transitioned from 5 to 10 gCOD/L-d over 50 days

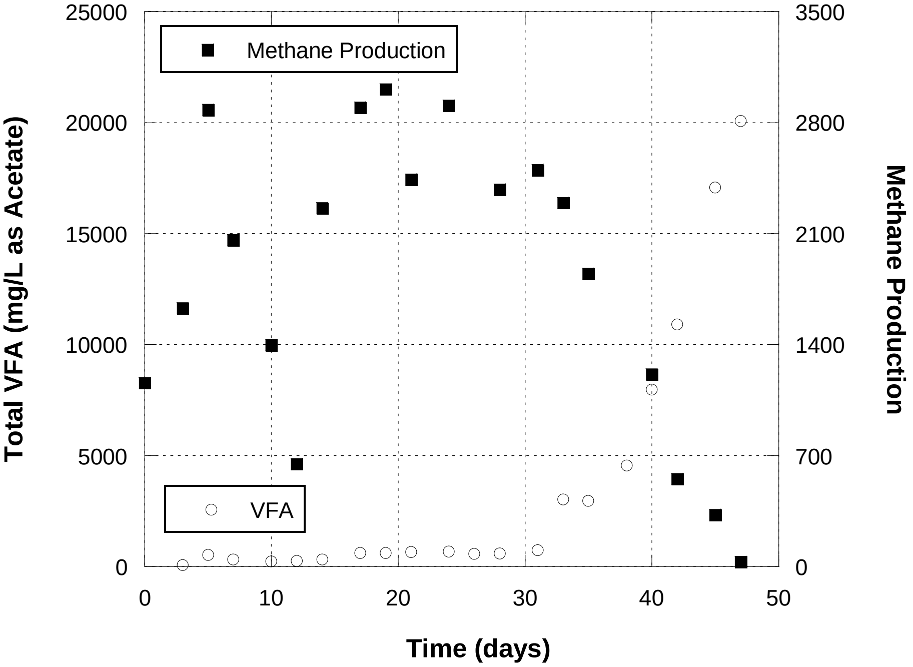

Figure G-3. Total VFA concentration and methane production rate vs. time for another laboratory digester with a 6gCOD/L-d average loading rate

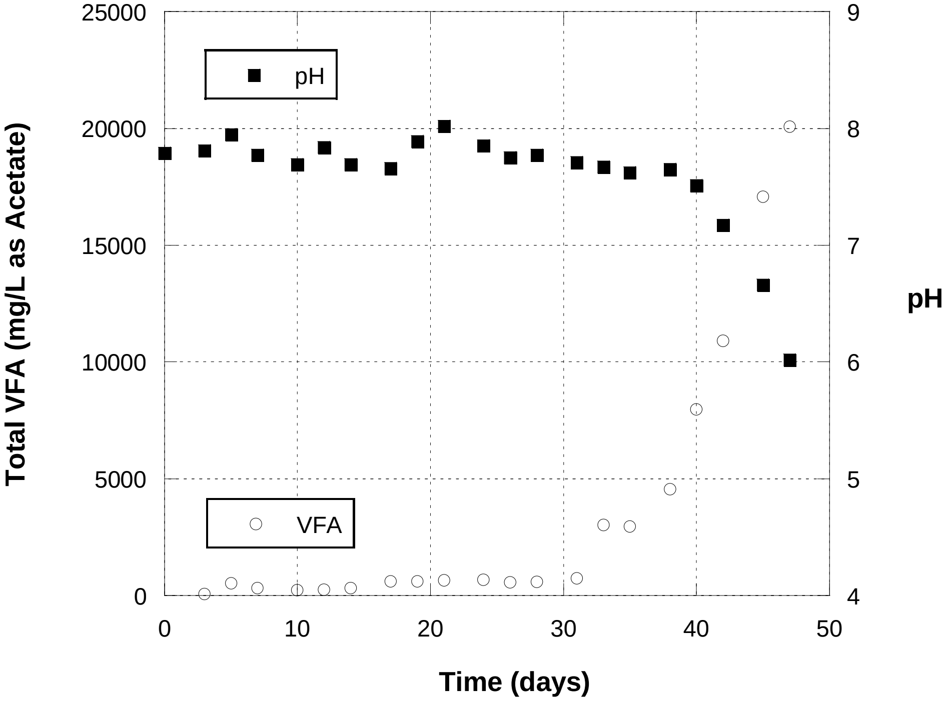

Figure G-4. Total VFA concentration and pH vs. time for another laboratory digester with a 6 gCOD/L-d average loading rate

Appendix F: TDA Biogas Purification Report

FINAL REPORT

Pilot-scale Biogas CO_2/Humidity Removal System and Desulfurization Sorbent

ESTCP Project Number ER 200933

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December 2015

OVERVIEW

A low cost two-stage complete biogas purification system has been developed that removes a wide variety of contaminants from the gases produced by an anaerobic digester. The contaminants removed include inorganic sulfur, organic sulfur, siloxanes, and bulk gases such as CO_2, and moisture, producing a product that is greater than 95% bio-methane. The first stage is based on a low-cost, high-capacity and expendable sorbent called SulfaTrap^{TM} that simultaneously removed sulfur and siloxane down to ppb levels. The second stage is a vacuum swing adsorption system based on a regenerable mesoporous carbon media modified with surface functional groups that reduces the CO_2 and H_2O concentration in the biogas to pipeline specifications.

The purification system was demonstrated in conjunction with a food waste anaerobic digester run at the U.S. Air Force Academy (USAFA) in Colorado Springs, CO. In this project the pilot scale biogas purification system was installed and tested with biogas generated via anaerobic digestion of a variety of food wastes, including pre- and post-consumer food waste, waste cooking oil, and grease trap waste to produce pipeline quality bio-methane. The sulfur in the raw biogas was typically around 1,000 – 1,500 ppm H_2S with trace amounts of organic sulfur compounds. The SulfaTrap^{TM}-R7 desulfurization sorbent removed the sulfur compounds to less than 0.25 ppmv.

We initially carried out breakthrough tests with the CO_2 sorbent beds in the field. We used desulfurized food waste derived biogas to measure the capacity of the saturated VSA adsorbent beds, which was above 4.4% wt. CO_2. We then optimized the VSA cycles in the field, and the optimized VSA cycle scheme was used to produce high purity bio-methane with a methane recovery greater than 90%. VSA cycle schemes with both feed end and product end pressurizations provided sorbent CO_2 working capacities of 2.8% wt., and the CO_2 concentration in the bio-methane product was reduced to less than 0.5% by vol. The dew point of the biogas was reduced from 10-15°C to less than -40°C, providing essentially a dry bio-methane product. The methane purity of the bio-methane produced was confirmed by a CO_2 probe and an IR based methane analyzer. We operated the biogas purification system for a total of 54 hours, purifying more than 3,620 SCF of biogas to produce bio-methane with greater than 90% methane recovery.

We also demonstrated the CO_2 sorbent's performance in a bench-scale two-bed vacuum swing system, demonstrating the life of our sorbent for over 2,900 cycles. We carried out a design for a VSA unit that is sized to process 2,000 m^3/day of biogas with a composition of 60% CH_4, 40% CO_2 (on dry basis) that is saturated with water at 24°C. We estimated the vacuum power requirement to be 14.6 kW_e, the sorbent bed size to be 600 L/bed, the operating power cost was \$0.04 per m^3 CH_4 produced and the total operating cost including the sorbent replacement cost was \$0.07 per m^3 CH_4 produced with a methane purity and recovery of 99.5% and 80.3%, respectively. The methane recovery can be further increased to 90% or above by relaxing the methane purity to 96%+% and increasing operating power cost to \$0.05 per m^3 CH_4 produced, which results in a total operating cost (including sorbent replacement) of \$0.08 per m^3 CH_4 produced for CO_2 and H_2O removal and the total cost of sulfur removal is \$41.3 per kg sulfur.

1.0 INTRODUCTION

Food is the largest component (21 percent) of municipal solid waste. Hence, innovative processes are needed that divert food waste from landfills and recover valuable resources. Anaerobic digestion is an effective process where food wastes including pre- and post-consumer food waste, waste cooking oil, and grease trap waste are converted to biogas, which can be further purified and converted to bio-methane, which contains more than 95% methane. Bio-methane can then be used for transportation purposes or to generate combined heat and electricity using fuel cells. A major challenge is the cost-effective purification of biogas while simultaneously minimizing energy requirements.

Biogas is often produced by anaerobic digestion in municipal wastewater treatment facilities (WWTFs) and wastewater treatment plants for the food and beverage industry. Biogas is the result of decomposition of organic wastes, but the methane is diluted with large amounts of CO_2 (greater than 30%) and it therefore possesses less energy per unit volume than pipeline methane (natural gas). In addition to CO_2 and CH_4, the biogas generated in the digesters and fermentation units also contain moisture at saturation and various trace contaminants such as sulfur compounds (e.g., hydrogen sulfide) and siloxanes. Table 1 shows the typical biogas composition generated from anaerobic digestion. These contaminants must be removed and CO_2 and the other inerts reduced to produce a higher quality fuel that contains more than 90% methane (bio-methane).

Table 1. Typical ADG biogas composition after bulk sulfur removal.

Gas Pressure	5-20 in. water column, positive
Gas Temperature	110°F
Gas Composition, by volume	60% CH_4, 35% CO_2, and 5% N_2
Moisture Content	Saturated
Siloxanes	
Total	4.5 ppmv
D4	0.4 ppmv
D5	4.1 ppmv
Halogens	1 ppmv
Sulfur	
Hydrogen sulfide	200 ppmv
Carbonyl sulfide	5 ppmv
Carbon disulfide	1 ppmv
Dimethyl sulfide	5 ppmv
Dimethyl disulfide	5 ppmv
Other disulfides	2 ppmv
Methyl mercaptan	5 ppmv
Ethyl mercaptan	1 ppmv
BTX	less than 1 ppmv

Although various adsorbents or solvent systems are available to remove hydrogen sulfide (H_2S), the most common form of sulfur in the biogas, the biogas also contains a wide range of organic sulfur compounds ranging from mercaptans to higher molecular weight disulfides.

Unfortunately, the conventional desulfurization systems do very little to remove the organic sulfur compounds, particularly the disulfides. The conventional sorption systems such as iron sponge and SulfaTreat^{TM} also have disadvantages with respect to safety and material handling. Another class of compounds present in biogas are the siloxanes. Siloxanes are generated during anaerobic digestion of waste activated sludge that concentrates silicone-based personal hygiene, health-care and industrial products. Siloxanes must be removed from biogas prior to its use as an energy source.

1.1 BACKGROUND

Food waste based anaerobic digester units capable of producing pipeline quality methane could be instrumental in eliminating the difficulties associated with its disposal and be a source of heating and electricity and significantly reduce disposal costs and operating expenses. If consumed properly, use of food waste derived fuels can also protect against environmental problems such as groundwater leaching and greenhouse gas emissions (methane emissions) associated with land filling of the food wastes. In today's scenario of growing energy demands worldwide any methane emitted into the atmosphere is an untapped resource of energy that has a global warming potential (GWP) of 25 (over 100 years). TDA's CO_2 removal system could also be used for capturing CO_2 from other industrial gases, such as off-gases from refineries, cement plants etc.

Biogas to pipeline or transportation methane technology can be part of new digestion system installations or an add-on to current systems. According to the U.S. Environmental Protection Agency (EPA), biogas recovery systems are technically feasible at more than 8,000 U.S. dairy and swine operations in the U.S. and biogas recovery is also feasible at some poultry operations (AgSTAR Oct 2010). As of July 2010 there were 157 large-farm located anaerobic digesters operating in the U.S. (Key 2011), and it is estimated that an average of 15 new digesters are coming online each year (AgSTAR 2011). This corresponds to a total addressable market in the dairy farm area of $348 million.

Even though the anaerobic digester system includes a desulfurization system, existing systems will remove only H_2S and will leave behind other organic sulfur species such as higher sulfides and mercaptans. Depending on the biomass feedstock and digester design, the concentration of these higher sulfide species ranges from 0.1 ppmv to as high as 30 ppmv. The main source of the VSCs in biosolids is protein degradation, especially degradation of the amino acid methionine (Higgins et al., 2004). Similarly, H_2S can be formed from the degradation of the sulfur containing amino acid cysteine. Once H_2S and MeSH are formed, they can be methylated to form Me_2S and can be oxidized to form Me_2Se_2 and other higher sulfides. In short,

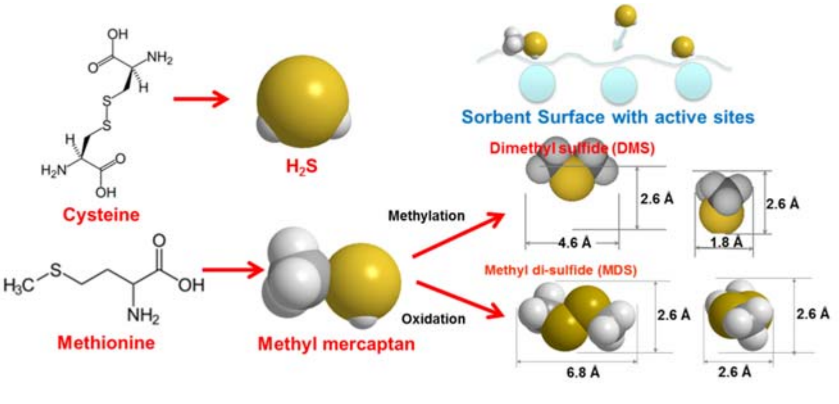


Figure 1. Some of the disulfide molecules present in the biogas.

sulfur is always present at significant levels in animal wastes. In the digester, hydrolysis of sulfur containing proteins (e.g., cysteine, cystine, methionine) and organic sulfur compounds produces H_2S, mercaptans and organic sulfides and disulfides.

The sulfur concentration of the biogas could be as high as 1.5% vol. Even conventional CHPs require some level of sulfur removal to prevent corrosion of the metal components, acidifying the engine oil and emissions of SO_2. A sulfur limit of 100 ppmv is often recommended for trouble-free operation of conventional CHPs. These limits can easily be achieved using off-the-shelf desulfurization technology. However, the sulfur limits must be reduced by an additional two orders of magnitude (to 4 ppmv or lower) if the biogas is to be further purified to pipeline or transportation methane levels. This sulfur limit needs to reduced to by an additional order of magnitude (to 0.1 ppmv or lower) for it to be used as fuel cell feedstock. In several studies (Matsuzaki 2001) the poisoning effects of H_2S on the Ni-YSZ (yttria stabilized zirconia) cermet electrolytes have been documented. One study shows 30% decline in cell performance as the sulfur concentration in the fuel gas exceeds 0.4 ppmv (Israelson, 2003). Therefore, long-term stable electrochemical performance requires the feed sulfur level be reduced to ultra low (ppb) levels.

Conventional Desulfurization Technology

Biogas can be desulfurized by various physical, biological and chemical processes. Because it is difficult to reduce the sulfur content from the percent range to ppb range, usually a two-step cleaning process is followed (e.g., a rough gas cleaning a step followed by adsorption for sulfur polishing). Below we describe the currently available bulk desulfurization process. All of these are designed for H_2S removal, remove little, if any of the organic sulfur compounds (particularly the disulfides), and reduce the sulfur from the percent levels to tens of ppm (but not ppbs).

Biological Desulfurization: In this process, H_2S is adsorbed in water and then degraded biologically with microorganisms of the species *Thiobacillus* and *Sulfolobus*. These bacteria require oxygen in the immobilization bioreactors. This approach works well for plants of less than 200kW capacity. Trickling filters and other bio-scrubbers are used with caustic soda reduce the H_2S content to 75-100 ppmv range.

Sulfide Precipitation: For the fixation of sulfur, a mixture of Fe^{2+} (e.g., $FeCl_2$) and Fe^{3+} ($FeCl_3$) are contacted in a mixing tank to precipitate a stable iron (II) sulfide and sulfur. A fresh supply of iron salt must be continuously provided. The process can reduce the sulfur level to less than 30 ppmv, but is relatively expensive due to the high cost of the iron salt.

Absorption in Ferric Chelate Solution: This is known as the LO CAT process. In a ferric chelate solution Fe^{3+} ions are reduced to Fe^{2+}, while H_2S is oxidized to elementary sulfur. A chelating agent is needed to ensure the Fe^{2+} ions do not react spontaneously to iron sulfide and/or iron hydroxide and can be continuously used. The chelate is regenerated by converting Fe^{2+} to Fe^{3+} in a separate reactor. The sulfur concentrate is collected at the reactor bottom and periodically removed. This process removes most of the H_2S (e.g., 99.9% removal efficiency) and is viable for biogas with high levels of sulfur (up to 15,000 ppmv). However, the LO CAT® process cannot remove mercaptans, COS and higher sulfides.

Solid Scavengers: Iron sponge and bog iron ores can be used to effectively remove H_2S with high capacity. There are several products that use iron oxides to remove a bulk of the sulfur. Iron oxides remove sulfur by forming insoluble iron sulfides. The most well known iron oxide product is called "iron sponge." Iron-oxide media such as SulfaTreat®, Sulfur-Rite®, and Media-G2® have been offered as improved alternatives to iron sponge (Zicari, 2003). Among various varieties, SulfaTreat® supplies a natural ore comprised of iron hydroxide [$Fe(OH)_3$] and iron oxide (Fe_2O_3) mixture to remove H_2S. These sorbent is placed in a tower reactor, and is periodically removed when it is saturated with sulfur. The biogas and the sorbent are contacted at 50°C; the gas has to be humidified to prevent water carryover from the sorbent. The H_2S concentration can be reduced to less than 4 ppmv, however, the so-called "H_2S scavengers" can only remove H_2S, and cannot remove COS, mercaptans and other sulfur species.

Chemical Sorbents: The H_2S content of the biogas could also be reduced to the 2-3 ppm using a chemical absorbent such as zinc oxide (ZnO) and its derivatives. Because sulfur is removed via a chemical reaction these systems operate at relatively high temperatures (300-400°C), these sorbents are not compatible with some downstream uses of the methane, for example a molten carbonate fuel cell (MCFC), which needs a cold feed stream for heat management reasons.

Physical Adsorbents: The technologies listed above have been applied effectively to the bulk H_2S removal from the biogas, however, they do not reduce the sulfur content to the ppb levels. Adsorptive removal of sulfur is an attractive option to achieve ultra low sulfur concentrations. Activated carbons are somewhat effective at removing H_2S, if the biogas is free of oxygen. However, the sulfur capacity and removal efficiency of the carbon beds are poor unless they are chemically modified. One approach is to impregnate the activated carbon with potassium iodide (KI) at a concentration of 1-5% by weight. In the presence of oxygen and water, H_2S dissolves in the water layer on the carbon surface and reacts with the oxygen at 50-70°C. Potassium carbonate (K_2CO_3) at 10-20% weight concentration works in a similar manner. H_2S concentrations in the gas can be reduced to less than 1 ppmv with these adsorbents. Unfortunately, neither the carbon sorbents nor their competitors based on silica, alumina, or zeolite can remove the larger and more complex mercaptans, sulfides and disulfides (which are also present at the 1-30 ppm level.)

Unfortunately, the conventional desulfurization systems do very little to remove the organic sulfur compounds, particularly the disulfides. The conventional sorption systems such as iron sponge and SulfaTreat™ also have disadvantages with respect to safety and material handling.

Conventional CO_2 Removal Technology

There are commercial systems available that produce pipeline methane from biogas. However, these systems are more energy intensive and require a separate dehydration system to meet pipeline specification. TDA's VSA system provides process intensification by removing moisture and CO_2 simultaneously. Also, the sorbent used in commercial systems are not tolerant to sulfur compounds present in the biogas while TDA's system maintains its CO_2 capacity in the presence of sulfur compounds.

The commercial technologies already available for biogas upgrading are: pressurized water system (PWS), pressure swing adsorption system (PSA) and membrane system, and below we describe their strengths and weaknesses.

Pressure Swing Adsorption (PSA): Pressure swing adsorption (PSA) is a process in which CO_2 and other trace gases are removed from biogas according to the species' molecular characteristics and affinity for the adsorbent material. An adsorptive material such as activated carbon or a molecular sieve (zeolite) is used to adsorb the CO_2 at high pressure (4-7 atm). The process then swings to low pressure to desorb the CO_2 from the adsorbent material. This allows the gas to be separated into the two separate streams: the CO_2 and methane. Prior to the PSA process, sulfur and water vapor must be removed from the raw biogas since these substances can damage the sorbent (activated carbon or zeolites) material used (Munz 2011). Commercial PSA systems include BGX Solutions unit that operates on a fast-cycle PSA technology are available from Xebec Corporation. This technology is based on the company's hydrogen product platform but that is modified to remove CO_2 from low quality methane streams. HADETEC BV offers a vacuum PSA (VPSA) process for CO_2 removal from biogas using a 3-4 bed PSA process. The CO_2 is adsorbed on a molecular sieve and the methane goes through up to the NG quality and the gas needs to be pretreated and pressurized while also usingvacuum to achieve higher methane recovery (The Rootselaar Group, 2011).

Pressurized Water Scrubbing (PWS): In pressurized water scrubbing (PWS) system carbon dioxide is absorbed in water while the methane passes through since CO_2 is more soluble in water than methane. The separation typically occurs at high pressure since the solubility of CO_2 increases with increased pressure. The absorption process occurs in a counter-current flow absorber column where the biogas is pressurized and fed at the bottom of the column and the water is fed in the top. A small amount of methane absorbs into the water since it is partially soluble in water. The water stream exits the column and is depressurized to release the CO_2. The gas stream is typically run through the PWS system multiple times. This process can also remove hydrogen sulfide and ammonia present in raw biogas (Nozic, 2006). Several companies offer this technology. However, high methane purities are not possible and the PWS process is highly energy intensive with an operating cost of $\$0.12/m^3$ methane produced.

Amine System: Monoethanolamine (MEA) or diethanolamine (DEA) can be used as a solvent to remove CO_2 from biogas. In MEA washing, the biogas flows into an absorber and contacts an aqueous solution of MEA flowing counter-currently to the flue gas stream. The CO_2 in the biogas and MEA react exothermically to form a water soluble salt. The MEA-rich stream exits the absorber at the bottom and is heated in a heat exchanger by the MEA-lean stream leaving the stripper. The MEA-rich stream enters the stripper where the reaction is reversed and the CO_2 is removed through the top of the stripper. The MEA-lean stream leaves through the bottom and goes into the heat exchanger. The MEA-lean stream is recycled back into the absorber (D.Singh, 2003). Before the MEA capturing process, H_2S must be removed from the flue gas stream since the MEA is degraded by sulfur species (Yeh, 2005). Also, the regeneration energy requirement for amines are more than thrice of the TDA's sorbent.

Membrane System: Membrane systems to separate CO_2 from the methane in biogas work according to the principle of selective permeation through the membrane. The biogas must be cleaned of H_2S and pressurized before entering the membrane system. The membranes made of acetate-cellulose separate small polar molecules such as carbon dioxide, moisture and the remaining H_2S from the methane. In tradition membrane systems, a purity of 96% methane can be achieved (IEA Bioenergy, 2011). However, they have a bigger methane loss and the operating cost is about \$0.07/m^3 methane produced.

1.2 OBJECTIVE OF THE DEMONSTRATION

CDM Federal Programs Corp. (CDM Smith) led a \$1.9 million research project (Project # ER-200933) funded by the Department of Defense (DoD) Environmental Security Technology Certification Program (ESTCP) to demonstrate "Renewable Energy Production from DoD Installation Solid Wastes by Anaerobic Digestion". This project set out to demonstrate and validate the ability to digest wastes common to DoD installations, including pre- and post-consumer food waste, waste cooking oil, and grease trap waste to produce pipeline quality methane by removing non-methane portions of the biogas such as CO_2, H_2O, H_2S etc. In this ESTCP project CDM Smith installed an anaerobic digestion system at the U.S. Air Force Academy (USAFA) in Colorado Springs, CO, and provided the technical support services and equipment for the CO_2, H_2O and sulfur removal needed to upgrade the bio-methane produced to pipeline quality.

TDA developed a CO_2 and humidity removal system for biogas to produce pipeline quality methane under funding from EPA (EPD-12-037) and has also been supplying sulfur removal sorbents for to a variety of government and commercial demonstrations run with biogas. In this project, TDA designed and built a stand-alone test skid for upgrading biogas to pipeline grade methane (CO_2 & moisture removal) and also supplied 70 L of desulfurization sorbent (1 year supply) for the demonstration at the U.S. Air Force Academy (USAFA). The objective of this combined demonstration of CDM Smith's food waste digestion and TDA's gas clean-up technologies is to validate the use of food waste from DoD installations to generate transportation methane (a renewable fuel) and thereby reduce their carbon foot print.

1.3 REGULATORY DRIVERS

Renewable fuels include liquid and gaseous fuels and electricity derived from renewable biomass energy sources, as opposed to fossil fuels. Many renewable fuels achieve significant lifecycle greenhouse gas emissions reductions relative to fossil fuels. Increased use of renewable fuels in the United States can reduce dependence on foreign sources of crude oil and foster development of domestic energy sources, while at the same time providing important reductions in greenhouse gas emissions that contribute to climate change.

To accelerate use of fuels derived from renewable sources, Congress established standards under the Energy Policy Act of 2005 designed to encourage the blending of renewable fuels into our nation's motor vehicle fuel supply. Congress strengthened the renewable fuels program under the Energy Independence and Security Act of 2007 to include specific annual volume standards for total renewable fuel and also for the specific renewable fuel categories of cellulosic biofuel, biomass-based diesel, and advanced biofuel. The revised statutory requirements also include new criteria for both renewable fuels and for the feedstocks used to produce them, including lifecycle greenhouse gas emission thresholds. Under the new regulations the transportation methane generated from biogas qualifies under the cellulosic biofuels and is being widely sought out by municipalities, DoD establishments and power producers to meet their specific annual quota under renewable fuel standard program.

2.0 TECHNOLOGY

TDA has developed a two-stage complete biogas purification system that removes the various contaminants such as inorganic sulfur, organic sulfur, siloxanes, CO_2, and moisture to produce greater than 95% bio-methane. The first stage is based on a low-cost, high-capacity and expendable sorbent called SulfaTrap^{TM} that simultaneously removed sulfur and siloxane down to ppb levels. The second stage is a vacuum swing adsorption system based on a regenerable mesoporous carbon media modified with surface functional groups to reduce the CO_2 and H_2O concentration in the biogas to pipeline specifications. Figure 2 shows the two stage biogas purification process to bio-methane.

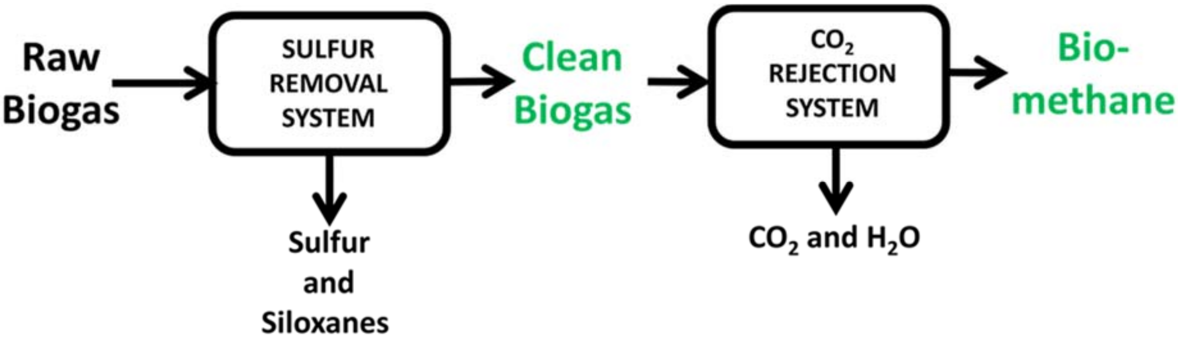


Figure 2. Two stage biogas purification process to bio-methane.

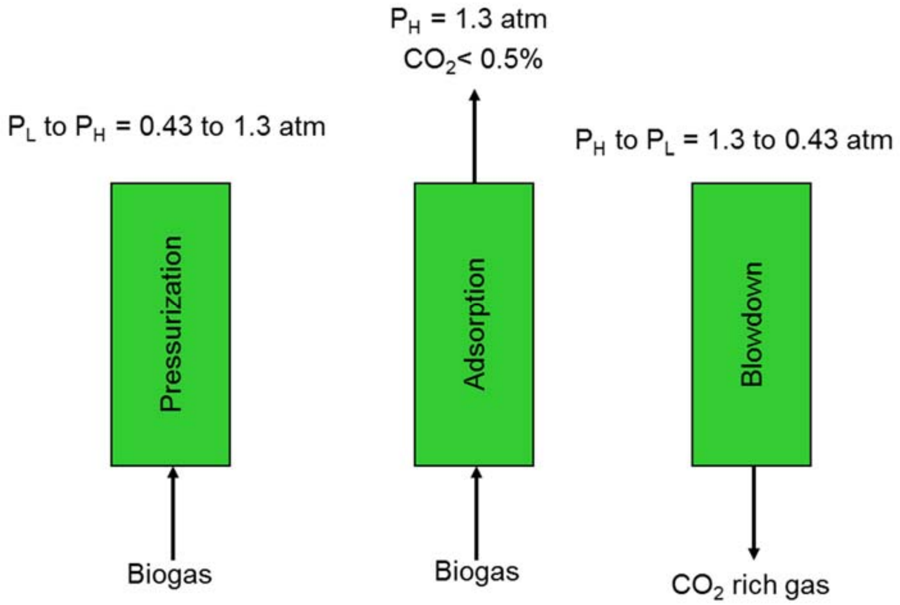
2.1 TECHNOLOGY DESCRIPTION

Sulfur Removal System

TDA Research Inc. (TDA) has developed a low-cost, high-capacity expendable sorbent SulfaTrap^{TM}-R7 that can remove both H_2S and organic sulfur species in biogas to the ppb levels. Another class of compounds present in biogas is siloxanes. Siloxanes are generated during anaerobic digestion of waste activated sludge that concentrates silicone-based personal hygiene, health-care and industrial products. Siloxanes must be removed from biogas prior to use as an energy source. SulfaTrap^{TM}-R7 contains TDA proprietary mixed metal oxide phase that removes both the sulfur and siloxane compounds in the biogas.

CO_2 Rejection System

The vacuum swing adsorption system uses TDA Research, Inc's proprietary CO_2 adsorbent to reduce the CO_2 and other inerts in the biogas to less than 5%. The approach is similar to the PSA and VSA systems that have been successfully used for years in small to medium scale air separation processes to produce very high purity oxygen. A simple vacuum swing cycle consists of three steps as shown in Figure 4. The adsorption of CO_2 from the biogas stream is carried out at the biogas delivery pressure (about 1.3 atm), while the sorbent is regenerated and CO_2 recovered under vacuum (at about 0.2 atm). The bed is subsequently pressurized with the feed (biogas) gas. The methane loss from the system is reduced by using intermediate pressure equalization steps between the main adsorption and regeneration portions of the cycle. The methane loss with the full vacuum swing cycle is minimal (i.e., less than 10%).



P_H = 1.3 atm
CO_2< 0.5%
P_L to P_H = 0.43 to 1.3 atm
P_H to P_L = 1.3 to 0.43 atm
Pressurization
Adsorption
Blowdown
Biogas
Biogas
CO_2 rich gas

Figure 3. Schematic of a simplified 3-bed vacuum swing adsorption cycle for CO_2 removal from methane biogas.

TDA's CO_2 sorbent is a proprietary mesoporous carbon that contains surface functional groups that are selective for CO_2 removal. The carbon support is previously developed for ultra-capacitors, and has large pores to achieve liquid transport. TDA's proprietary preparation process enables TDA to introduce stable surface functional groups and control the pore size distribution, For example, Figure 4 shows three different mesoporous carbon formulations having a much wider pore size distributions in the 10-100 Å range while Figure 5 shows TDA's mesoporous carbons having a narrow pore size distribution 15-20 Å.

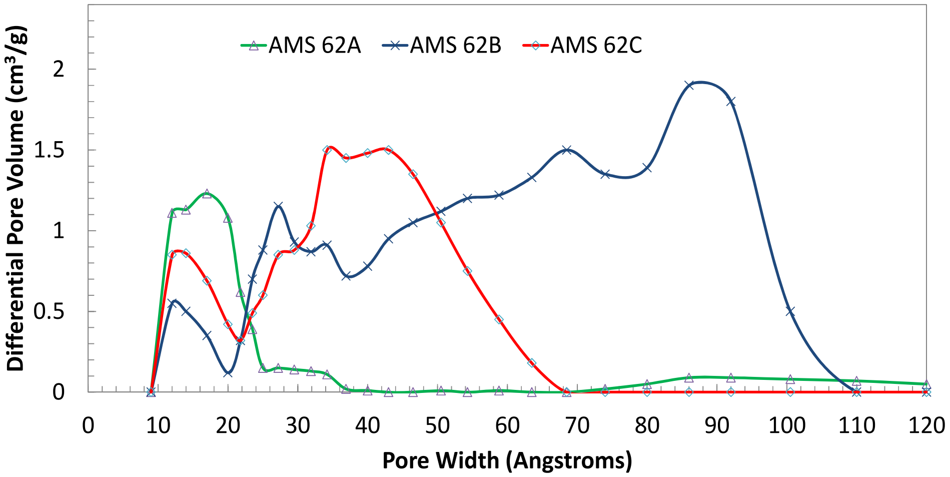


Figure 4. TDA's mesoporous carbons with a wide pore size distribution (10-100 Å).

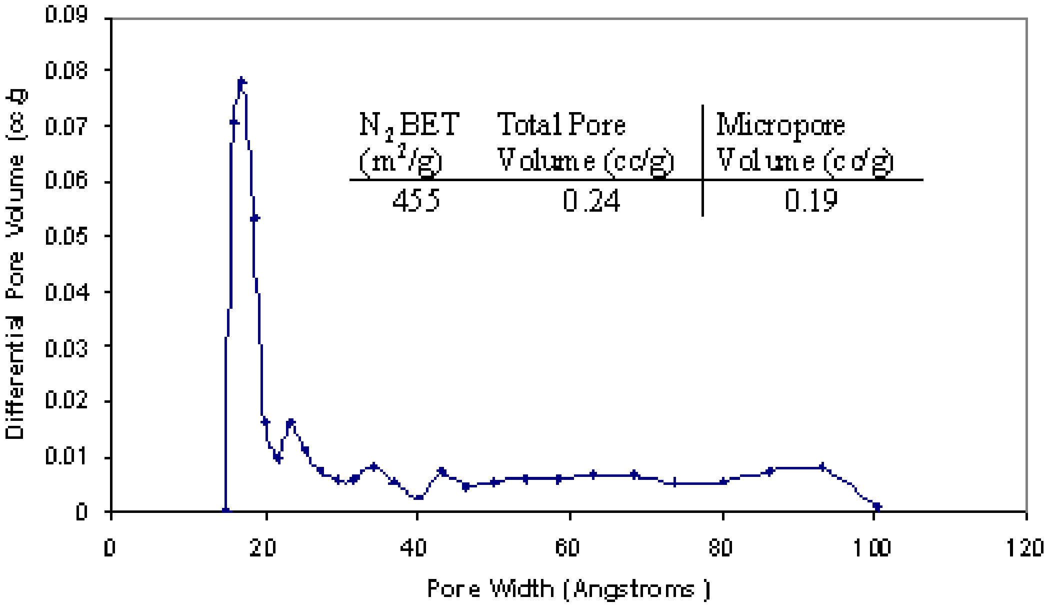


Figure 5. TDA's mesoporous carbons with a narrow pore size distribution (15-20 Å).

2.2 TECHNOLOGY DEVELOPMENT

Sulfur Sorbent

CDM Smith provided a wide range of operating conditions for the sulfur removal sorbent i.e., 40 to 60°F for pilot scale operation and 98°F for full scale operation and humidity levels up to 100% RH at operating temperature. Hence, we prepared and tested two batches of desulfurization sorbents in bench-scale apparatus at TDA using simulated biogas:

- SulfaTrap^{TM}-R7B –wet gas
- SulfaTrap^{TM}-R7E – wet & dry gas

Both sorbents are now available in commercial quantities from SulfaTrap LLC, the licensor of TDA Research's sulfur sorbents. In these bench scale evaluations we included a commercial biogas desulfurization sorbent SulfaTreat Select Premium along with the two SulfaTrap^{TM} samples. SulfaTreat Select premium works only in the presence of high levels of moisture. Figure 6 shows the comparison of the three sorbents under high temperature (50°C) and high moisture (sat. H_2O at 22°C) and the two SulfaTrap^{TM}-R7 samples achieved slightly higher capacity ~27% wt. sulfur compared to 25.2% wt. sulfur for the SulfaTreat Select Premium. Figure 7 shows the comparison under low temperature (22°C) and high moisture (sat. H_2O at 22°C). Hence, the SulfaTrap^{TM}-R7E sample retained its capacity at low temperature i.e., achieved a high loading of 26.2% wt. sulfur while the capacity of the SulfaTrap^{TM}-R7B and SulfaTreat Select Premium samples decreased to less than 20%. It is to be noted that SulfaTrap samples have higher bulk density compared to SulfaTreat Select Premium, which results in a significantly higher breakthrough time (volumetric loading) for SulfaTrap^{TM}-R7B compared to SulfaTreat Select premium.

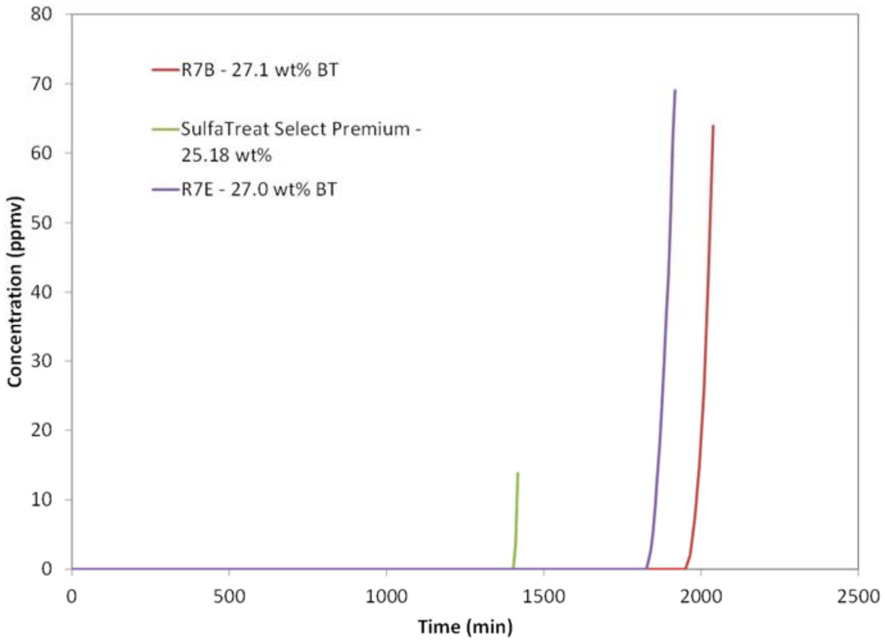


Figure 6. H_2S removal from simulated biogas in bench-scale with various biogas desulfurization sorbents at high temperature and high moisture. T= 50°C, 2000 ppmv H_2S, 40% CO_2, 60% CH_4, 22°C sat. (2.7%) H_2O, GHSV=4,000 h^{-1}.

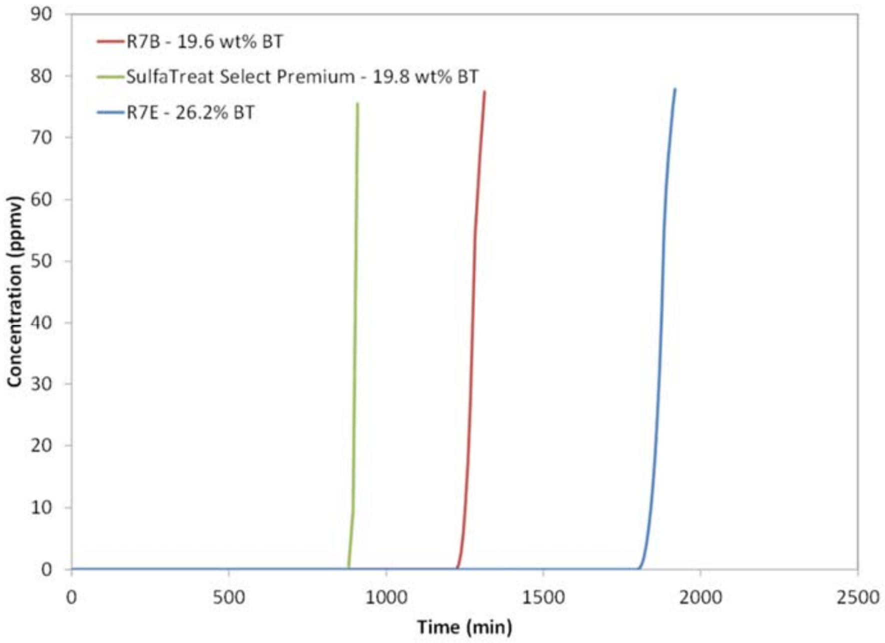


Figure 7. H_2S removal from simulated biogas in bench-scale with various biogas desulfurization sorbents at low temperature and high moisture. T= 22°C, 2000 ppmv H_2S, 40% CO_2, 60% CH_4, 22°C sat. (2.7%) H_2O, GHSV=4,000 h^{-1}.

We then down selected to the two SulfaTrap^{TM}-R7 samples due to their high capacity at low operating temperatures and tested the two samples under low temperature (22°C) and low moisture (4,000 ppmv H2O, 20°F dew point). We found that under low moisture condition SulfaTrap^{TM}-R7E achieved a high capacity of 17.9% wt. sulfur while SulfaTrap^{TM}-R7B achieved a low capacity of 2.4% wt. sulfur at breakthrough (Figure 8). These bench-scale tests showed that SulfaTrap^{TM}-R7E is the sorbent of choice, since it can work under a wide variety of operating conditions including the extremes of low temperature and low moisture expected during winter and the high temperature and high moisture conditions expected during summer.

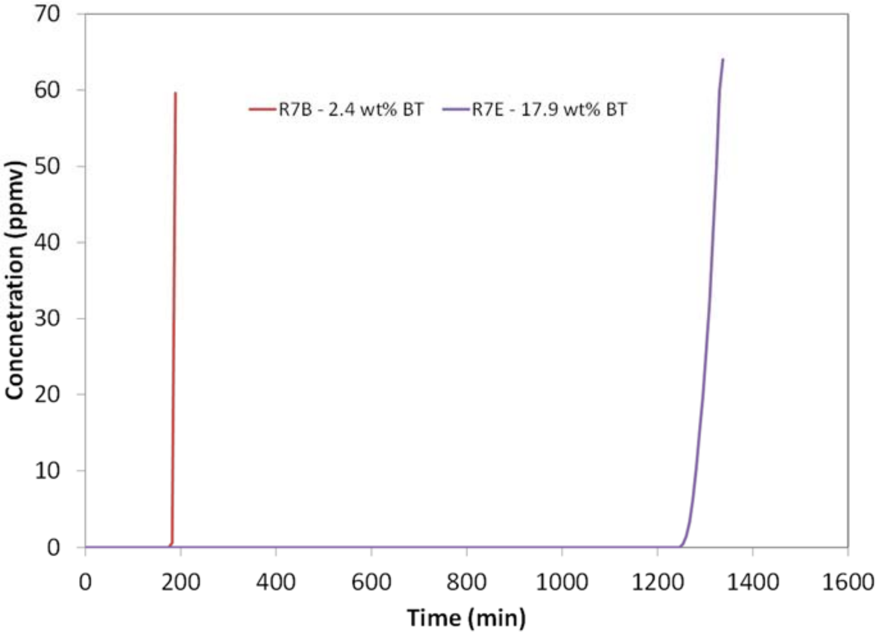


Figure 8. H_2S removal from simulated biogas in bench-scale with various SulfaTrap^{TM}-R7 sorbents at low temperature and low moisture. T= 22°C, 2000 ppmv H_2S, 40% CO_2, 60% CH_4, 20°F sat. (4,000 ppmv) H_2O, GHSV=4,000 h^{-1}.

Next, we carried out detailed bench-scale evaluations with the SulfaTrap^{TM}-R7E (sulfur sorbent of choice). SulfaTrap^{TM}-R7E achieved a high sulfur capacity under different levels of moisture (Figure 9). The sulfur capacity was above 25% wt. sulfur down to 40°F dew point. It had a slight decrease in capacity, achieving a breakthrough capacity of 17.9% wt. sulfur, when the moisture was reduced to 20°F dew point. We then varied the operating temperature while keeping moisture level in the simulated biogas at 72°F dew point (Figure 10). SulfaTrap^{TM}-R7E retained a high capacity of 26+% wt. sulfur at operating temperatures between 72 to 122°F (22 to 50°C).

Finally, we tested SulfaTrap^{TM}-R7E using simulated biogas containing 400 ppmv H_2S and compared the sorbent performance against simulated biogas containing 2,000 ppmv H_2S. The sulfur breakthrough results are summarized in Figure 11. SulfaTrap^{TM}-R7E retained its high sulfur capacity at 400 ppmv H_2S achieving a sulfur loading of 25.4% wt. sulfur.

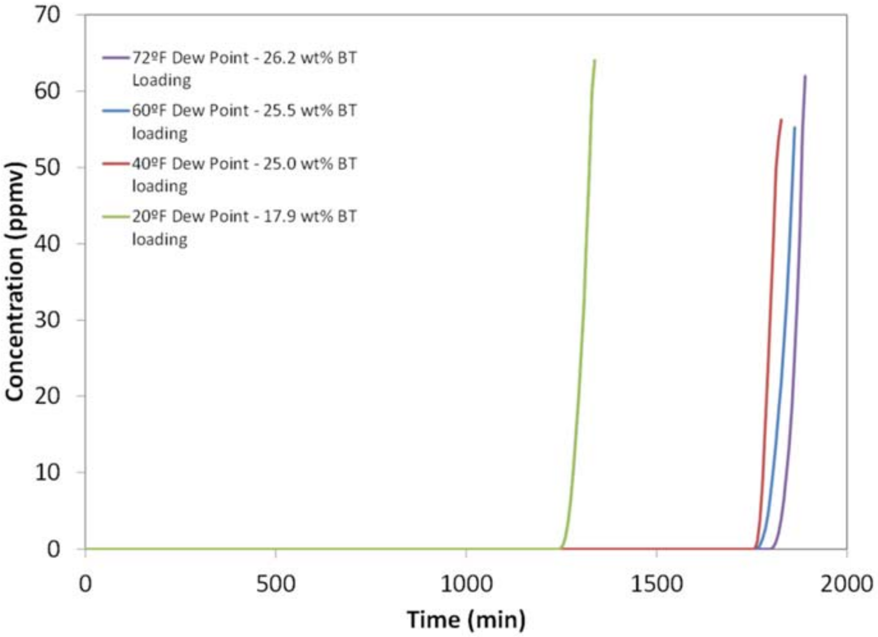


Figure 9. H_2S **removal from simulated biogas in bench-scale at low temperature and different moisture levels. T= 22°C, 2000 ppmv** H_2S**, 40%** CO_2**, 60%** CH_4**, varying** H_2O**, GHSV=4,000** h^{-1}**.**

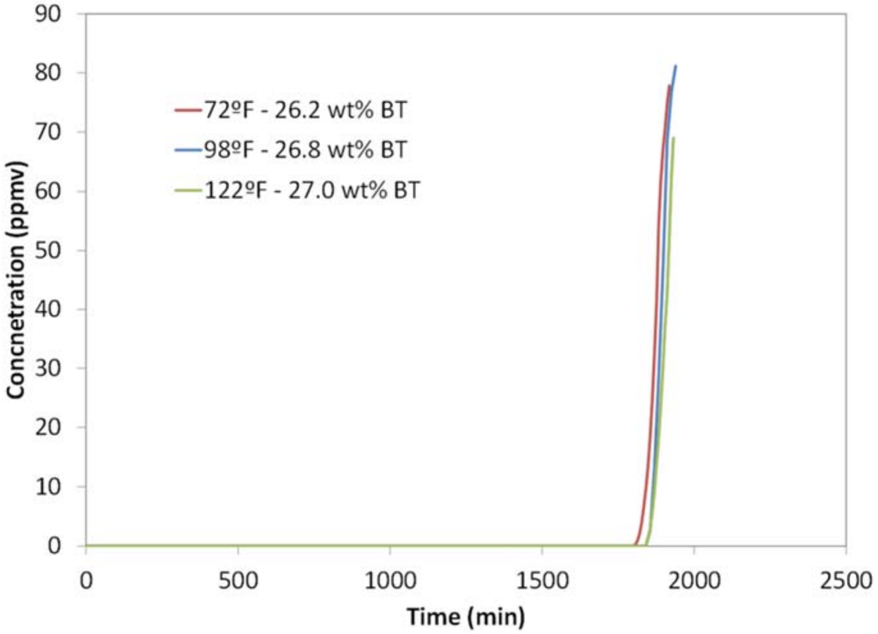


Figure 10. H_2S **removal from simulated biogas in bench-scale at different temperature and high moisture level. T= varying, 2000 ppmv** H_2S**, 40%** CO_2**, 60%** CH_4**, 72°F sat. (2.7%)** H_2O**, GHSV=4,000** h^{-1}**.**

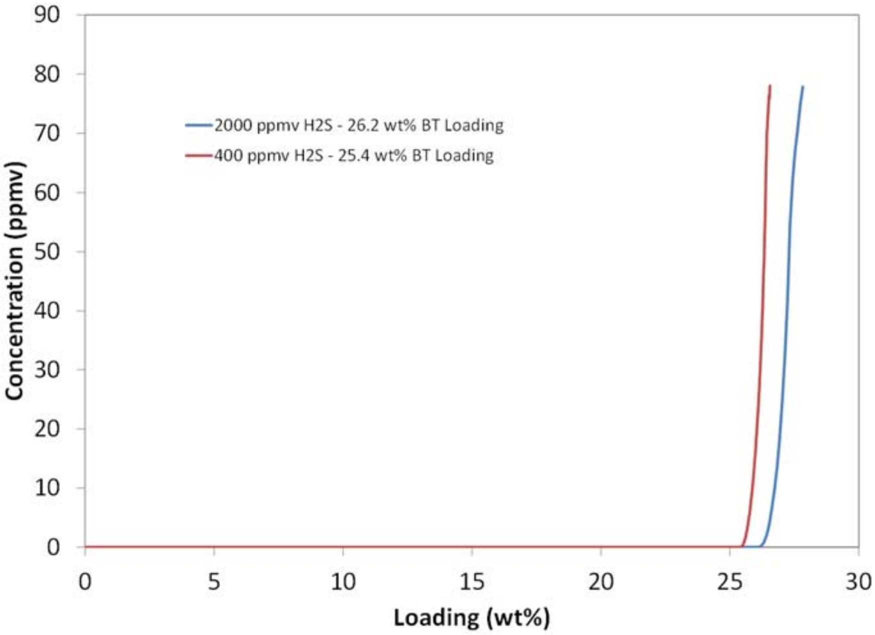


Figure 11. H_2S removal from simulated biogas in bench-scale at low temperature and high moisture level. T= 22°C, varying H_2S, 40% CO_2, 60% CH_4, 72°F sat. (2.7%) H_2O, GHSV=4,000 h^{-1}.

CO_2 Rejection System

TDA has previously demonstrated the CO_2 sorbent's performance in a bench-scale two-bed vacuum swing system (Figure 12) under the EPA sponsored SBIR project (EP-D-11-051). This system is capable of counter-current adsorption and desorption operation simulating the VSA operation expected in the full-scale system. In this system, the desired gas mixtures (CH_4 and CO_2) are directed into a bench-scale reactor that contains the sorbent. All gas flows are controlled with electronic mass flow controllers. An in-line sparger is used to introduce moisture at 100% relative humidity in the biogas. After mixing in a manifold, the feed gas mixture is then directed into the reactor. A valve system allows the gases to bypass the reactor and flow directly to the analytical system for accurate measurement of the feed gas composition as needed. The sorbent reactor consists of a 1.5 inch outside-diameter spring loaded stainless reactor. One hundred g of sorbent particles in the 8-20 mesh size are loaded in to the reactor for testing. The reactor is spring loaded and has a length/diameter (L/D) ratio of 8 with a bed volume of 100 mL. The reactor has three thermocouple ports to monitor the sorbent bed temperature. A back pressure regulator is used to control the adsorption pressure. After exiting the reactor, the CO_2, and CH_4 content of the stream are monitored by an on-line NOVA Multi-gas Analyzer and Vaisala CO_2 and humidity probes. Continuous analysis of CO_2 allows us to monitor breakthrough gas concentrations and to measure a total CO_2 adsorption capacity. The desorption line is equipped with a BOC Edwards scroll (oil-free) vacuum pump. The pump can easily reach vacuums of less than 1 psia. The apparatus is fully automated using a control system from Opto 22 Corporation and can run without an operator for long periods of time, including overnight. The control system controls the test conditions, logs the analytical data, and also safely shut down the apparatus in case of a malfunction. We used a simulated biogas composition of 60% CH4 and 40% CO_2 on a dry basis for the bench-scale evaluations (the water content was 3% by vol.).

We used the this previously built system in the EPA SBIR project to run bench-scale tests in which we demonstrated the performance of our sorbent for over 2,900 cycles without any loss in performance. In these tests the sorbent beds produced high purity methane above 99%. Figure 13 shows the results from these bench-scale tests.

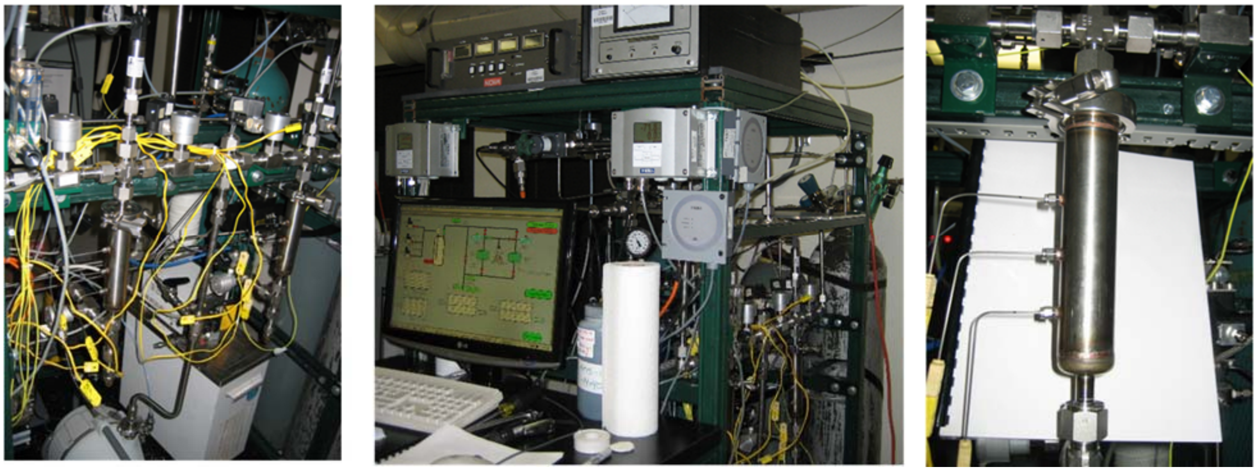


Figure 12.Picture of the bench-scale 2-bed VSA system.

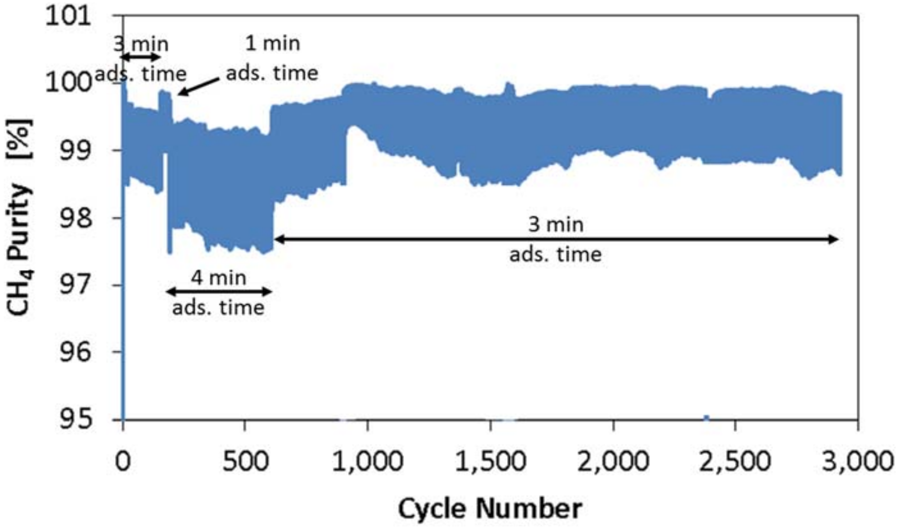


Figure 13. Bench-scale tests in a two-bed vacuum swing cycling system. CH_4 = 60%, CO_2 = 40%, (dry basis), H_2O = sat. at 22°C, space velocity = 125 h^{-1}; T = ambient, P_{ads} = 19.0 psia, P_{des} = 0.2 psia, L/D = 8.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

We compared TDA's VSA system against other competing technologies for biogas purification, such as the high pressure (HP) water system and a membrane system. Of these the HP water system is the only system that currently has full scale commercial systems in place. However, the HP water system cannot achieve greater than 97% methane purity and is the most energy and capital intensive process. Membrane systems are under development and are prone to leaks from pin holes and damage from impurities such as sulfur compounds. TDA's vacuum swing sorbent system is tolerant to all the contaminants present in the biogas. Our process is the least energy intensive among the options available, it has a slightly higher methane loss than the membrane system. Table 2 shows the comparison of these technologies based on their power cost per m^3 of CH_4 produced. TDA's Case 1 and 2 have the lowest power cost at \$0.04 and \$0.05 per m^3 CH_4 produced followed by the membrane system at \$0.06 and finally the HP water system at \$0.12.

Table 2. Comparison of different technologies based on per m^3 methane produced.

	HP water system	Membrane System	TDA VSA System Case 1	TDA VSA System Case 2
Fermentation gas flow (m^3/day)	2000	2000	2000	2000
Methane in the feed (m^3/day)	1200	1200	1200	1200
Methane Purity	97%	99.5%	99.5%	99.5%
Methane Recovery	97%	90%	80.0%	90.0%
Methane produced	1164	1080	960	1080
Power required (kW$_e$)	57.0	25.0	14.6	21.8
Power cost (\$/m^3 CH_4) @ \$0.1/kWh	\$0.12	\$0.06	\$0.04	\$0.05
Sorbent Amount (lbs/year)			1376	1376
Sorbent Cost (@ \$10/lb) \$/m^3 CH_4			\$0.03	\$0.03
Total Operating Cost including sorbent replacement (\$/m^3 CH_4)			\$0.07	\$0.08

3.0 PERFORMANCE OBJECTIVES

The performance objective for TDA supplied biogas purification system is to produce bio-methane (treated biogas) that meets the natural gas specifications. The success criteria were set based on the natural gas specifications, which include:

< 4 ppmv Sulfur
$\geq 95\%$ Methane (CH_4) purity in the product gas
$< 3\%$ Nitrogen (N_2) and Carbon Dioxide (CO_2) in the product gas
$< 0.2\%$ Oxygen (O_2) in the product gas
< 7 lbs/MMscf Moisture

Table 3. Performance Objectives.

Performance Objective	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives			
Gas purification	Methane recovery	≥ 80% methane recovery	≥ 90% methane recovery
	Natural gas specifications	≥ 95% CH_4 in treated biogas	≥ 96% CH_4 in treated biogas
		< 4 ppm H_2S in treated biogas	< 0.25 ppm H_2S in treated biogas
		< 3% N_2 and CO_2 in treated biogas	< 2.7% N_2 and CO_2 in treated biogas
		< 0.2% O_2 in treated biogas	< 0.5% O_2 in treated biogas
		< 7 lbs/MMscf Moisture	< 7 lbs/MMscf Moisture
Qualitative Performance Objectives			
Ease of use	Feedback from field technician on usability of technology and time required	A single field technician able to effectively operate the system remotely with minimal on-site help	System was operated remotely from TDA facilities in Wheat Ridge, CO with minimal to none on-site help

Also we set a qualitative performance objective that the system should be easy to operate remotely with minimal on-site help and a quantitative objective that methane recovery should be greater than 80%.

Methane Recovery is defined as the amount of CH_4 present in the biogas that is recovered as bio-methane (treated biogas).

$$Methane\ recovery\ (\%) = \frac{CH_4\ present\ in\ bio-methane\ product}{CH_4\ present\ in\ biogas}\ x\ 100$$

In order to calculate methane recovery, the volumetric flow rates of the raw biogas feed to TDA's biogas purification system and the bio-methane product (treated biogas) produced are measured using flowmeters upstream (FM-101 Flow Technology's FT series turbine meter) and downstream (FM-401 Brooks Instrument's thermal flowmeter) of the 3-bed VSA system, respectively. We also had in-line CO_2 and humidity probes (from CO_2 meters.com and Kahn Instruments) to quantify the amount of CO_2 and H_2O present in the raw and treated biogas. We also confirmed the methane purity of the raw biogas feed and the treated biogas (bio-methane) using Infrared analyzer in the CDM Smith test Skid to confirm that the bio-methane has greater than 95% methane in it.

CDM Smith also took gas samples of the raw biogas feed before and after both the sulfur sorbent bed and the VSA system and sent them to outside laboratory (ALS Environmental, Simi Valley, CA) for analysis. The samples were received intact under chain of custody by the Laboratory and were stored in accordance with the analytical method requirements till their analysis. The analysis was performed as soon as possible after receipt by the laboratory.

Fixed Gases Analysis: The samples were analyzed for fixed gases (oxygen/argon, nitrogen, methane and carbon dioxide) according to modified EPA Method 3C (single injection) using a gas chromatograph equipped with a thermal conductivity detector (TCD).

Sulfur Analysis: The samples were also analyzed for twenty sulfur compounds per ASTM D 5504-12 using a gas chromatograph equipped with a sulfur chemiluminescence detector (SCD). All compounds with the exception of hydrogen sulfide and carbonyl sulfide are quantitated against the initial calibration curve for methyl mercaptan.

4.0 SITE DESCRIPTION

CDM Smith selected U.S. Air Force Academy (USAFA) located in Colorado Springs, CO as the field test site. A site selection white paper was submitted by CDM Smith to ESTCP on March 3, 2011, which was approved by ESTCP on April 27, 2011. Final approval from USAFA for use of the site for this ESTCP demonstration project was secured on April 12, 2013.

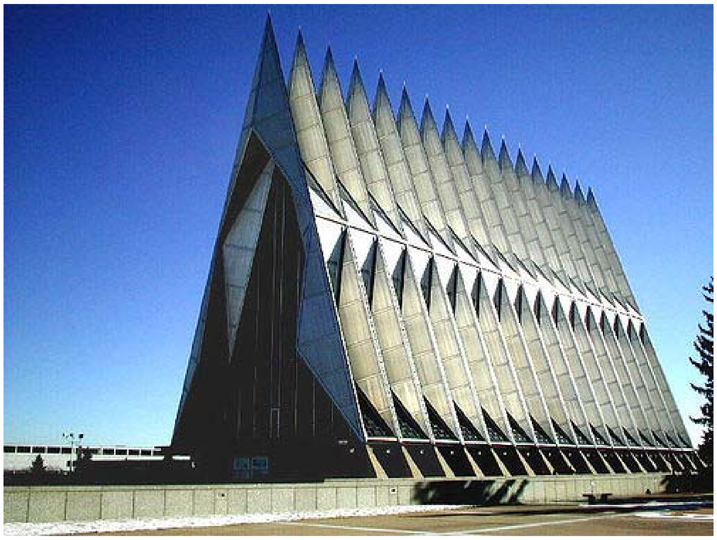


Figure 14. USAFA (Colorado Springs, CO).

USAFA has many attributes making it an excellent site for the ESTCP demonstration. These characteristics include:

- Plentiful supply of food waste and grease trap waste
  USAFA educates 4,500 cadets who eat 3 meals per day/7 days per week at Mitchell Hall. Thus a readily available source of food waste exists. A large grease trap also exists on site and is a ready source of fats, oils, and grease for the CDM Smith demonstration of food waste anaerobic digestion.

- Existing food waste processing capability
  Food waste is sluiced off of plates and containers, ground, and dewatered prior to being bagged and dropped into roll off containers for landfilling. This pretreatment makes transport and handling of the digester feed stock efficient.

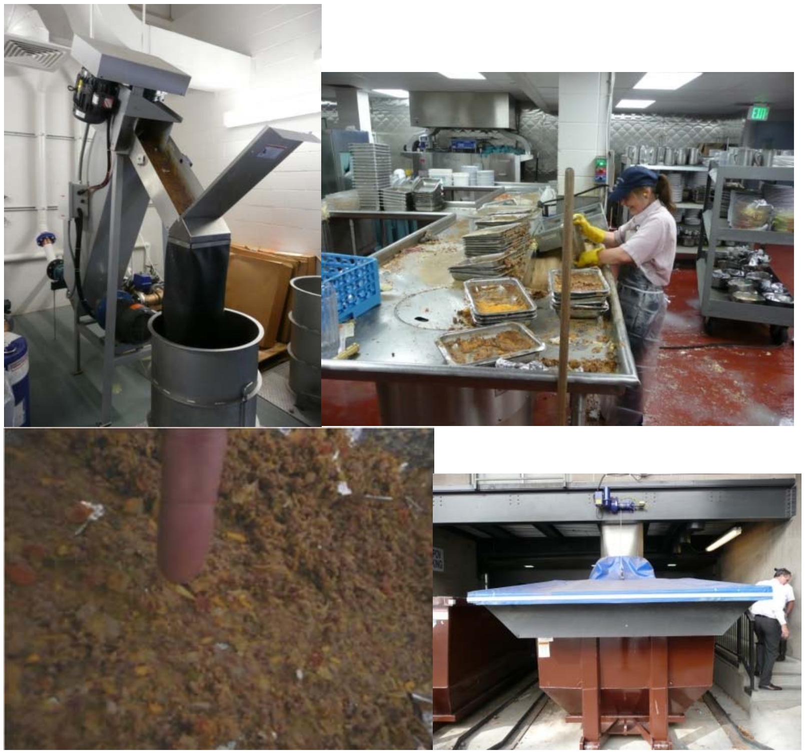


Figure 15. Existing food waste processing at USAFA.

- Operational wastewater treatment plant on-base
  There is an existing anaerobic digester in the wastewater treatment plant and provides an excellent location for the demonstration and provides utilities including electricity,

natural gas, and non-potable/potable water. Demonstration digested sludge can be discharged into full-scale digester 3 according to USAFA staff. Demonstration bio-methane produced by TDA skid (adsorption step product) and the residual/waste biogas (desorption product) can be routed to an existing flare that is currently used to burn full-scale digester biogas.

The scope of the field tests include the anaerobic digestion of the food wastes generated in the USAFA canteens to generate biogas, which is further purified and upgraded to bio-methane (natural gas specification). TDA's responsibility included just the supply of the sulfur sorbent (SulfaTrap^{TM}-R7E) and the VSA system for upgrading biogas to bio-methane, while CDM Smith was responsible for the generation of the biogas from food wastes.

4.1 SITE LOCATION AND INSTALLATION

The pilot plant was installed at the USAFA wastewater treatment plant located approximately ten miles north of downtown Colorado Springs off Stadium Boulevard and Community Center Drive. The unit was installed on the north end of the plant's anaerobic digesters as this space is easily accessible for construction, it had nearby utilities which were tapped for connections, the existing digesters and biogas flare were used to manage the digested waste and excess biogas, and the site was reasonably close to Mitchell Hall, the source of the food waste feedstock. The aerial and ground photographs of the installation site before installation are provided in Figure 16. The bottom right picture in the Figure 16 shows the CDM Smith food waste digestion pilot plant installed along with the biogas storage sphere. The biogas storage sphere was used to store the desulfurized biogas produced from food wastes. Once the biogas sphere is full, the gas was sent to TDA's VSA system to upgrade it to bio-methane.

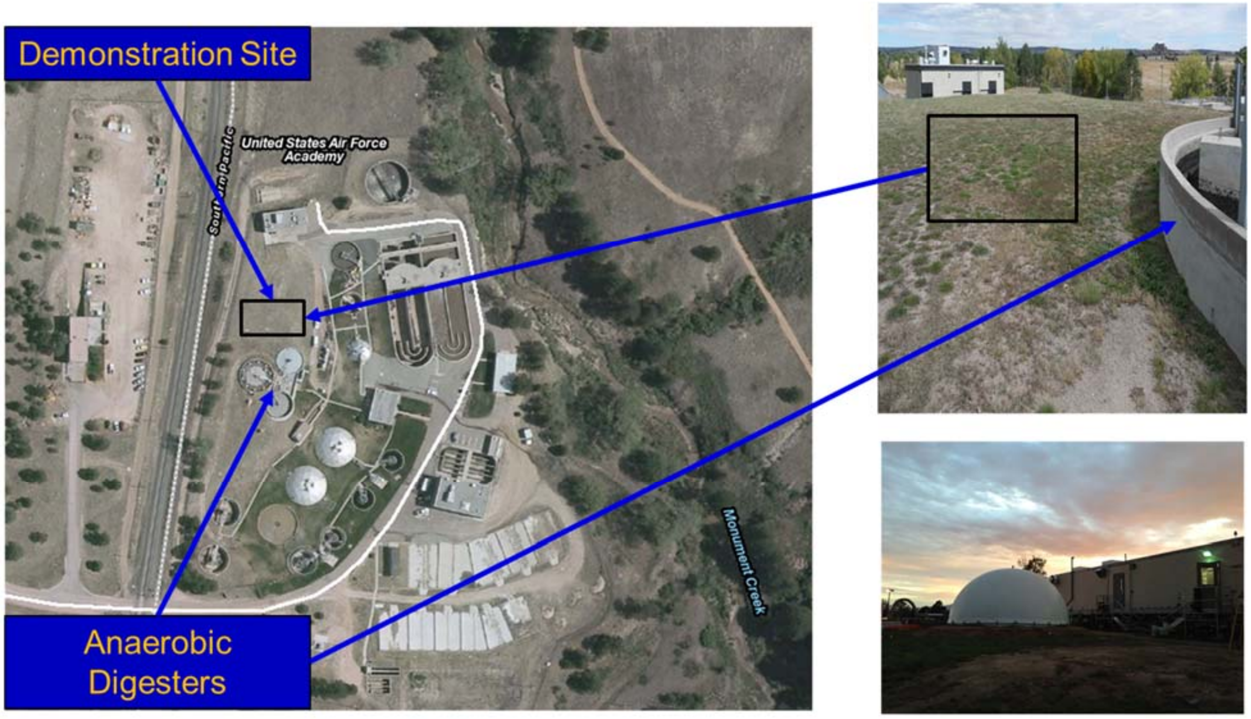


Figure 16. USAFA field test site.

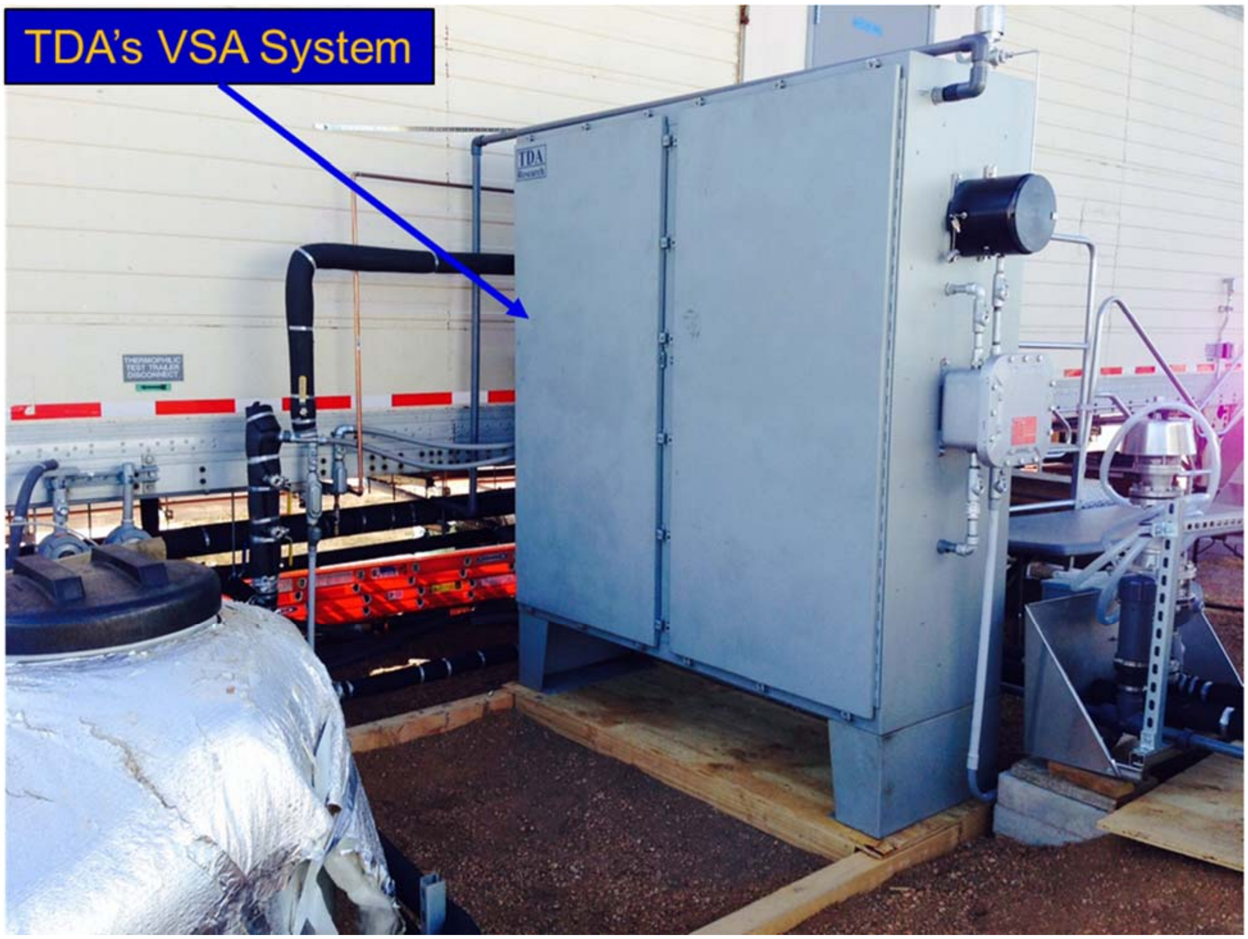


Figure 17. TDA’s VSA system installed at USAFA (Colorado Springs, CO).

Figure 17 shows the TDA’s VSA system installed at USAFA (Colorado Springs, CO). As seen in the picture TDA’s unit was located next to the trailer containing the CDM Smith food waste digestion pilot plant and the biogas sphere.

5.0 TEST DESIGN

This section provides the detailed description of the system design and testing conducted during the field test (demonstration) with TDA's biogas purification sub-systems i.e., the SulfaTrap^{TM} sorbents and the VSA system.

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

TDA's biogas purification system has two stages: Stage 1 removes the sulfur and siloxanes, and Stage 2 removes the CO_2, and moisture to produce bio-methane that contains greater than 95% methane. The first stage is based on a low-cost, high-capacity and expendable sorbent called SulfaTrap^{TM} that simultaneously removed sulfur and siloxane down to ppb levels. The second stage is a vacuum swing adsorption system based on a regenerable mesoporous carbon media modified with surface functional groups to reduce the CO_2 and H_2O concentration in the biogas to pipeline specifications. A schematic of the two-stage system is shown in Figure 2.

A detailed description of the SulfaTrap^{TM} sorbent selection for the first stage and the VSA technology were provided in Section 2.1.

VSA System Description

TDA completed a detailed design and fabricated a fully automated carbon dioxide and moisture removal VSA based demonstration system, as part of the joint effort of the CDM Smith subcontract under the ESTCP project (ER 200933) and the EPA sponsored SBIR Project (EP-D-12-037). The demonstration system was installed at the USAFA waste water treatment plant for field testing with the CDM Smith provided biogas derived from food waste. This system was installed downstream of the food waste digester, desulfurization system, and a storage sphere with 2,000 ft^3 volume. The desulfurization system was used to reduce the sulfur and siloxanes in the biogas to below their detectable limit. The storage sphere was used to store biogas and feed TDA's carbon dioxide and moisture removal VSA system. The VSA system was run in a batch mode and is also capable continuous operation achieving the following performance targets:

> 95% Methane (CH_4) purity in the product gas
> 80% Methane Recovery
< 3% Combined Nitrogen (N_2) and Carbon Dioxide (CO_2) in the product gas
< 0.2% Oxygen (O_2) in the product gas
< 7 lbs/MMscf Moisture

The carbon dioxide and moisture removal system was designed and fabricated with the following characteristics:

- Rated for a Class 1 Division 1 environment. Electronics such the control laptop were de-rated since they are kept a minimum of 10 feet from the biogas lines
- Be fully automated
- Use a regenerable (non-consumptive) media for carbon dioxide adsorption
- Be skid mounted

- Have process control and data logging capability
- Carbon steel piping, vessels and appurtenances are permissible
- Equipped for installation in an outdoor environment

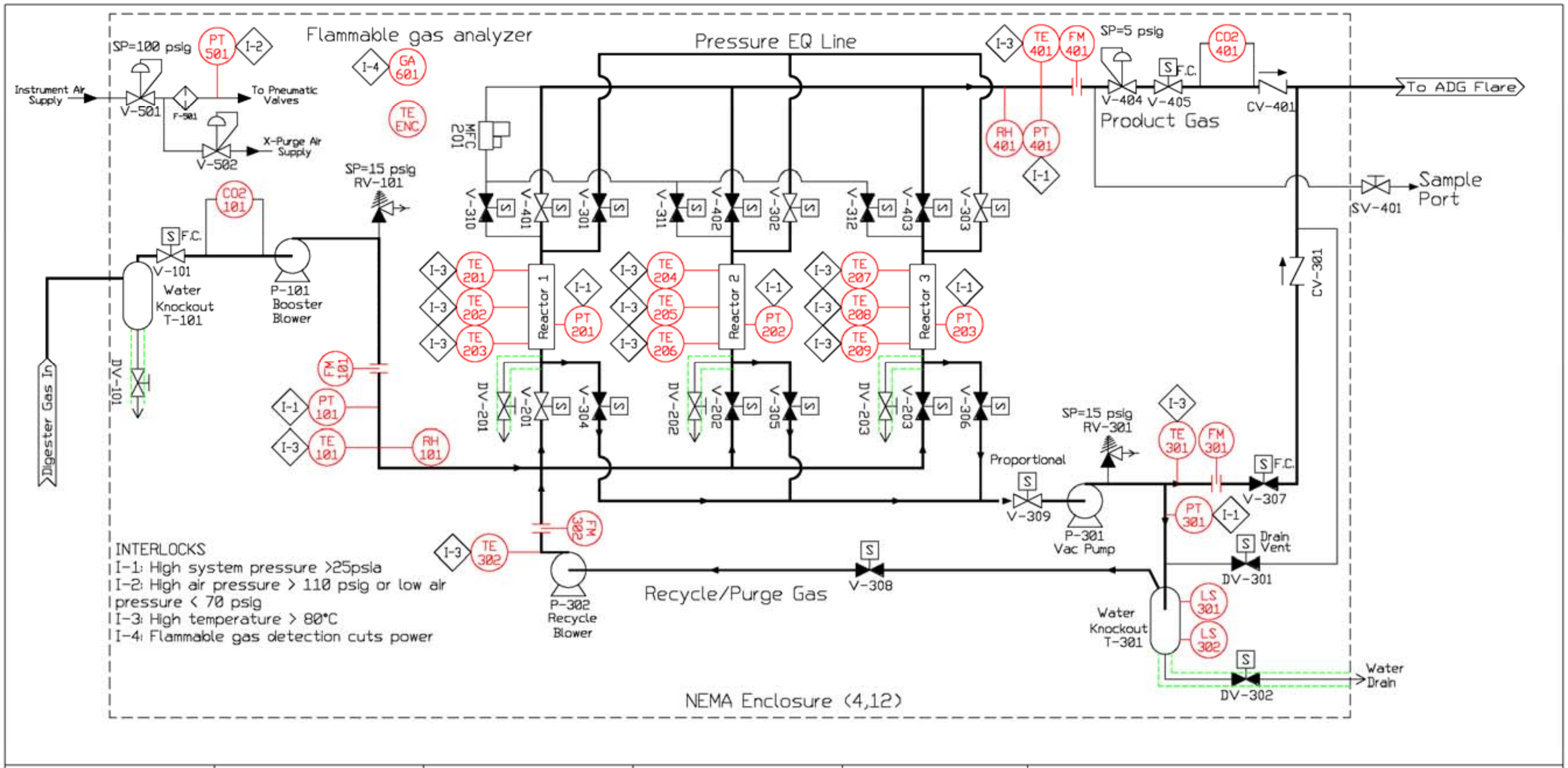
The objective of the field demonstration is to validate anaerobic digestion of food wastes and digester gas treatment technologies in the field through pilot-scale operation, while testing different operational configurations and inputs to determine the most cost effective and stable means of operation. The technical objectives of this demonstration/validation project include: demonstrate anaerobic digestion of commonly available, high-organic waste streams at DoD installations to produce methane-rich biogas; determine suitable waste mixtures and feeding strategies for biogas production and associated engineering design parameters that can guide technology implementation at DoD installations (CDM Smith Scope); validate the ability to produce a valuable end product (bio-methane) from a waste stream for application within the DoD; and document cost and performance of the purification technology (TDA Scope). Prior to transferring the demonstration system to the USAFA we powered-up the VSA system at TDA facilities where we carried out shake-down tests and validated the control sequence. In these tests at TDA we used simulated biogas mixtures containing CO_2 and N_2 mixtures as feed gas.

VSA System Design and Review

The Biogas CO_2 and Moisture Separation System (BioCAMSS a.k.a VSA system) is designed to treat biogas generated from anaerobic digestion of solid wastes from the USAFA by removing the non-methane portions of the biogas (CO_2 and moisture) and producing pipeline quality methane. VSA system will treat biogas with the following inlet conditions:

Temperature:	20-110°F (ambient temperature in Colorado Springs, CO)
CH_4 Content:	50-75% (68% avg)
CO_2 Content:	25-50% (32% avg)
Moisture:	Saturated
Pressure:	0-14”W.C.
Flowrate:	0.14-1.4 L/s (8.4-84 SLPM, 28 SLPM average)

The system uses a 3-bed vacuum swing adsorption design with an inlet booster diaphragm pump, vacuum desorption pump (scroll-type), a recycle diaphragm pump, and all of the necessary valves and tubing to control flow through the system. It is an automated self-contained system using an OPTO22 controller but was connected to a laptop for remote viewing and adjustment of operating variables. The entire system is built within a NEMA 4/12 electrical enclosure. The enclosure utilizes a Type-X purge system. Type X purging reduces the classification within the protected enclosure from Division 1 to nonhazardous. Failure to maintain pressure within the protected enclosure and/or adequate exhaust flow from the enclosure vent is detected by an alarm/ indicator. The dilution purge time is an automatically controlled operation and once the enclosure has been purged of ignitable or flammable concentrations, only positive pressure and adequate exhaust flow from enclosure vent are required to be maintained within the protected enclosure. If the alarm is actuated, the power to the entire enclosure is turned off. Heat tracing is provided on the condensate drain lines to prevent freezing. These are simple heat tapes with integral thermostats.


SP=100 psig
PT 501
I-2
Instrument Air Supply
V-501
F-501
To Pneumatic Valves
X-Purge Air Supply
V-502
Flammable gas analyzer
I-4
GA 601
TE ENC
MFC 201
Pressure EQ Line
I-3
TE 401
FM 401
SP=5 psig
CO2 401
S F.C.
V-404
V-405
CV-401
To ADG Flare
Product Gas
RH 401
PT 401
I-1
Sample Port
SV-401
CO2 101
S F.C.
V-101
Water Knockout T-101
P-101 Booster Blower
SP=15 psig RV-101
V-310
V-401
V-301
V-311
V-402
V-302
V-312
V-403
V-303
TE 201
TE 202
TE 203
Reactor 1
PT 201
TE 204
TE 205
TE 206
Reactor 2
PT 202
TE 207
TE 208
TE 209
Reactor 3
PT 203
CV-301
Digester Gas In
DV-101
FM 101
PT 101
TE 101
RH 101
DV-201
V-201
V-304
DV-202
V-202
V-305
DV-203
V-203
V-306
SP=15 psig RV-301
Proportional
TE 301
FM 301
S F.C.
V-307
V-309
P-301 Vac Pump
PT 301
Drain Vent
DV-301
INTERLOCKS
I-1: High system pressure >25psia
I-2: High air pressure > 110 psig or low air pressure < 70 psig
I-3: High temperature > 80°C
I-4: Flammable gas detection cuts power
FM 302
TE 302
P-302 Recycle Blower
Recycle/Purge Gas
V-308
Water Knockout T-301
LS 301
LS 302
DV-302
Water Drain
NEMA Enclosure (4,12)

Reactor Vessels	P-101, P-302	P-301	T-101, T-301	HEAT TRACING
6 in SCH10S 304 SS 20 L 40 in Long	Air Dimensions R254-FT-ME3 Max P: 75 psig Max Vac: 24.9 inHg Max Flow: 3.8 cfm 1 HP 230 VAC 3ph -20 to 40°C	Edwards XDS5 Max P(in): 7 psig Max P(out): 15 psig Max Flow: 3.5 cfm 0.4 HP 230 VAC 3ph 10 to 40°C	McMaster-Carr 9934K39 316SS 1 GAL Max Press: 200 psi Max Temp: 340°C	McMaster-Carr 3554K21 (typ.) Various length self-regulated heat cable. 63W max.

TDA RESEARCH INC.
12345 W. 52ND AVE. WHEAT RIDGE, CO 80033
PHONE: (303) 422-7819 FAX: (303) 422-7763

DRAWN	DATE	TITLE				
mcc	1/24/2014	BioCAMSS CO2/H2O Removal System				
CHECKED	DATE					
kal	1/24/2014					
APPROVED	DATE	SCALE	SHEET SIZE	SHEET	DRAWING NO.	REV.
mcc	1/24/2014	N/A	B	1 OF 1	TDA-CDM-PID	6

Figure 18. Process and Instrumentation Diagram (P&ID) for BioCAMSS.

TDA initially prepared a detailed design of the pilot scale CO_2 and humidity removal unit to meet all of CDM Smith's Requirements. Figure 18 and Figure 19 shows the P&ID and the 3-D layout of the pilot scale unit. A simplified block diagram of the mechanical interface requirements for the prototype unit is provided in Figure 4. Complete design and interface documents were provided to CDM Smith as part of the design package for review on January 9, 2013. Then the design and interfaces (both mechanical and electrical) were revised as needed to address the questions raised by CDM Smith during the review (March 15, 2013). TDA successfully completed the design review for the pilot scale CO_2 and humidity removal Unit in March 2013 and started the fabrication of the prototype unit.

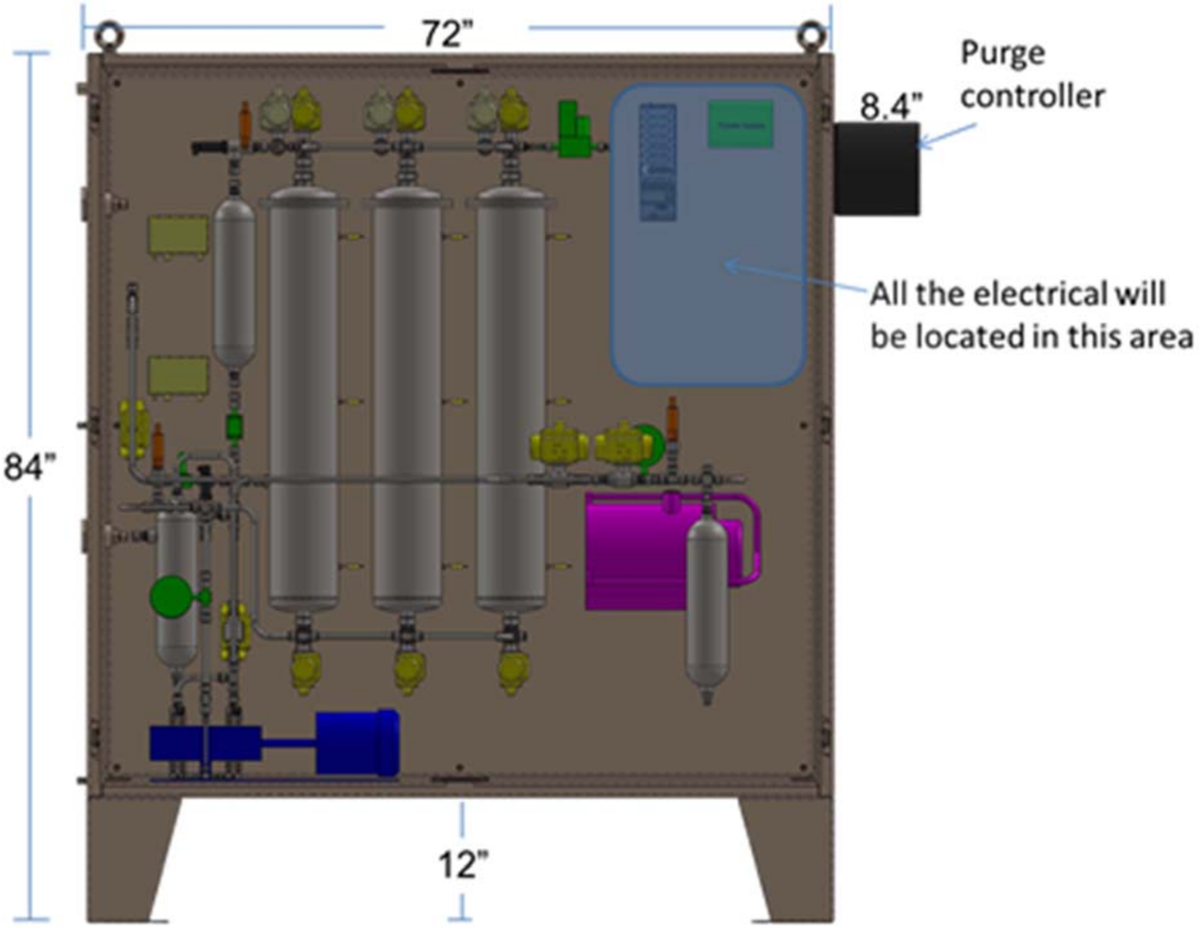


Figure 19. 3-D layout of the pilot scale CO_2 and H_2O removal unit.

VSA System Fabrication

We fabricated the three reactors and built the skid mounted pilot scale unit including the control system following the approved design. The system is rated for Class1 Div 1. Pictures of the VSA system during fabrication showing the major components are provided in Figure 20 through Figure 23.

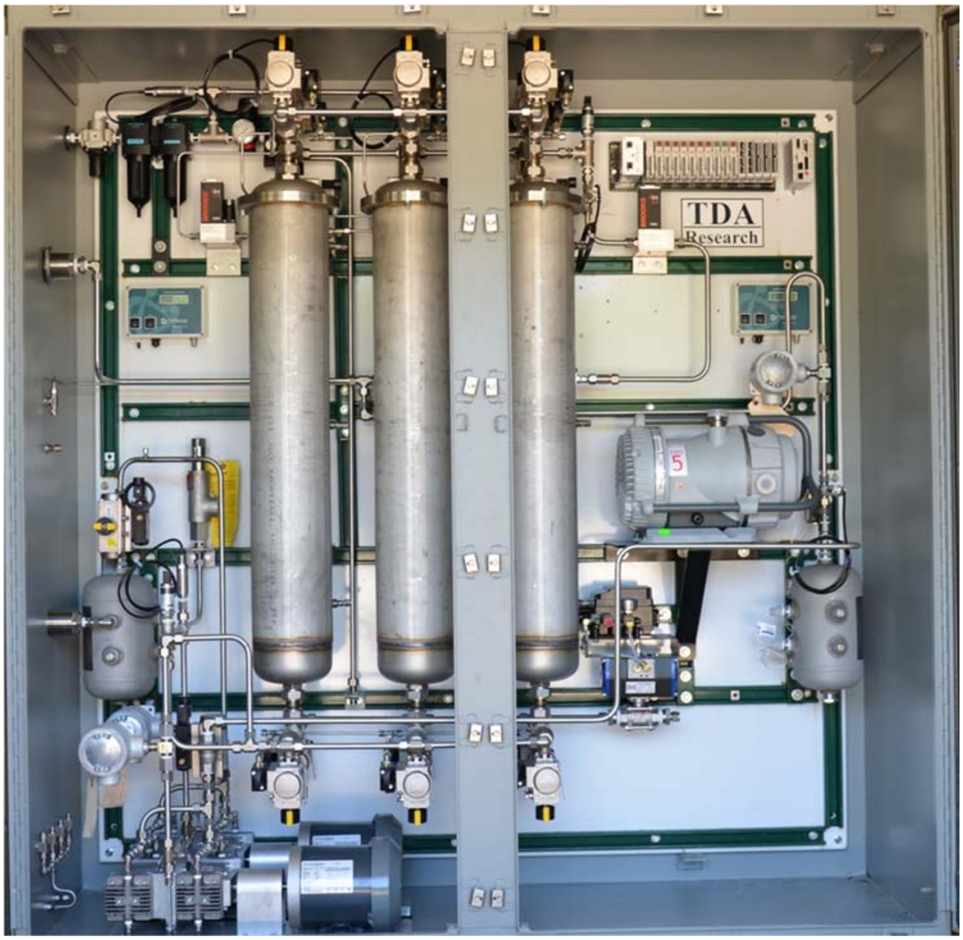


Figure 20. Picture of the pilot scale CO_2 and H_2O removal unit.

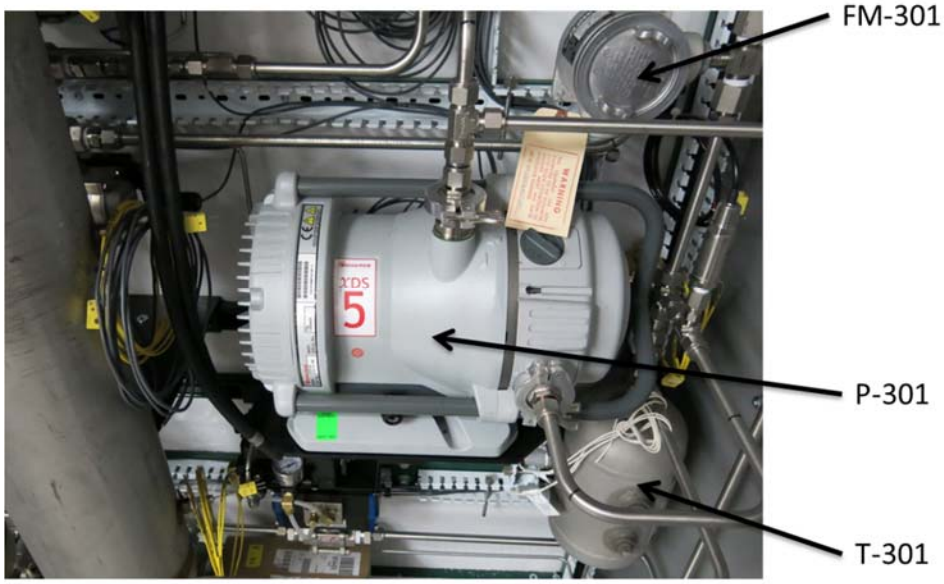


Figure 21. Picture of the pilot scale unit showing the blowdown gas flowmeter (FM-301), water knockout (T-301) and the vacuum pump (P-301).

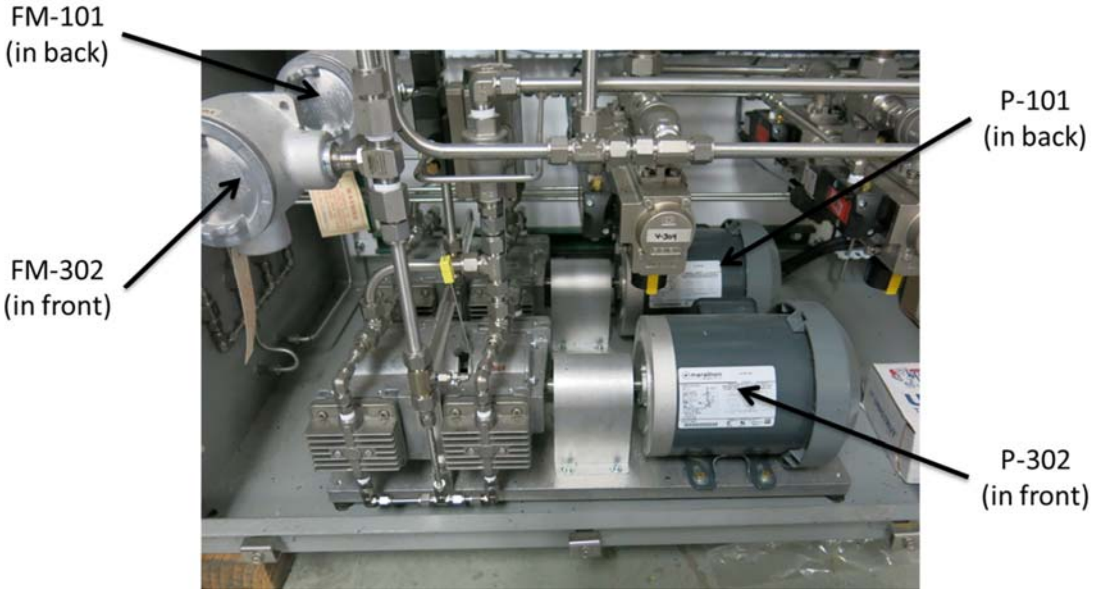

FM-101
(in back)
P-101
(in back)
FM-302
(in front)
P-302
(in front)

Figure 22. Picture of the pilot scale unit showing the feed biogas flowmeter (FM-101), recycle gas flowmeter (FM-302), feed biogas booster blower (P-101) and the recycle gas blower (P-302).

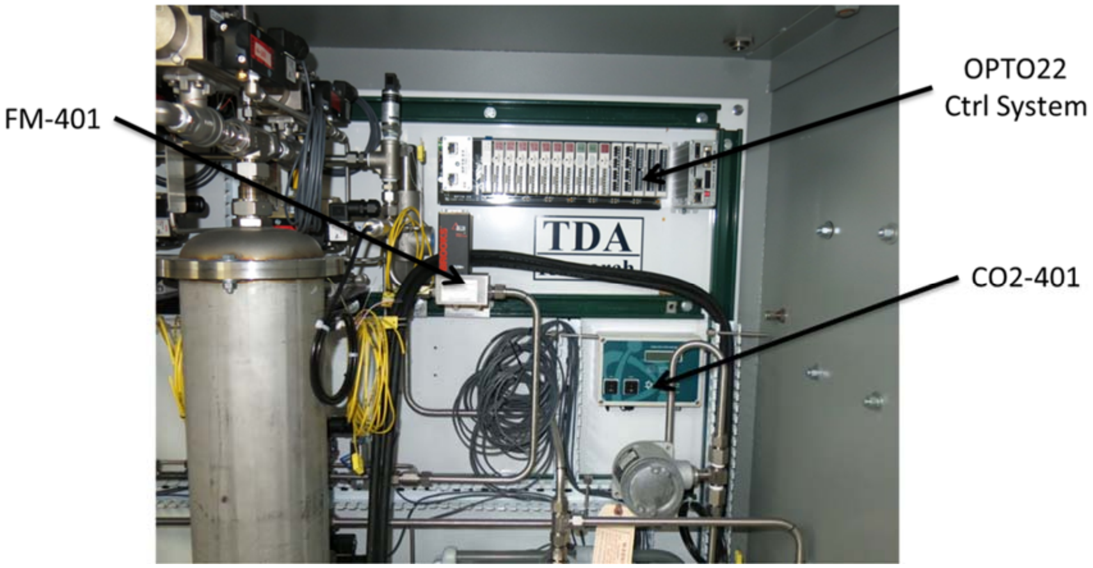

FM-401
OPTO22
Ctrl System
TDA
CO2-401

Figure 23. Picture of the pilot scale unit showing the product methane flowmeter (FM-401), product CO_2 analyzer (CO2-401), and OPTO22 Control System.

CO_2 Sorbent Production for Pilot Unit

TDA scaled–up the production of the CO2 and moisture removal sorbent for biogas purification application and prepared the sorbent needed for the VSA system (pilot unit). We measured the surface area and CO_2 and CH_4 adsorption capacities for each of the preparation batch to ensure that the material prepared meets the specifications of CO_2/CH_4 equilibrium selectivity (on wt. basis) of 6.0 or higher, with surface area of 130-200 m^2/g.

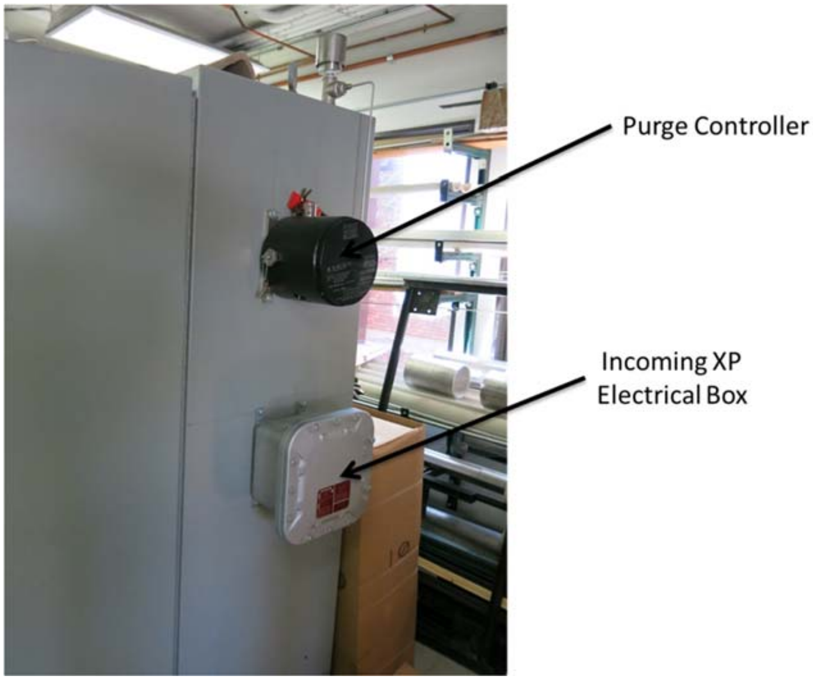


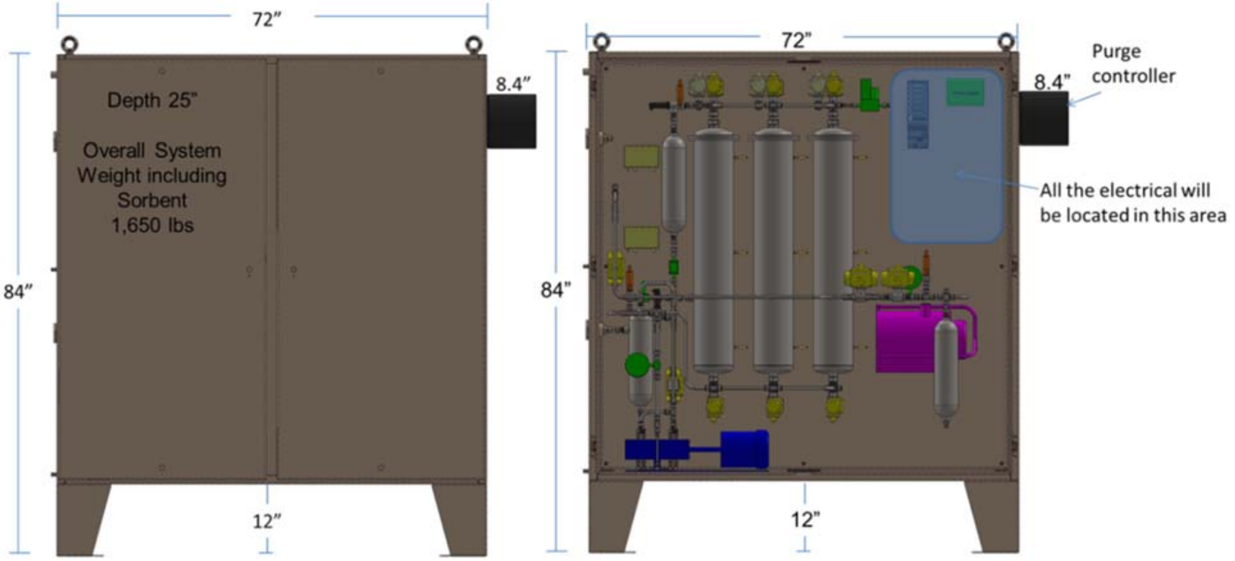
Figure 24. Picture of the pilot scale unit showing the Type X purge controller and the incoming XP electrical box.

The carbon was produced using a continuous rotary kiln, collected and stored in gallon jugs, and the BET surface areas were measured. The sorbent produced for the pilot scale test unit has the following properties: CO_2/CH_4 equilibrium selectivity on wt. basis of 6.3 and above (average of 6.7±0.3) and a sorbent surface area of 166±37 m^2/g. The adsorption data along with selectivity for the sorbent samples that are prepared in our pilot plant facility for the pilot scale test unit are summarized Table 4.

Table 4. Summary of properties of sorbent prepared for pilot scale test unit.

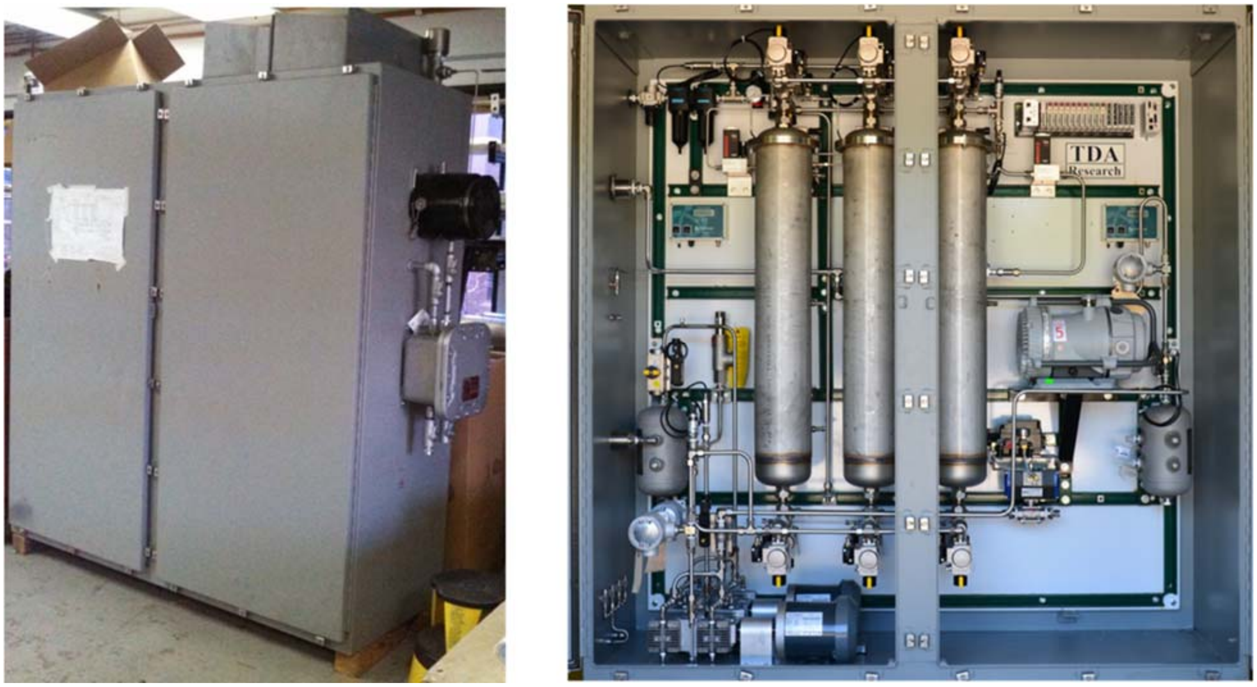
Sample #	Temperature (^oC)	Bulk Density (g/cc)	BET Surface Area (m^2/g)	Amount Adsorbed		CO_2/CH_4 wt. ratio @ 1 atm	$t_{1/2}$ (eqm.)		Kinetic Ratio CH_4/CO_2
				CO_2 @ 1 atm	CH_4 @ 1 atm		CO_2 seconds	CH_4 seconds	
TMLR 101013 #4 AMS-187	22	0.285	201	8.32	1.33	6.3	2	7	3.5
	60			5.10	0.77	6.6	2	9	4.5
TMLR 101413 #8 AMS-187	22	0.318	173	7.75	1.17	6.6	3	16	5.3
	60			4.71	0.67	7.0	2	17	8.5
TMLR 101513 #14 AMS-187	22	0.314	176	8.44	1.26	6.7	3	5	1.7
	60			5.10	0.73	7.0	2	8	4.0
TMLR 101513 #18 AMS-187	22	0.300	114	7.82	1.1	7.1	4	27	6.8
	60			4.61	0.66	7.0	2	24	12.0
Pilot Scale Sorbent Average	22	0.304	166	8.08	1.22	6.7	3	14	4.6
	60			4.88	0.71	6.9	2	15	7.3
Pilot Scale Sorbent Std Dev.	22	0.015	37	0.35	0.10	0.3	0.8	10.0	2.2
	60			0.26	0.05	0.2	0.0	7.5	3.8

5.2 PILOT SCALE UNIT



72"
Depth 25"
Overall System Weight including Sorbent 1,650 lbs
8.4"
84"
12"
72"
Purge controller
8.4"
All the electrical will be located in this area
84"
12"

Figure 25. 3-D layout of the pilot scale VSA system for CO_2 and H_2O removal from biogas.

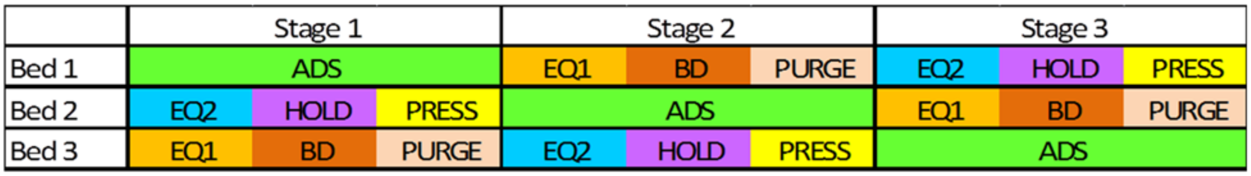


TDA Research

Figure 26. Picture of the pilot scale VSA system for CO_2 and moisture removal from biogas.

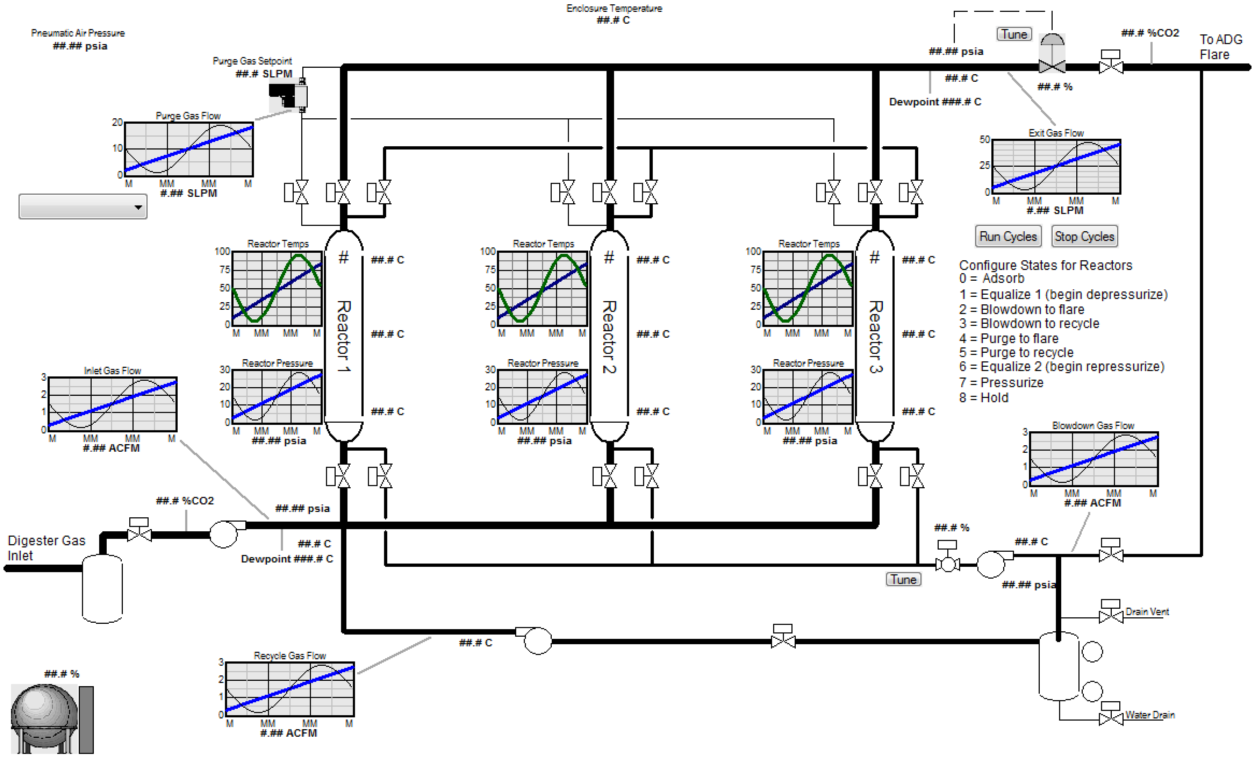
The pilot-scale biogas fully automated vacuum swing adsorption (VSA) based carbon dioxide and moisture removal system for biogas was designed and fabricated. Figure 25 shows the 3-D layout of the pilot unit. This system is part of the biogas purification subsystem and is installed downstream of the SulfaTrap™ desulfurization system, and a biogas storage sphere. The storage sphere was used to store biogas and feed the carbon dioxide and moisture removal system and it can achieve greater than 95% methane (CH_4) purity in the product gas with greater than 90% methane recovery, reducing the inerts to less than 3% (i.e., combined Nitrogen (N_2) and Carbon Dioxide (CO_2)) in the product gas and a moisture content lower than 7 lbs/MMscf. The system was designed and fabricated for operation in a Class 1 Division 1 environment and is skid mounted located inside a NEMA 4 enclosure equipped with a purge system and rated for installation in an outdoor environment. Figure 26 shows the picture of the system after fabrication.

5.3 TREATABILITY OR LABORATORY STUDY RESULTS



	Stage 1			Stage 2			Stage 3		
Bed 1	ADS			EQ1	BD	PURGE	EQ2	HOLD	PRESS
Bed 2	EQ2	HOLD	PRESS	ADS			EQ1	BD	PURGE
Bed 3	EQ1	BD	PURGE	EQ2	HOLD	PRESS	ADS		

Figure 27. 3-bed VSA cycle sequence.



Pneumatic Air Pressure
##.## psia
Enclosure Temperature
##.# C
Purge Gas Setpoint
##.# SLPM
Purge Gas Flow
#.## SLPM
Tune
##.## psia
##.# C
Dewpoint ###.# C
##.# %
##.# %CO2
To ADG Flare
Exit Gas Flow
#.## SLPM
Run Cycles
Stop Cycles
Reactor Temps
Reactor Pressure
##.## psia
Reactor 1
Reactor 2
Reactor 3
##.# C
Inlet Gas Flow
#.## ACFM
Blowdown Gas Flow
#.## ACFM
Digester Gas Inlet
##.# %CO2
##.## psia
##.# C
Dewpoint ###.# C
##.# %
Tune
##.# C
##.## psia
Drain Vent
Water Drain
##.# C
Recycle Gas Flow
#.## ACFM
##.# %

Configure States for Reactors
0 = Adsorb
1 = Equalize 1 (begin depressurize)
2 = Blowdown to flare
3 = Blowdown to recycle
4 = Purge to flare
5 = Purge to recycle
6 = Equalize 2 (begin repressurize)
7 = Pressurize
8 = Hold

Figure 28. Snap-shot of the OPTO-22 control screen for the 3-bed VSA system.

Tests at TDA using Simulated Biogas

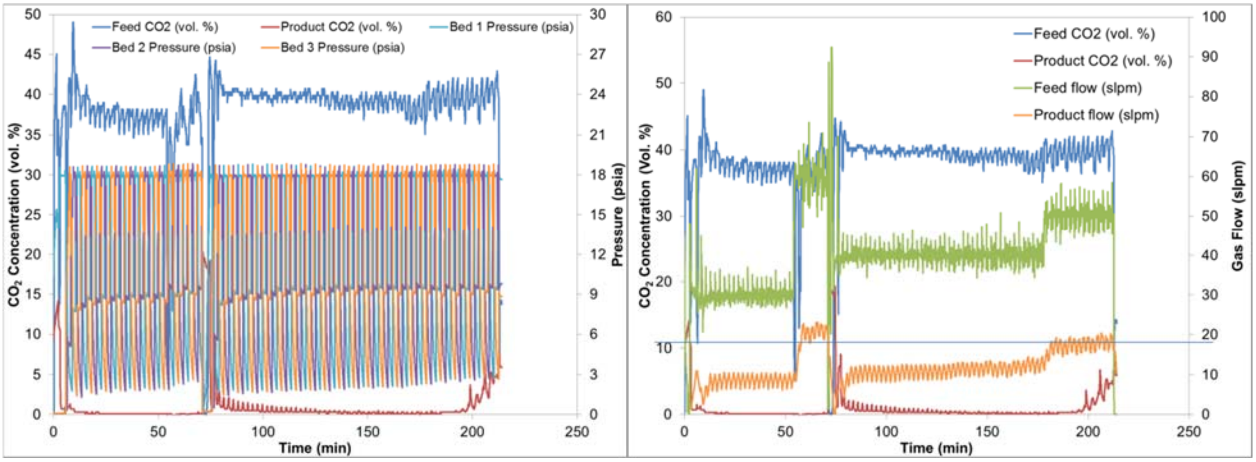


Figure 29. Snap-shot of the 3-bed VSA system operation at TDA using simulated biogas under simple VSA cycle scheme without equalization and desorption product recycle.

Figure 27 shows the 3-bed VSA cycle sequence. The programming of the VSA cycle sequence was done in the OPTO-22 control system. Figure 28 shows the snapshot of the OPTO-22 control screen. We validated the control system for the VSA cycles in the pilot scale unit in the tests at TDA. Figure 29 shows the results from tests at TDA using simulated biogas when the system was operated under a simple VSA scheme without equalization and recycle of the desorption product, which will improve the methane recovery to above 90%.

5.4 FIELD TESTING

Start-up and VSA Cycle Optimization

The purification system was demonstrated in conjunction with a food waste anaerobic digestion study conducted at the U.S. Air Force Academy (USAFA) in Colorado Springs, CO. This particular test site was selected due to the plentiful supply of food and grease trap waste. A variety of food wastes, including pre- and post-consumer food waste, waste cooking oil, and grease trap waste from USAFA was used to produce biogas in the CDM Smith's pilot scale anaerobic digester unit and this biogas was sent to desulfurizer column and the sulfur free biogas was stored in a biogas sphere and once the sphere is full the biogas was sent to TDA's VSA unit to produce pipeline quality bio-methane. TDA's 3-bed VSA system is designed for 24/7 continuous operation and can treat up to 3 scfm. However, we only operated the 3-bed VSA system during regular business hours so that we always have an operator available on-site. This operator's role is only to provide TDA unit the permission to operate. The unit was operated by TDA personnel remotely from our offices in Wheat Ridge, CO and was shut down at the end of the day's operation. We operated the VSA system only when the digester was full, which is typically 2-3 days in a week.

We started the field tests with VSA unit on February 28, 2015 and the biogas sphere contained raw biogas on the first day of test. Then, the desulfurizers were loaded with SulfaTrap^{TM} sample and desulfurized biogas was stored in the sphere, which was later used for breakthrough tests through

March 28, 2014. During these tests, we noticed that when we ran VSA cycles through multiple beds the check valve leaked the CO_2 rich desorption product into the CO_2 free (bio-ethane) product manifold. Hence, we increased the check valve rating to higher pressure say 3-5 psi to prevent back flow this helped in preventing contamination of bio-methane exiting the beds. Then in April 2014, we optimized VSA cycle design, by exploring different cycle design options such as feed end pressurization, product end pressurization, pressure equalization, and biogas flow rate.

System Operation

Table 5. Summary of the field tests carried out with TDA's 3-bed VSA system.

Date	Test Duration (min)	Cycle time (sec)	Number of Cycles	Feed Biogas			Product Bio-methane					Sorbent Capacity (% wt. CO_2)
				Total flow (SCF)	flow (slpm)	CO_2 (vol. %)	Total flow (SCF)	flow (slpm)	CO_2 (vol. %)	CH_4 recovery (vol. %)	CH_4 Purity (vol. %)	
2/28/2014	78.5	810	5.8	28.0	10.1	35.8	6.3	2.262	3.7	34	96.3	0.5
3/6/2014	270.0	1050	15.4	123.6	12.96	45.2	39.5	4.142	13	51	87	1.0
3/14/2014	60.0			101.7	48							
3/18/2014	248.0			420.4	48							
3/28/2014	140.0			237.3	48							
4/1/2014	91.8	810	6.8	123.4	38.1	49.1	58.8	18.1	0.9	67	99.1	3.6
4/8/2014	162.1	1251	12.0	214.4	37.4	49.4	44.7	7.8	0.1	41	99.9	2.6
4/10/2014	134.8	810	10.0	181.2	38.1	49.1	39.2	8.2	0.3	60	99.8	2.6
4/15/2014	121.7	810	9.0	169.6	39.5	51.7	35.9	8.4	0.7	44	99.3	2.8
4/15/2014	94.7	810	7.0	127.9	38.3	51.5	38.5	11.5	0.4	62	99.6	2.7
4/23/2014	108.4	810	8.0	148.3	38.7	50.1	39.9	10.4	1.7	53	98.3	2.7
4/24/2014	378.7	810	28.0	543.4	40.6	52.3	153.6	11.5	0.8	59	99.2	2.9
7/16/2014	81.1	810	6.0	103.1	36.0	50.0	26.4	9.2	2.8	83	97.2	1.5
7/21/2014	9.7	810	0.7	8.0	23.3	58.0	2.8	8.1	1.3	82	98.7	5.6
7/22/2014												
7/23/2014	145.4	1140	7.7	149.9	29.2	58.0	46.9	9.1	1.8	73	98.2	3.3
7/25/2014	155.8	1550	6.0	132.9	24.2	42.0	76.7	13.9	8.7	91	91.3	2.4
7/29/2014	412.2	1110	22.3	282.5	19.4	42.0	157.5	10.8	2.8	93	97.2	1.5
7/30/2014	150.8	1110	8.2	117.3	22.0	42.0	63.3	11.9	1.7	92	98.3	1.7
7/31/2014	168.2	1110	9.1	161.2	27.1	42.0	81.3	13.7	1.3	86	98.7	2.1
8/31/2014	240.5	1110	13.0	247.2	29.1	42.0	132.9	15.6	2.2	91	97.8	2.2

The CDM Smith digester was offline for maintenance during May – June 2014 and the tests were re-started in July 2014. In the tests carried out in July 2014 we operated the VSA system under optimized test conditions and demonstrated high bio-methane purity and recovery. The Summary of the field test results are provided in Table 5.

System Shutdown

The field tests were completed on August 31, 2014 and TDA's unit were shipped back to TDA in the beginning of September 2014.

5.5 SAMPLING METHODS

In order to calculate methane recovery, the volumetric flow rates of the raw biogas feed to TDA's biogas purification system and the bio-methane product (treated biogas) produced were measured using flowmeters upstream (FM-101 Flow Technology's FT series turbine meter) and downstream (FM-401 Brooks Instrument's thermal flowmeter) of the 3-bed VSA system, respectively. We also had in-line CO_2 and humidity probes (from CO_2 meters.com and Kahn Instruments) to quantify the amount of CO_2 and H_2O present in the raw and treated biogas. We also confirmed the methane purity of the raw biogas feed and the treated biogas (bio-methane) using Infrared analyzer in the CDM Smith test Skid to confirm that the bio-methane has greater than 95% methane in it.

CDM Smith also took gas samples of the raw biogas feed before and after both the sulfur sorbent bed and the VSA system and sent them to outside laboratory (ALS Environmental, Simi Valley, CA) for analysis. The samples were received intact under chain of custody by the Laboratory and were stored in accordance with the analytical method requirements till their analysis. The analysis was performed as soon as possible after receipt by the laboratory. The Analysis methods are described in Section 3.0.

5.6 SAMPLING RESULTS

Typical composition of the raw biogas and the bio-methane produced in the field tests are provided in Table 6. The sulfur in the raw biogas was typically around 1,000 – 1,500 ppm H_2S with trace amounts of organic sulfur compounds. SulfaTrap^{TM}-R7 desulfurization sorbent removed the sulfur compounds to less than 0.25 ppmv.

Table 6. Typical composition of raw, sweetened biogas and bio-methane from food wastes during field tests.

Sample Date:	Raw biogas 7/16/2014	Sweetened biogas 7/16/2014	Bio-methane 7/16/2014
CH_4	64.40	61.70	96.35
CO_2	34.80	36.00	2.03
N_2	0.60	1.66	1.11
O_2/Ar	0.23	0.67	0.52

We initially carried out breakthrough tests with the CO_2 sorbent beds in the field using desulfurized food waste derived biogas to measure the capacity of the saturated VSA adsorbent bed, which were above 4.4% wt. CO_2. Figure 30 shows the CO_2 breakthrough for one of the three beds, "CO2_101" is the inlet CO_2 concentration to the VSA bed and "CO2_401" is the exit CO_2 concentration from the VSA bed. We optimized the VSA cycles in the field and the optimized VSA cycle scheme was used to produce high purity bio-methane with methane recovery greater than 90%. VSA cycle schemes with both feed end and product end pressurizations provided working capacities in excess of 2.8% wt. and the CO_2 concentration in the bio-methane product was reduced to less than 0.5% by vol. The dew point of the biogas was reduced from 10-15°C to less than -40°C, providing essentially a dry bio-methane product. Figure 31 and Figure 32 show the CO_2 and H_2O removal, respectively, from actual biogas at USAFA. Figure 33 shows the methane purity of the bio-methane as measured by an IR based methane analyzer. We operated the biogas purification system for a total of 54 hours purifying more than 3,620 SCF of biogas to produce bio-methane with greater than 90% methane recovery.

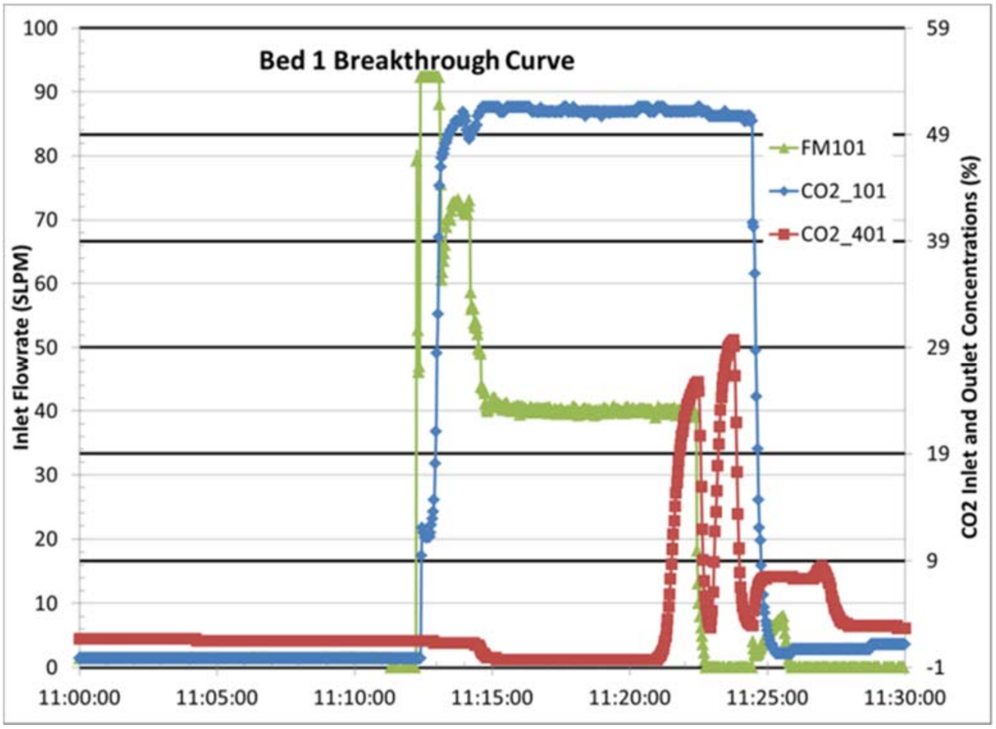


Figure 30. CO_2 Breakthrough curve from single bed saturation experiment conducted with actual biogas at USAFA (Colorado Springs, CO).

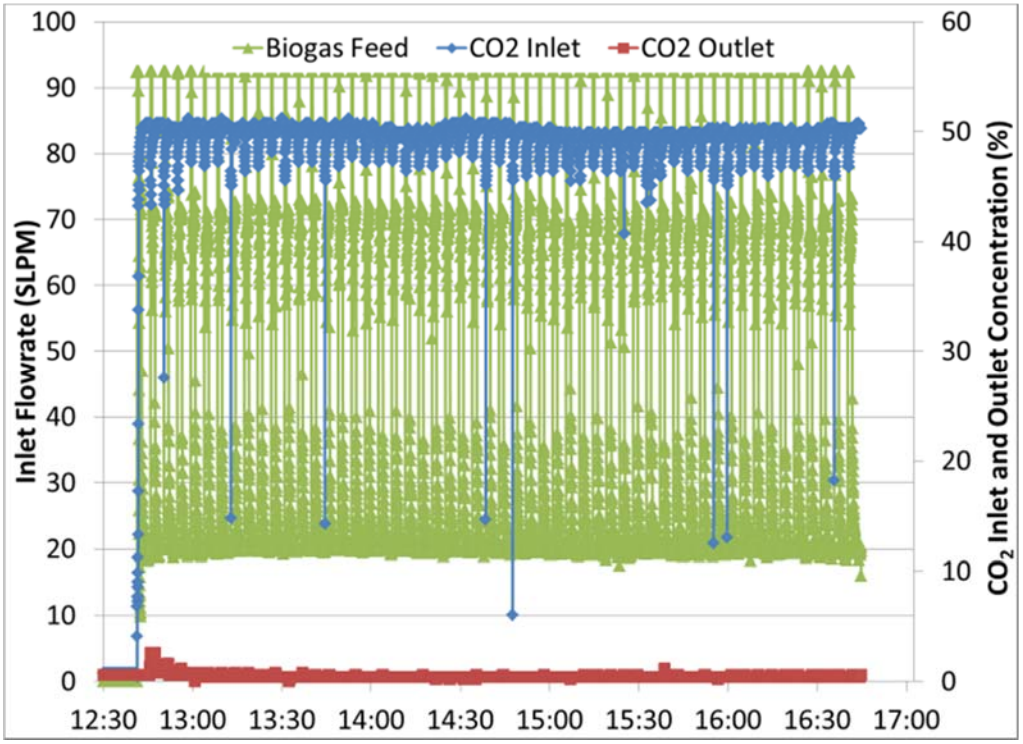


Figure 31. Biogas purification system performance for CO_2 removal from actual biogas at USAFA (Colorado Springs, CO).

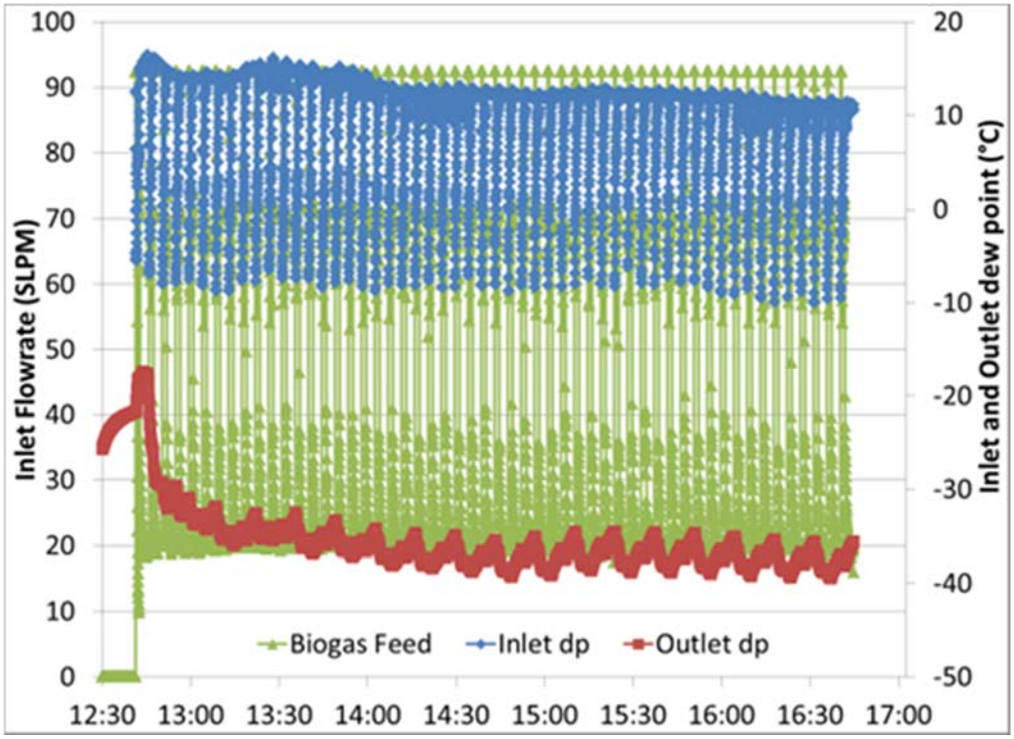


Figure 32. Biogas purification system performance for H_2O removal from actual biogas at USAFA (Colorado Springs, CO).

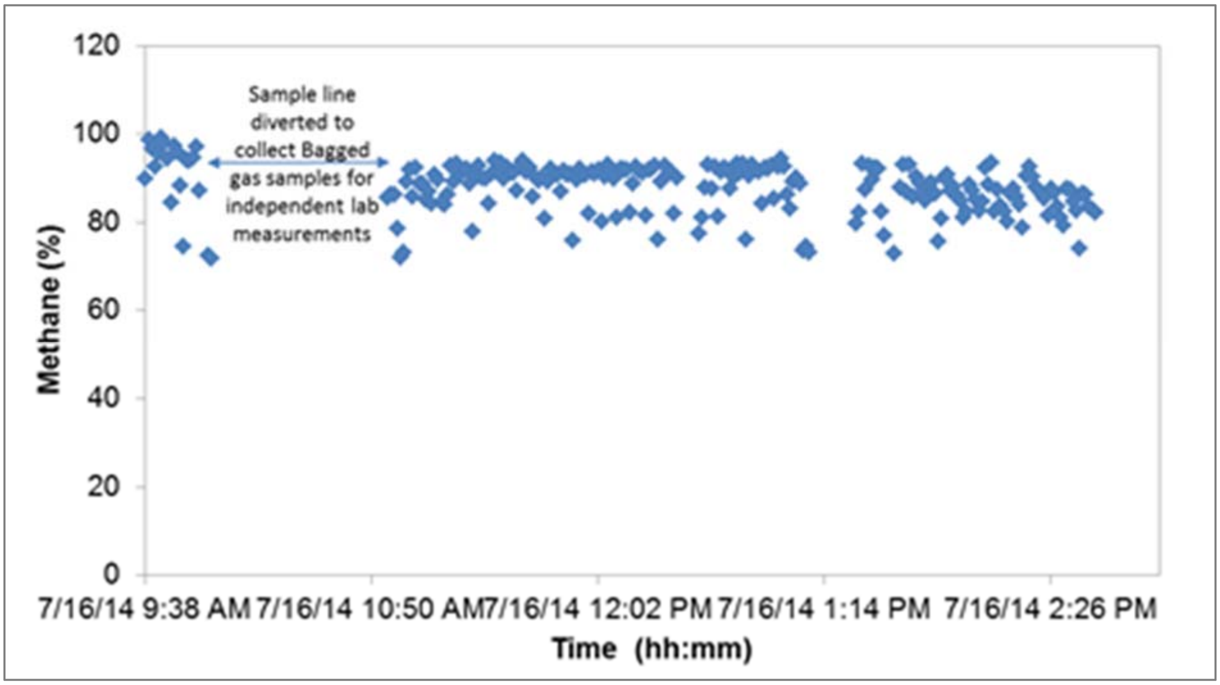
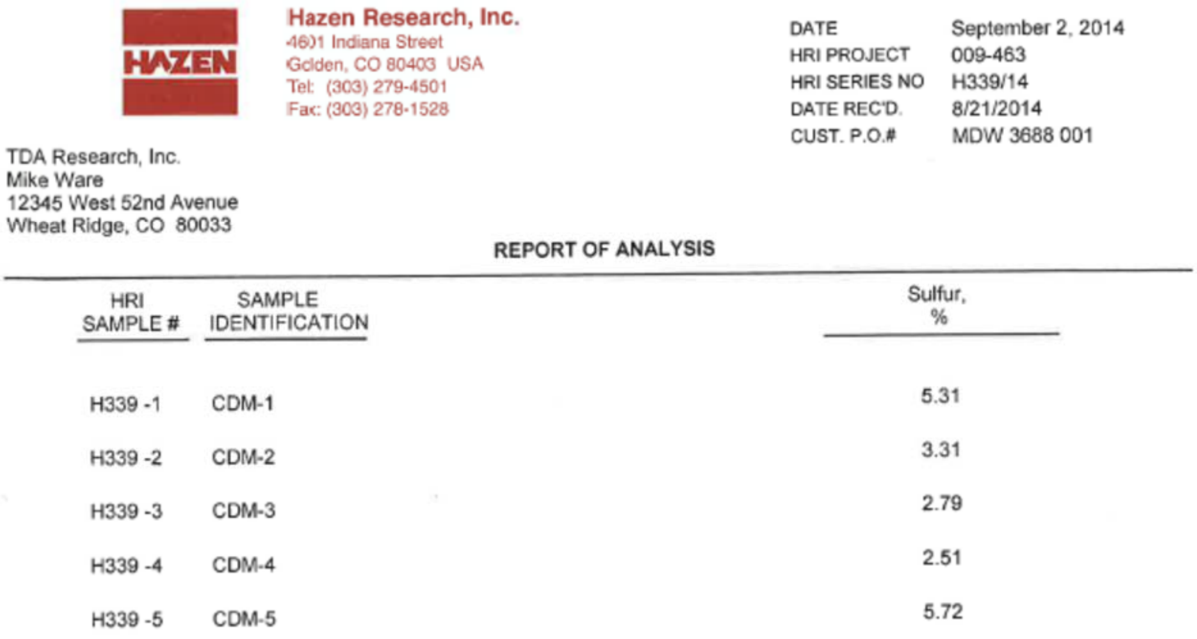


Figure 33. Biogas purification system performance under actual biogas at USAFA (Colorado Springs, CO) showing the high purity bio-methane production.

Post Analysis of Sulfur Sorbent

We carried out post sulfur analysis of the R7 sorbent removed from CDM Smith desulfurizer (reactor). The gas flow direction is from samples coded CDM-1 to CDM-5. With the sorbent being pulled at the following axial positions in the bed z=0; Z=1/4L; Z=1/2L; Z=3/4L, z=L. The exit end showed higher sulfur loading similar to the inlet, while the other locations showed expected trend of deceasing sulfur loading in the gas flow direction. The snapshot of post analysis report provided by Hazen Laboratory in Golden, CO is provided in Table 7.

Table 7. Post sulfur analysis of the sulfur sorbent used in the field tests.



Hazen Research, Inc.
4601 Indiana Street
Golden, CO 80403 USA
Tel: (303) 279-4501
Fax: (303) 278-1528

DATE September 2, 2014
HRI PROJECT 009-463
HRI SERIES NO H339/14
DATE REC'D. 8/21/2014
CUST. P.O.# MDW 3688 001

TDA Research, Inc.
Mike Ware
12345 West 52nd Avenue
Wheat Ridge, CO 80033

REPORT OF ANALYSIS

HRI SAMPLE #	SAMPLE IDENTIFICATION	Sulfur, %
H339 -1	CDM-1	5.31
H339 -2	CDM-2	3.31
H339 -3	CDM-3	2.79
H339 -4	CDM-4	2.51
H339 -5	CDM-5	5.72

6.0 PERFORMANCE ASSESSMENT

6.1 QUANTITATIVE PERFORMANCE OBJECTIVES

Methane Recovery

After, optimization of the VSA cycle parameters in the field tests in July 2014, we were able to achieve greater than 80% methane recovery with the use of VSA cycles that incorporated pressure equalization. This was further improved to 90+% with the use of an advanced VSA cycle scheme with recycle, as shown in the field tests summary provided in Table 5.

Natural Gas Specification

As shown in the results in Table 6 and Figure 31 through Figure 33, TDA's biogas purification system (SulfaTrap^{TM}-R7 and VSA system combination) cleaned up the biogas so that the resulting purified biogas (bio-methane) met the natural gas specification.

- methane purity was greater than 95% as confirmed from the field data from IR based analyzer and the bagged samples analyzed a third party laboratory
- total sulfur concentration in the bio-methane produced was less than 0.25 ppm (well below the target of 4 ppm)
- the total N_2 and CO_2 on an average was less than 2.61% and the average CO_2 content was reduced to less than 1.5% from 48.2% by vol.
- the dew point bio-methane was reduced to less than < 40°C i.e., < 7lbs/MMscf moisture

6.2 QUALITATIVE PERFORMANCE OBJECTIVES

Ease of use

We received feedback from field technician (TDA operator) on usability of the technology and time required to run the system. In these field tests a single field technician was able to effectively operate the system remotely from TDA facilities in Wheat Ridge, CO with minimal to no on-site help.

7.0 COST ASSESSMENT

7.1 FULL SCALE SYSTEM DESIGN

CO_2 and H_2O Removal System

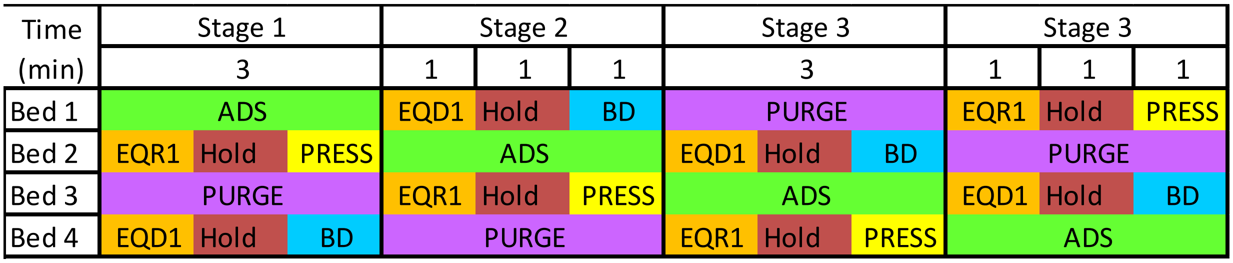
In this full-scale system design for the CO_2 and H_2O removal system we used a 4 bed VSA system instead of a 3-bed VSA system since it provides more flexibility in vacuum swing adsorption cycle scheduling. This allows us to maximize the purge time, which provides higher methane purity and recovery. Table 8 shows the design basis for purifying 2,000 m^3/day of biogas to produce bio-methane with the methane purity target of 99% and 90% methane recovery. Table 9 shows 4-bed VSA cycle schedule with the same purge time as the adsorption time.

Table 10 shows the bed sizing for a 2,000 m^3/day of biogas flow. We estimated the size of the VSA beds to be 600 L each with the methane purity target of 99% and along with a 90% methane recovery. Figure 34 shows the PFD for the 4-bed VSA system with the stream numbers marked. Table 11 shows the stream summary around the 4-bed VSA system for a 2,000 m^3/day of biogas flow.

Table 8. Full Scale Design Basis.

Biogas flow	2000 m^3/day 49.0 cfm
Feed Composition:	
CH_4	65%
CO_2	35%
Experimental Data:	
Sorbent working capacity	1.8% wt. CO_2
Simulation Data:	
Adsorption Product Purity	99.2%
Desorption Product Purity	87.8%
Methane Recovery	92.6%
Total Gas Processed per pass	3360 m^3/day 82.4 cfm
Number of Beds	4
Full Cycle time	12
Adsorption time	3
Full cycles per day	120

Table 9. 4-bed VSA cycle schedule.



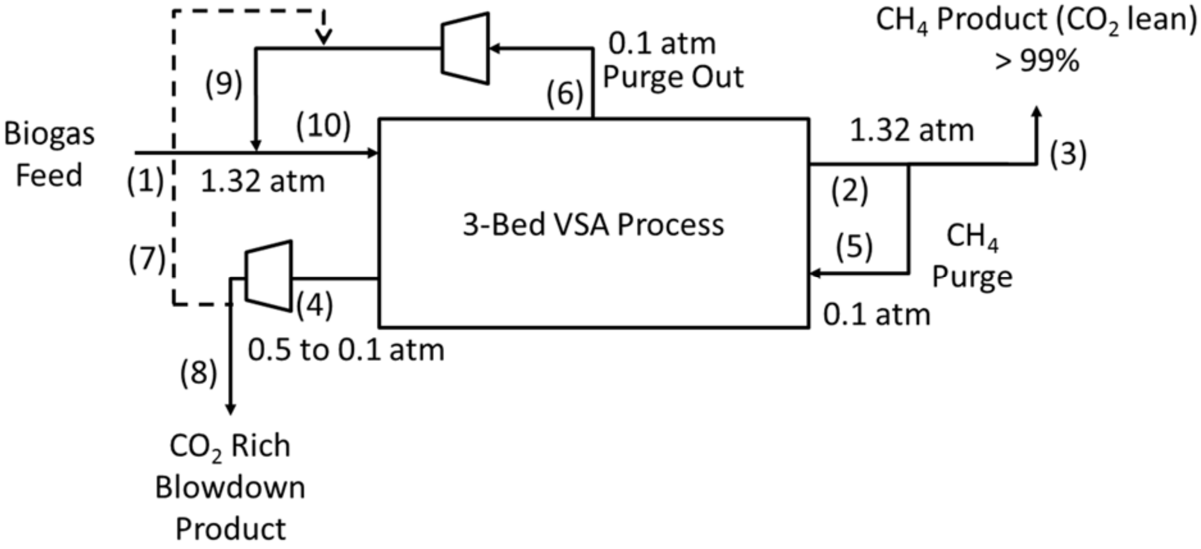
Time	Stage 1			Stage 2			Stage 3			Stage 3		
(min)	3			1	1	1	3			1	1	1
Bed 1	ADS			EQD1	Hold	BD	PURGE			EQR1	Hold	PRESS
Bed 2	EQR1	Hold	PRESS	ADS			EQD1	Hold	BD	PURGE		
Bed 3	PURGE			EQR1	Hold	PRESS	ADS			EQD1	Hold	BD
Bed 4	EQD1	Hold	BD	PURGE			EQR1	Hold	PRESS	ADS		

3- bed 1 EQ VSA Cycle Steps:

Step 1 Adsorption at 19 psia (ADS)
Step 2 Equalization to 8 psia (EQD1)
Step 3 Hold
Step 4 Blowdown to 2 psia (BD)
Step 5 Product Purge at 2 psia (PURGE)
Step 6 Equalization to 8 psia (EQR1)
Step 7 Hold
Step 8 Product pressurization to 19 psia (PRESS)

Table 10. 4-bed VSA bed sizing for 2,000 m^3/day biogas flow.

CO_2 to be removed	17.2 cfm 206.0 cf/cycle 51.5 cf/cycle/bed 2.9 kg/cycle/bed
Sorbent needed per bed	156.4 kg/bed 592.6 L/bed
Design Factor (1.0125)	600 L/bed
Total Sorbent needed	634 kg 2400 L
L/D	4.9
Bed Outer Diameter	22 "
Bed Inner Diameter	21.25 "
Bed Length	8.6 ft



Biogas Feed
(1)
1.32 atm
(9)
(10)
(7)
(4)
0.5 to 0.1 atm
(8)
CO₂ Rich Blowdown Product
(6)
0.1 atm Purge Out
3-Bed VSA Process
CH₄ Product (CO₂ lean) > 99%
1.32 atm
(3)
(2)
(5)
CH₄ Purge
0.1 atm

Figure 34. Streams around the 4-bed VSA system marked in the simplified PFD.

Table 11. Stream data for 4-bed VSA system.

Stream No.	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Description	Biogas Feed	Adsorption Out	CH_4 Product	Blowdown Product	CH_4 Purge	Purge Out	BD Recycle	Desorption Product	Recycle Stream	Feed to Beds
P (atm)	1.32	1.32	1.32	0.5->0.1	0.10	0.10	0.10	0.10	1.32	1.32
Flow rate (scfm)	49.0	33.6	29.8	33.8	3.8	18.6	14.5	19.3	33.2	82.4
CH_4 (scfm)	31.9	33.3	29.5	4.1	3.8	4.1	1.8	2.3	5.9	37.7
CO_2 (scfm)	17.2	0.3	0.2	29.7	0.0	14.6	12.7	16.9	27.3	44.5

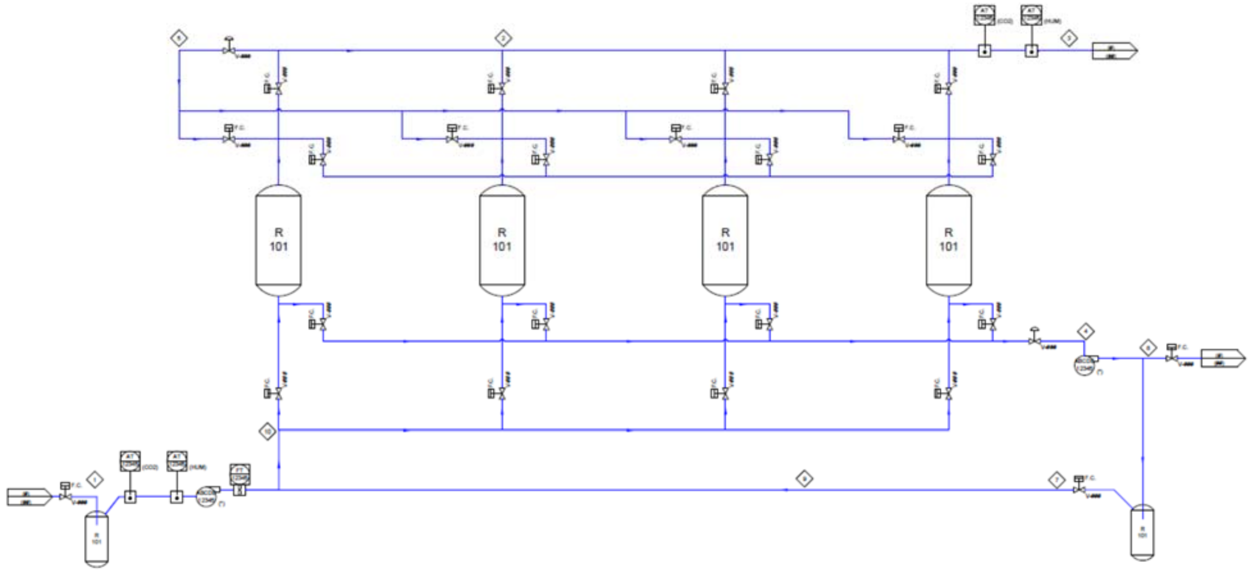

R 101
R 101
R 101
R 101
R 101
R 101

Figure 35. P&ID for the 4-bed VSA system including process instrumentation for control.

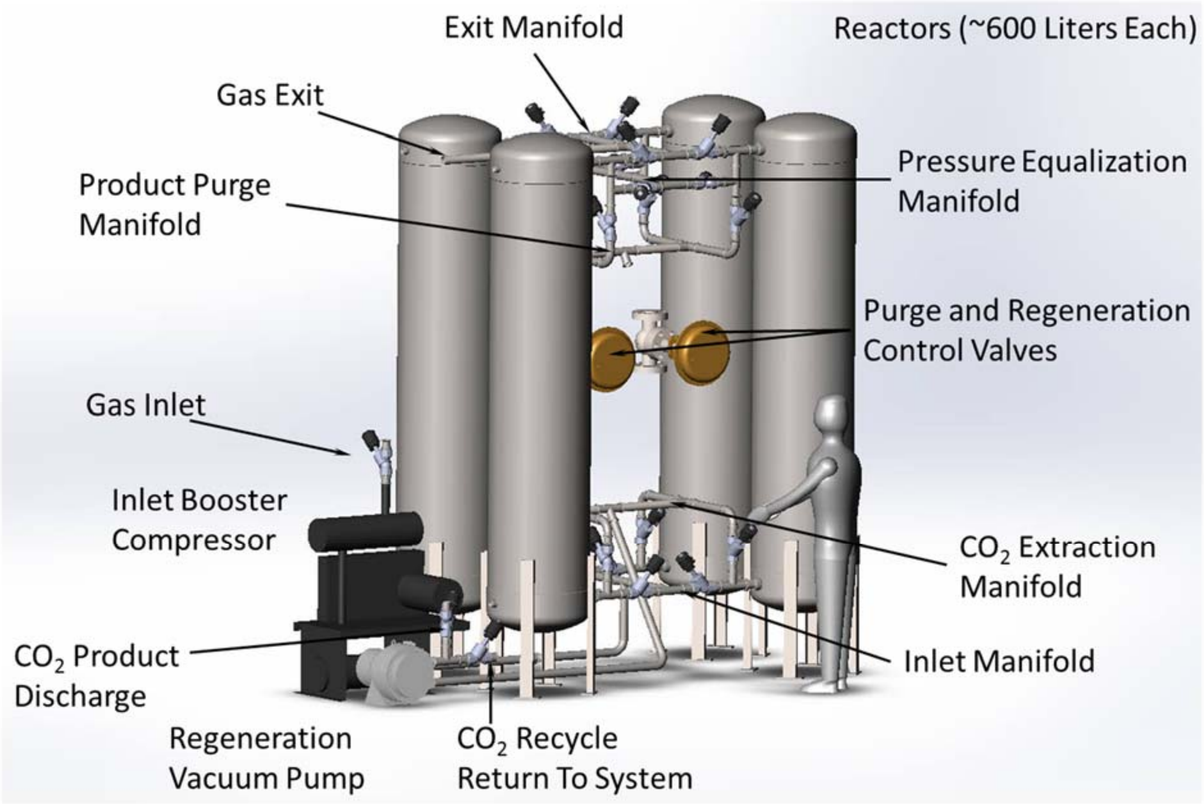

Exit Manifold
Reactors (~600 Liters Each)
Gas Exit
Product Purge Manifold
Pressure Equalization Manifold
Purge and Regeneration Control Valves
Gas Inlet
Inlet Booster Compressor
CO_2 Extraction Manifold
CO_2 Product Discharge
Inlet Manifold
Regeneration Vacuum Pump
CO_2 Recycle Return To System

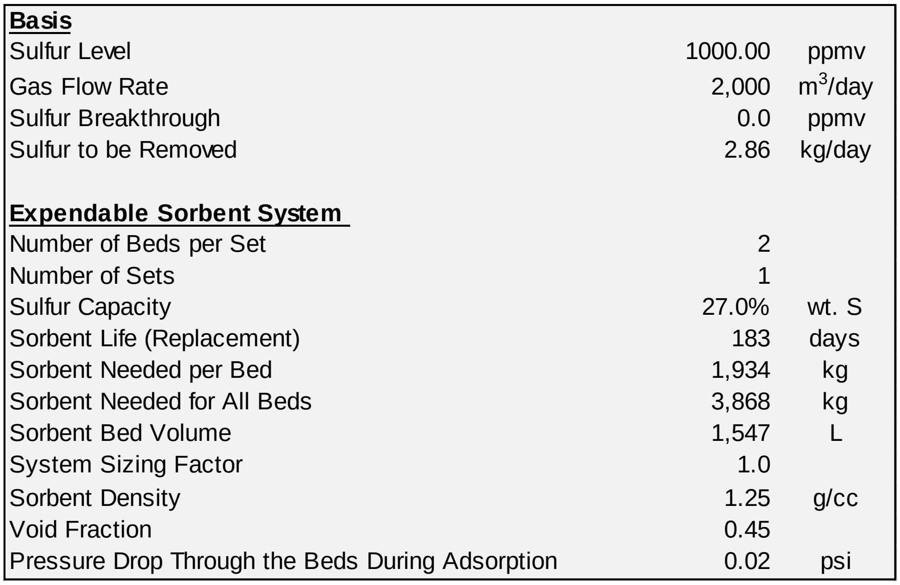
Figure 36. 3-D layout of a 2,000 m^3/day VSA based biogas purification system.

Figure 35 shows the P&ID of the 4-bed VSA system including the process instrumentation needed to control the VSA cycle schedule. Figure 36 shows the preliminary 3-D layout for the 4-bed VSA system.

Sulfur Removal System

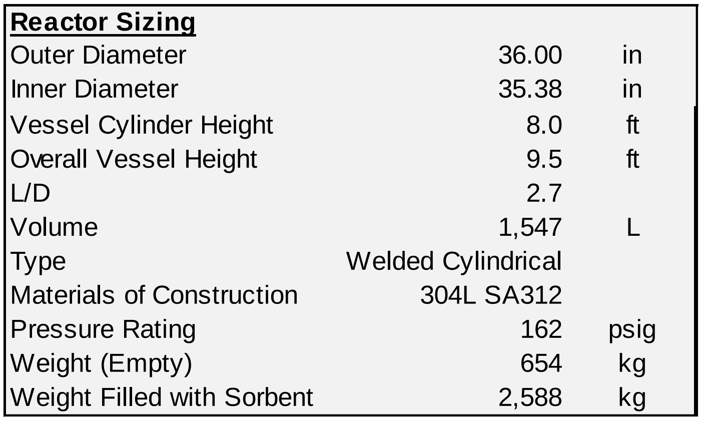
In this full-scale system design for the sulfur removal system we used a lead-lag system with two beds and a bed life of 6 months. Table 12 shows the sulfur sorbent bed sizing for a 2,000 m^3/day of biogas flow. We assumed an average sulfur level of 1,000 ppmv H_2S in the raw biogas. We estimated the size of the sulfur sorbent bed for 6-month bed life to be 1,544 L to remove more than 99.9% of the sulfur present in the biogas. Table 13 shows the reactor sizing for the lead-lag system. The system consists of two lead-lag beds of outer diameter 36" and bed height of 8' each with an individual L/D of 2.7. Figure 37 shows the P&ID of the 4-bed VSA system including the process instrumentation needed to control the VSA cycle schedule. Figure 38 shows the preliminary 3-D layout for the 4-bed VSA system.

Table 12. Sulfur sorbent bed sizing for 2,000 m^3/day biogas flow.



Basis		
Sulfur Level	1000.00	ppmv
Gas Flow Rate	2,000	m^3/day
Sulfur Breakthrough	0.0	ppmv
Sulfur to be Removed	2.86	kg/day
Expendable Sorbent System		
Number of Beds per Set	2	
Number of Sets	1	
Sulfur Capacity	27.0%	wt. S
Sorbent Life (Replacement)	183	days
Sorbent Needed per Bed	1,934	kg
Sorbent Needed for All Beds	3,868	kg
Sorbent Bed Volume	1,547	L
System Sizing Factor	1.0	
Sorbent Density	1.25	g/cc
Void Fraction	0.45	
Pressure Drop Through the Beds During Adsorption	0.02	psi

Table 13. Reactor sizing for 2,000 m^3/day biogas flow.



Reactor Sizing		
Outer Diameter	36.00	in
Inner Diameter	35.38	in
Vessel Cylinder Height	8.0	ft
Overall Vessel Height	9.5	ft
L/D	2.7	
Volume	1,547	L
Type	Welded Cylindrical	
Materials of Construction	304L SA312	
Pressure Rating	162	psig
Weight (Empty)	654	kg
Weight Filled with Sorbent	2,588	kg

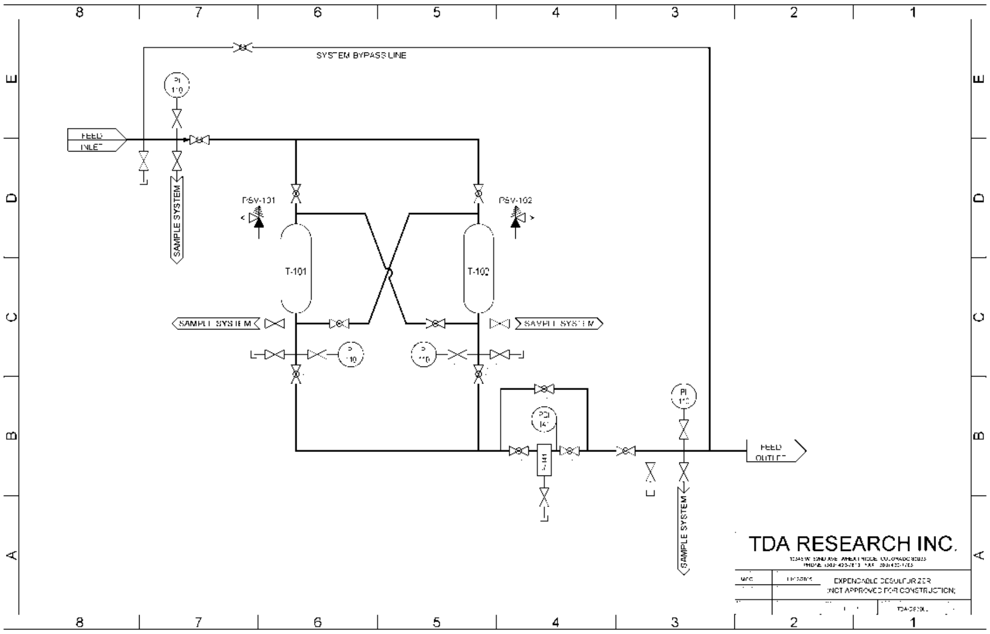

8
7
6
5
4
3
2
1
E
D
C
B
A
SYSTEM BYPASS LINE
PI 110
FEED INLET
SAMPLE SYSTEM
PSV-101
PSV-102
T-101
T-102
SAMPLE SYSTEM
SAMPLE SYSTEM
PDI 141
PI 110
FEED OUTLET
SAMPLE SYSTEM
TDA RESEARCH INC.
EXPENDABLE DESULFURIZER
(NOT APPROVED FOR CONSTRUCTION)

Figure 37. P&ID for the lead-lag sulfur removal.

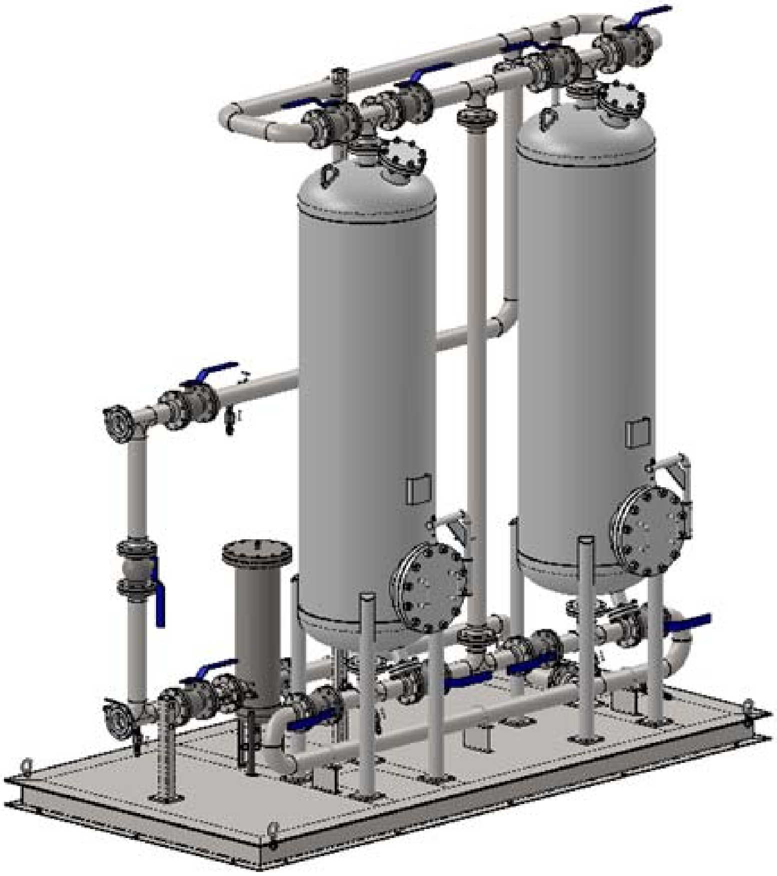


Figure 38. 3-D layout of a 2,000 m^3/day Lead-lag SulfaTrap™ sulfur removal system.

7.2 COST MODEL

The cost model is described in the schematic below:

Total Direct and Indirect Cost (TD&IDC) = Bare Equipment Cost + Installation Cost

Total Plant Cost (TPC) = TD&IDC + Engineering + Overhead & Adminstration
+ Contingency + Fees

Total Capital Requirement (TCR) = TPC + + Startup Cost + Spare Parts
+ Initial Sorbent Inventory + Facilities + Land

Operating & Maintenance (O&M) Cost = Operating Labor + Sorbent Replacement
+ Parasitic Power + Sorbent Disposal + Overhead

Annual Operating Cost (AOC) = O&M cost+ Capital Recovery

$$\text{Cost of CO}_2\text{ removal } (\$/m^3\ CH_4 \text{ produced}) = \frac{AOC\ for\ CO_2\ removal}{m^3\ CH_4\ produced}$$

$$\text{Cost of CO}_2\text{ removal } (\$/\text{MMBTU}) = \frac{\text{Cost of CO}_2\text{ removal } (\$/m^3\ CH_4 \text{ produced})}{Heating\ value\ of\ CH_4\ (MMBTU)/m^3\ CH_4\ produced}$$

$$\text{Cost of sulfur removal } (\$/\text{kg sulfur removed}) = \frac{AOC\ for\ sulfur\ removal}{kg\ sulfur\ removed}$$

7.3 COST DRIVERS

The important cost drivers are the operating and maintenance cost and the amount of methane recovered in the bio-methane product. There are no site-specific characteristic that will significantly impact cost. Higher methane recovery implies higher value in the product stream.

7.4 COST ANALYSIS

We estimated the bare equipment cost (direct cost) and used 15% of the bare equipment cost for installation, 2% for engineering, 5% for overhead, 10% for contingency and 5% for fees to estimate the total plant cost. In order to estimate the total capital required we used 2% of direct cost for startup cost, 3% of direct costs for spare parts, 5% for facilities, and a sorbent cost of $10/lbs for CO_2 sorbent and $12/L for sulfur sorbent. This capital requirement does not include any land cost since we expect that to be part of the digestion system. We used capital recovery factor of 5%, sorbent replacement frequency of 4 yrs for CO2 sorbent and 6 months for sulfur sorbent with a disposal cost of $500/tonne, operating labor cost at $15/hr, overhead at 20% of direct labor cost and parasitic power at $0.10/kWh to estimate operating and maintenance (O&M) cost.

TDA's CO_2 removal system once starts operation requires minimal to no operator time, hence we used 0.1 person time during regular business hours, a total of 208 hours per year, which also includes the sorbent change out labor. We estimated the bare equipment (direct) cost of the 4-bed VSA system to be $181,000. We estimated the capital cost including installation, start-up, initial sorbent inventory, etc to be $295.3k. Table 14 shows the details of the capital cost estimate. We estimated the annual operational maintenance (O&M) cost including the capital recovery, sorbent replacement, vacuum power cost and the labor cost to be $35.8k. Table 15 shows the details of the O&M cost estimate.

Table 14.Capital cost estimate for the full-scale system sized to handle 2,000 m^3/day of biogas

DIRECT COSTS SUMMARY (2015 PRICES in thousands of dollars)

		Unit Cost		Equipment Cost
4	Reactor Vessel 712 liter each 304 SS	18.50		74.00
24	2" Automated Valve	1.00		24.00
2	2" proportioning control valve	5.00		10.00
1	booster inlet gas compressor	15.00		15.00
1	vacuum pump / recycle compressor	15.00		15.00
1	Turbine Flowmeter	3.00		3.00
2	CO2 Sensor	2.50		5.00
2	Humidity Sensor	2.50		5.00
1	Interconnect Piping	20.00		20.00
1	Mounting Skid	10.00		10.00

TOTAL DIRECT COSTS		**181.0**
INSTALLED EQUIPMENT (Installation labor, pipe, insulation , controls etc)	15%	**27.2**
TOTAL DIRECT AND INDIRECT COST		**208.2**
ENGINEERING (percentage of direct costs)	2%	4.2
OVERHEAD & ADMINISTRATION (percentage of direct costs)	5%	10.4
CONTINGENCY	10%	20.8
FEE (percentage of on-site costs)	5%	10.4
TOTAL PLANT COST		**253.9**
STARTUP COST (percentage of direct costs)	3%	5.4
SPARE PARTS (percentage direct equipment costs)	2%	3.6
INITIAL SORBENT INVENTORY ($10/ lbs)		21.9
FACILITIES	5%	10.4
LAND	see note	0.0
TOTAL CAPITAL REQUIREMENT		**295.3**

Note - Cost of land is not included

Table 15. O&M cost estimate for the full-scale system sized to handle 2,000 m^3/day of biogas.

Operating & Maintenance Costs		$/year	
Operating labor	$	3,120	0.1 person 1-shift/$15/hr
Sorbent replacement cost	$	4,386	4 yr life
Parasitic Power Cost	$	12,790	14.6 kW @$0.10/kWh
Disposal, $500/tonne	$	125	
Overhead	$	624	20% of direct labor cost
Total O&M	$	21,044	
Capital recovery, 5%	$	14,767	
Annual Operating Costs	$	35,811	
Cost of CO_2 removal	**$**	**0.08**	**per m^3 CH4**
	$	**2.32**	**per MMBTU**

We estimated the vacuum power requirement to be 14.6 kW_e, the sorbent bed size to be 600 L/bed, the operating power cost was $0.04 per m^3 CH_4 produced and the total operating cost including the sorbent replacement cost was $0.07 per m^3 CH_4 produced with a methane purity and recovery of 99.5% and 80.3%, respectively. The methane recovery can be further increased to 90% or above by relaxing the methane purity to 96%+% and increasing operating power cost to $0.05 per m^3 CH_4 produced, which results in a total operating cost (including sorbent replacement) of $0.08 per m^3 CH_4 produced.

Sulfur Removal System

We also completed a detailed cost analysis to estimate the cost of the sulfur removal. In this analysis we calculated the fixed and operating and maintenance costs including the capital charge for the lead-lag reactor system used for desulfurization. The cost of SulfaTrap^{TM}-R7E at large production volumes is estimated to be $12 per L of sorbent and the reactors are sized such that the lead reactor is replaced every 6 months and the lag reactor then becomes the lead reactor for the next 6 month interval. We estimated the bare equipment (direct) cost of the lead-lag system to be $24,400. We estimated the capital cost including installation, start-up, initial sorbent inventory, etc. to be $74k. Table 16 shows the details of the capital cost estimate. Table 17 shows the details of the O&M cost estimate. We estimated the total annualized operating maintenance cost including the capital charge for sorbent reactors to be $43,057 and the cost of sulfur removal is $41.3 per kg of sulfur.

Table 16.Capital cost estimate for the sulfur sorbent system.

DIRECT COSTS SUMMARY (2015 PRICES in thousands of dollars)

Equipment Cost		**Unit Cost**	Total Cost
2	Vessels 36in X 96in shell, 0.312in wt, 304L SA312	5.00	10.00
14	1.5in ball valves, manual, 150# RF, (feed lines)	0.20	2.80
2	SS ASME relief valve, 2"x3"	0.40	0.80
1	Inlet filter, 1.5in	1.50	1.50
1	Process Gages	2.00	2.00
5	Drain/instrument isolation needle valve, 1/2" FNPT, SS	0.05	0.25
12	Vent/sample isolation needle valve, 1/4" FNPT, SS	0.05	0.60
4	1" purge isolation ball valve, 316SS	0.06	0.24
1	Interconnect Piping	3.20	3.20
1	Mounting Skid	3.00	3.00

TOTAL DIRECT COSTS		**24.4**
INSTALLED EQUIPMENT (Installation labor, pipe, insulation , controls etc)	15%	**3.7**
TOTAL DIRECT AND INDIRECT COST		**28.0**
ENGINEERING (percentage of direct costs)	2%	0.6
OVERHEAD & ADMINISTRATION (percentage of direct costs)	5%	1.4
CONTINGENCY	10%	2.8
FEE (percentage of on-site costs)	5%	1.4
TOTAL PLANT COST		**34.2**
STARTUP COST (percentage of direct costs)	3%	0.7
SPARE PARTS (percentage direct equipment costs)	2%	0.5
INITIAL SORBENT INVENTORY ($12/ L)		37.1
FACILITIES	5%	1.4
LAND	see note	0.0
TOTAL CAPITAL REQUIREMENT		**74.0**

Note - Cost of land is not included

Table 17. O&M cost estimate for sulfur removal sorbent to handle 2,000 m^3/day of biogas.

Operating & Maintenace Costs	**$/year**	
Operating Labor	$ 780	1 hr per week @$15/hr
Sorbent Replacement Cost	$37,056	sorbent unit cost @ $12/L
Sorbent Changeout Labor	$ 180	12 man hr per replacement @ 15/hr
Disposal, $500/tonne	$ 1,930	
Overhead	$ 192	20% of direct labor
Total O&M	**$39,358**	
Capital recovery, 5%	**$3,699**	
Annual operating Cost	$43,057	
Cost of sulfur removal	**$ 41.31**	**per kg sulfur**

8.0 IMPLEMENTATION ISSUES

We encountered liquid water condensation at the bottom of the desulfurization sorbent reactor, which could be a possible reason for the premature breakthrough observed in the sulfur sorbent reactor compared to the bench-scale reactor tests in the laboratory.

In the field tests only one flare header was provided, which necessitated that we combine both the bio-methane product and the CO_2 rich desorption product before sending to the flare. This resulted in backflow across the check valve used on the bio-methane product line which contaminated the bio-methane product. This was later resolved in the field tests by using a high psi check valve. This issue will not be encountered in the full-scale system, since the bio-methane produced will be sent to either transportation vehicle fueling station or to the natural gas pipeline and the CO_2 desorption product is the only stream that will be sent to the flare.

9.0 REFERENCES

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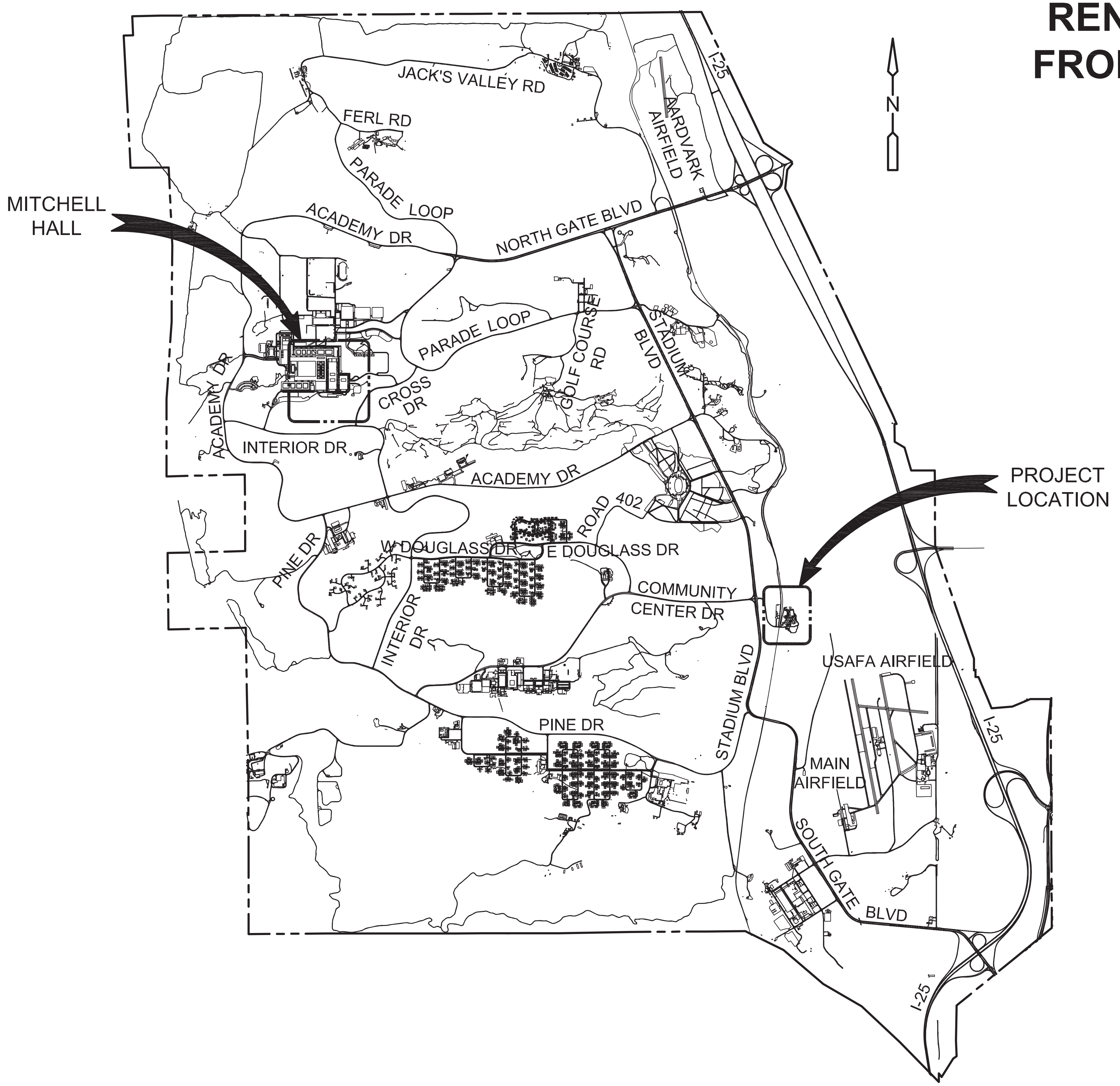
APPENDICES

Appendix A: Points of Contact

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone Fax E-mail	Role in Project
Dr. Ambal Jayaraman	TDA Research, Inc. 12345 W 52nd Avenue Wheat Ridge, CO 80033	Ph:303-940-5391 Fax: 303-422-7763 ajayaraman@tda.com	Project Manager for TDA Subcontract VSA Process Design
Dr. Gokhan Alptekin	TDA Research, Inc. 12345 W 52nd Avenue Wheat Ridge, CO 80033	Ph:303-940-2349 Fax: 303-422-7763 galptekin@tda.com	Sulfur Sorbent Selection
Dr. Steve Dietz	TDA Research, Inc. 12345 W 52nd Avenue Wheat Ridge, CO 80033	Ph:303-940-2312 Fax: 303-422-7763 sdietz@tda.com	CO_2 Sorbent Production
Mathew Cates	TDA Research, Inc. 12345 W 52nd Avenue Wheat Ridge, CO 80033	Ph:303-940-2350 Fax: 303-422-7763 mcates@tda.com	VSA System Design and Fabrication
Kerry Libberton	TDA Research, Inc. 12345 W 52nd Avenue Wheat Ridge, CO 80033	Ph:303-940-2342 Fax: 303-422-7763 kerrylib@tda.com	VSA System Fabrication and Testing

Appendix G: Engineering Drawings

RENEWABLE ENERGY PRODUCTION FROM DOD INSTALLATION WASTE BY ANAEROBIC DIGESTION PILOT PLANT DESIGN


MITCHELL HALL
PROJECT LOCATION
N
JACK'S VALLEY RD
FERL RD
PARADE LOOP
ACADEMY DR
NORTH GATE BLVD
AARDVARK AIRFIELD
I-25
PARADE LOOP
GOLF COURSE RD
STADIUM BLVD
CROSS DR
ACADEMY DR
INTERIOR DR
ACADEMY DR
ROAD 402
PINE DR
W DOUGLASS DR
E DOUGLASS DR
COMMUNITY CENTER DR
INTERIOR DR
USAFA AIRFIELD
STADIUM BLVD
PINE DR
MAIN AIRFIELD
I-25
SOUTH GATE BLVD
I-25

SHEET INDEX:

Drawing No.	Title	Sheet No.
G101	Title Sheet, Vicinity Map and Sheet Index	1
G102	Location Map and Facility Plan	2
G103	Legend - P&ID 1	3
G104	Legend - P&ID 2	4
G105	Legend - P&ID 3	5
P101	Process Piping and Instrumentation Diagram	6
P102	Process Gas System HVAC and Combustible Gas Detection	7
P103	Water Supply & Plumbing System	8
P104	Instrument & Service Air System Diagram	9
P105	Process Drain System Diagram	10
M101	Pilot Equipment Plan and Section	11
M102	Pilot Equipment Sections	12
M103	Mechanical Site Plan	13
E-1	Electrical Legend	14
E-2	Single Line Diagram	15
E-3	Pilot Equipment Electrical Plans	16
E-4	Electrical Notes	17
E-5	Control Diagrams 1 of 2	18
E-6	Control Diagrams 2 of 2	19

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REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY:
DRAWN BY: J. WEINER
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: APRIL 2011

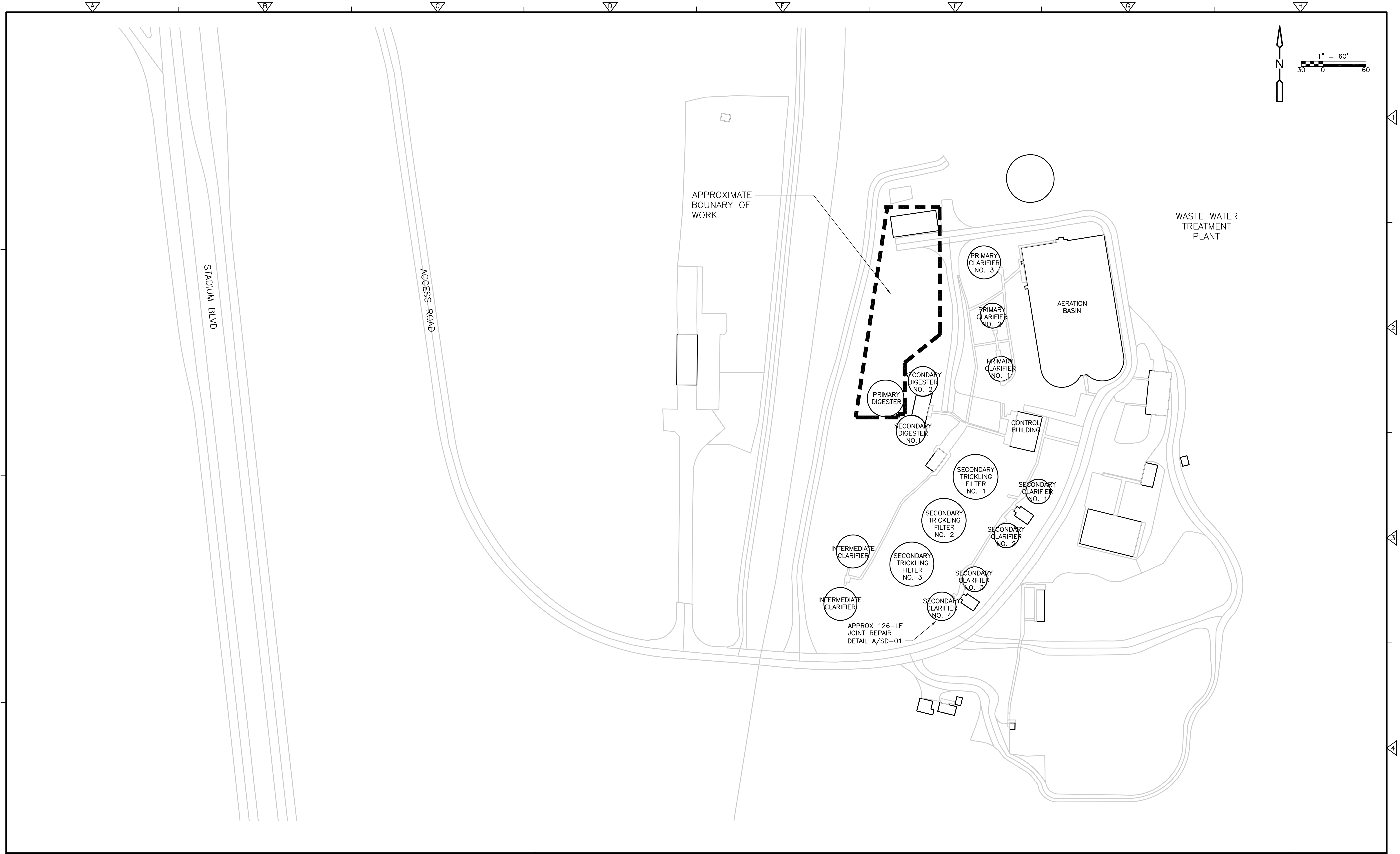
LINE IS 1 INCH
AT FULL SIZE
(34X22)
SCALE ACCORDINGLY

CDM
Camp Dresser & McKee Inc.
1218 3rd Avenue, Suite 100
Seattle, CA 98101
Phone: 206-336-4900
consulting • engineering • construction • operations

Renewable Energy Production from
DoD Installation Solid Waste by
Anaerobic Digestion

TITLE SHEET, VICINITY MAP
AND SHEET INDEX

PROJECT NO. 50957–73968
FILE NAME: G101
DRAWING NO.
GI01
SHEET NO.
1 OF 28


A
B
C
D
E
F
G
H
1
2
3
4
N
1" = 60'
30
0
60
STADIUM BLVD
ACCESS ROAD
APPROXIMATE BOUNARY OF WORK
WASTE WATER TREATMENT PLANT
PRIMARY CLARIFIER NO. 3
PRIMARY CLARIFIER NO. 2
PRIMARY CLARIFIER NO. 1
AERATION BASIN
SECONDARY DIGESTER NO. 2
PRIMARY DIGESTER
SECONDARY DIGESTER NO.1
CONTROL BUILDING
SECONDARY TRICKLING FILTER NO. 1
SECONDARY CLARIFIER NO. 1
SECONDARY TRICKLING FILTER NO. 2
SECONDARY CLARIFIER NO. 2
INTERMEDIATE CLARIFIER
SECONDARY TRICKLING FILTER NO. 3
SECONDARY CLARIFIER NO. 3
INTERMEDIATE CLARIFIER
SECONDARY CLARIFIER NO. 4
APPROX 126-LF JOINT REPAIR DETAIL A/SD-01

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APPROVED BY:
DATE: APRIL 2011

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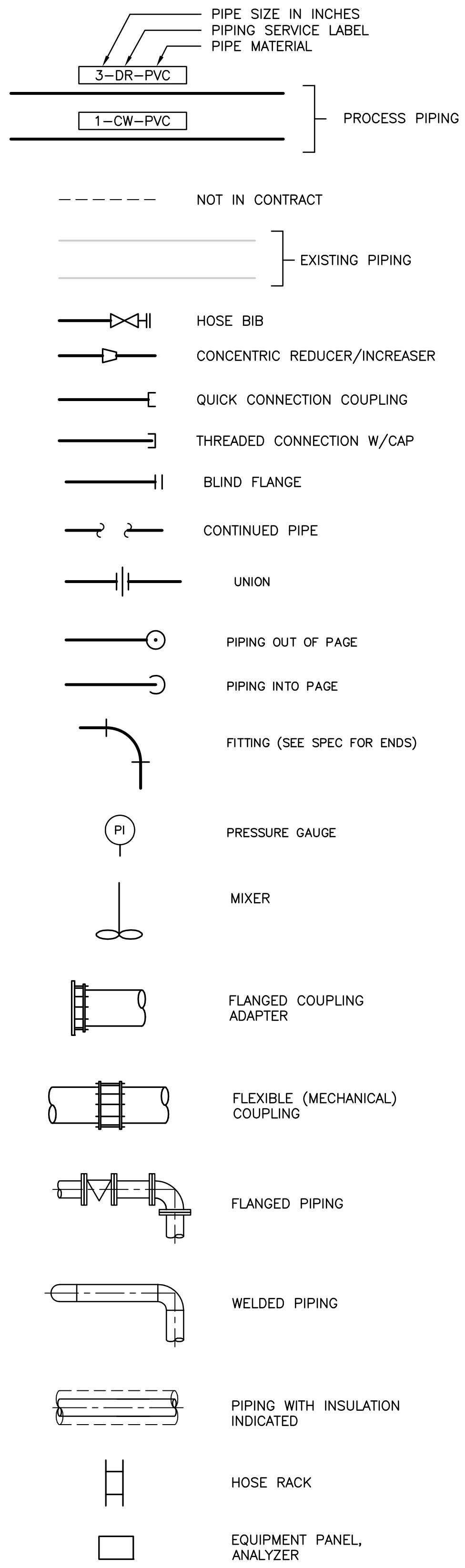
Renewable Energy Production from
DoD Installation Solid Waste by
Anaerobic Digestion

LOCATION MAP AND FACILITY PLAN

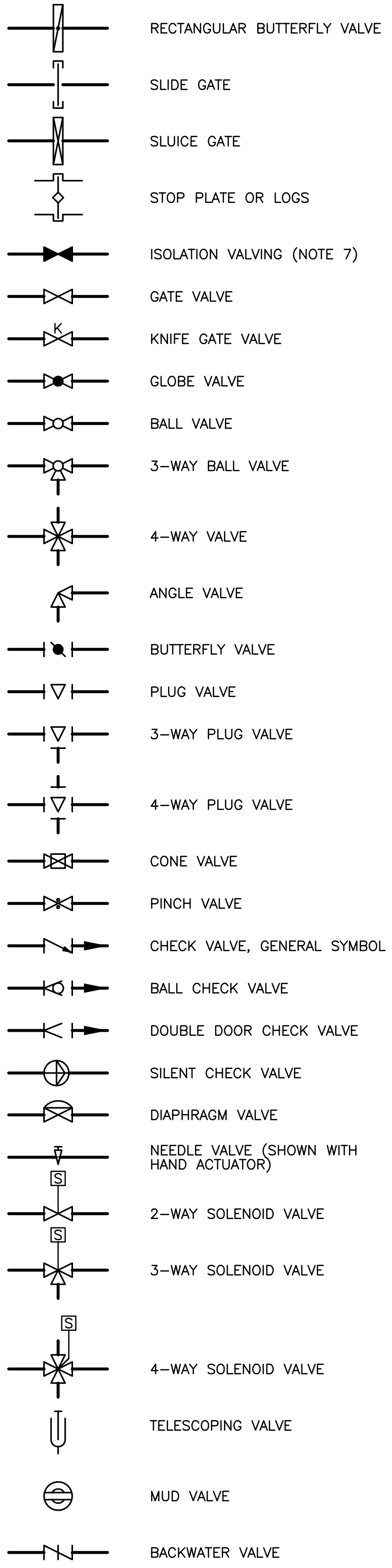
PROJECT NO. 50957-73968
FILE NAME: G102
DRAWING NO.
GI02
SHEET NO.
2 OF 28

PIPING SYMBOLS

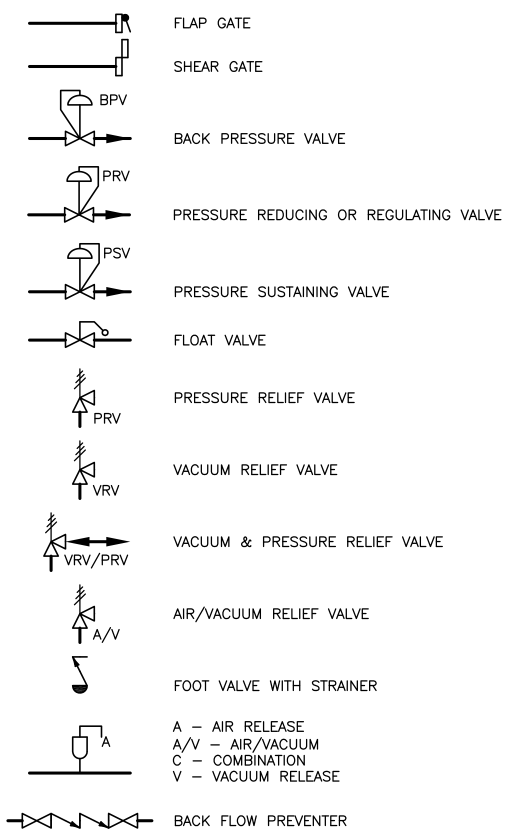


PIPE SIZE IN INCHES
PIPING SERVICE LABEL
PIPE MATERIAL
PROCESS PIPING
NOT IN CONTRACT
EXISTING PIPING
HOSE BIB
CONCENTRIC REDUCER/INCREASER
QUICK CONNECTION COUPLING
THREADED CONNECTION W/CAP
BLIND FLANGE
CONTINUED PIPE
UNION
PIPING OUT OF PAGE
PIPING INTO PAGE
FITTING (SEE SPEC FOR ENDS)
PRESSURE GAUGE
MIXER
FLANGED COUPLING ADAPTER
FLEXIBLE (MECHANICAL) COUPLING
FLANGED PIPING
WELDED PIPING
PIPING WITH INSULATION INDICATED
HOSE RACK
EQUIPMENT PANEL, ANALYZER

VALVE AND GATE SYMBOLS

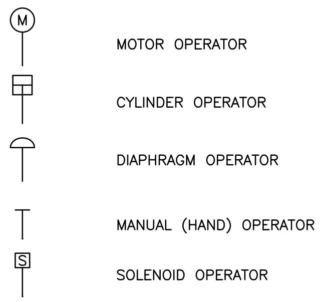


RECTANGULAR BUTTERFLY VALVE
SLIDE GATE
SLUICE GATE
STOP PLATE OR LOGS
ISOLATION VALVING (NOTE 7)
GATE VALVE
KNIFE GATE VALVE
GLOBE VALVE
BALL VALVE
3-WAY BALL VALVE
4-WAY VALVE
ANGLE VALVE
BUTTERFLY VALVE
PLUG VALVE
3-WAY PLUG VALVE
4-WAY PLUG VALVE
CONE VALVE
PINCH VALVE
CHECK VALVE, GENERAL SYMBOL
BALL CHECK VALVE
DOUBLE DOOR CHECK VALVE
SILENT CHECK VALVE
DIAPHRAGM VALVE
NEEDLE VALVE (SHOWN WITH HAND ACTUATOR)
2-WAY SOLENOID VALVE
3-WAY SOLENOID VALVE
4-WAY SOLENOID VALVE
TELESCOPING VALVE
MUD VALVE
BACKWATER VALVE



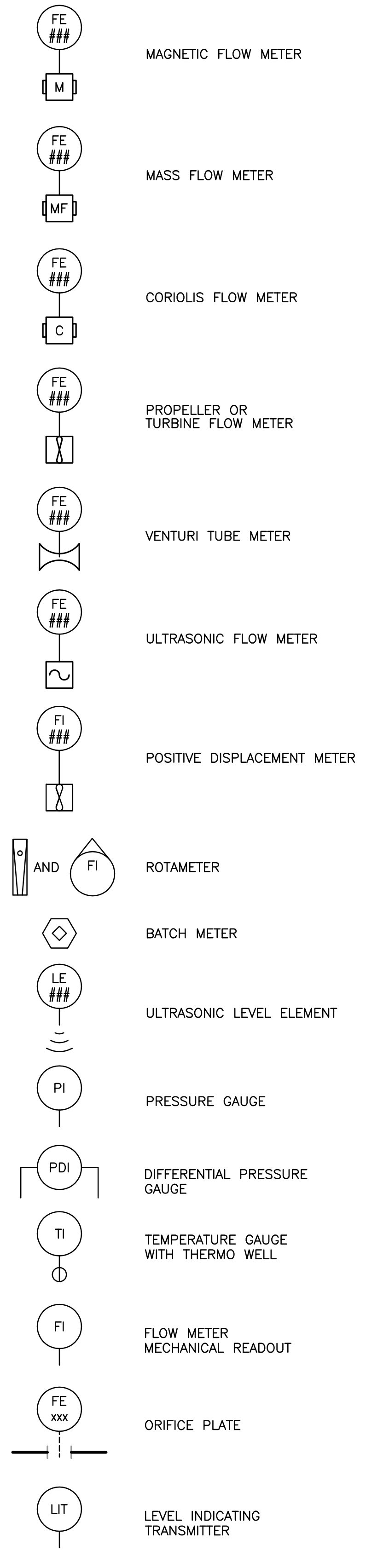
FLAP GATE
SHEAR GATE
BACK PRESSURE VALVE
PRESSURE REDUCING OR REGULATING VALVE
PRESSURE SUSTAINING VALVE
FLOAT VALVE
PRESSURE RELIEF VALVE
VACUUM RELIEF VALVE
VACUUM & PRESSURE RELIEF VALVE
AIR/VACUUM RELIEF VALVE
FOOT VALVE WITH STRAINER
A – AIR RELEASE
A/V – AIR/VACUUM
C – COMBINATION
V – VACUUM RELEASE
BACK FLOW PREVENTER

VALVE AND GATE OPERATORS

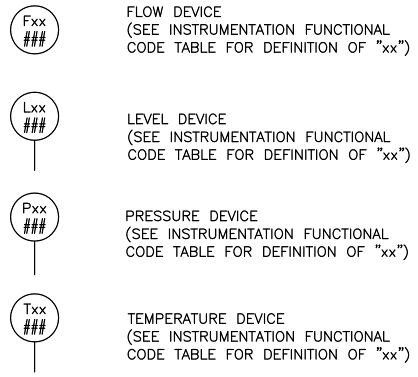


MOTOR OPERATOR
CYLINDER OPERATOR
DIAPHRAGM OPERATOR
MANUAL (HAND) OPERATOR
SOLENOID OPERATOR

PRIMARY ELEMENTS



MAGNETIC FLOW METER
MASS FLOW METER
CORIOLIS FLOW METER
PROPELLER OR TURBINE FLOW METER
VENTURI TUBE METER
ULTRASONIC FLOW METER
POSITIVE DISPLACEMENT METER
ROTAMETER
BATCH METER
ULTRASONIC LEVEL ELEMENT
PRESSURE GAUGE
DIFFERENTIAL PRESSURE GAUGE
TEMPERATURE GAUGE WITH THERMO WELL
FLOW METER MECHANICAL READOUT
ORIFICE PLATE
LEVEL INDICATING TRANSMITTER



FLOW DEVICE (SEE INSTRUMENTATION FUNCTIONAL CODE TABLE FOR DEFINITION OF "xx")
LEVEL DEVICE (SEE INSTRUMENTATION FUNCTIONAL CODE TABLE FOR DEFINITION OF "xx")
PRESSURE DEVICE (SEE INSTRUMENTATION FUNCTIONAL CODE TABLE FOR DEFINITION OF "xx")
TEMPERATURE DEVICE (SEE INSTRUMENTATION FUNCTIONAL CODE TABLE FOR DEFINITION OF "xx")

NOTES:

1. REFER TO SHEETS G104 AND G105 FOR ADDITIONAL INSTRUMENTATION EQUIPMENT IDENTIFICATION, LINE SYMBOLS, ADDITIONAL ABBREVIATIONS AND INSTRUMENT TAGGING CONVENTIONS.
2. THIS SHEET AND SHEETS G104 AND G105 ARE GENERAL LEGEND SHEETS. SOME SYMBOLS OR NOTATIONS MAY NOT BE USED ON THIS CONTRACT.
3. PIPING AND STRUCTURES ARE SHOWN FOR GENERAL UNDERSTANDING OF THE PROCESS ONLY. IN GENERAL, NOT ALL PIPES, VALVES, FITTINGS, EQUIPMENT, AND APPURTENANCES ARE SHOWN.
4. DASHED LINES FOR ELECTRICAL SIGNALS DO NOT REPRESENT THE NUMBER OF WIRES. SEE ELECTRICAL DRAWINGS AND SPECIFICATIONS FOR ACTUAL NUMBER OF WIRES REQUIRED.
5. THE PROCESS & INSTRUMENTATION DRAWINGS ARE SCHEMATIC. THEY SHALL BE USED IN CONJUNCTION WITH ALL OTHER CONTRACT DOCUMENTS TO DEFINE ALL DETAILS OF THE CONTRACT WORK.
6. ALL NECESSARY VALVES ARE NOT SHOWN ON THE P&ID'S FOR CLARITY. PROVIDE ISOLATION VALVES ON ALL SAMPLE LINES TO SENSORS, TWO VALVE MANIFOLDS FOR ALL ABSOLUTE AND GAUGE PRESSURE DEVICES, AND FIVE VALVE MANIFOLDS FOR ALL DIFFERENTIAL PRESSURE DEVICES.
7. MATERIALS OF CONSTRUCTION SHALL BE DETERMINED FROM THE BILL OF MATERIALS AND DETAILED DRAWINGS.
8. REDUCERS, TEES AND OTHER PIPELINE FITTINGS ARE TYPICALLY NOT SHOWN ON THE P&ID'S UNLESS NEEDED TO CLARIFY THE PROCESS LINE FUNCTIONS.

PIPE MATERIAL IDENTIFICATION:

BR	BRASS
CPVC	CHLORINATED POLYVINYL CHLORIDE
COP	COPPER
HDPE	HIGH DENSITY POLYETHYLENE
PVC	POLYVINYL CHLORIDE
PU	POLYURETHANE
SS	STAINLESS STEEL
STL	STEEL

REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY:
DRAWN BY: J. WEINER
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: APRIL 2011

LINE IS 1 INCH
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SCALE ACCORDINGLY

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Renewable Energy Production from
DoD Installation Solid Waste by
Anaerobic Digestion

LEGEND - P&ID 1

PROJECT NO. 50957-73968
FILE NAME: G103LGPD
DRAWING NO.
GI03
SHEET NO.
3 OF 28

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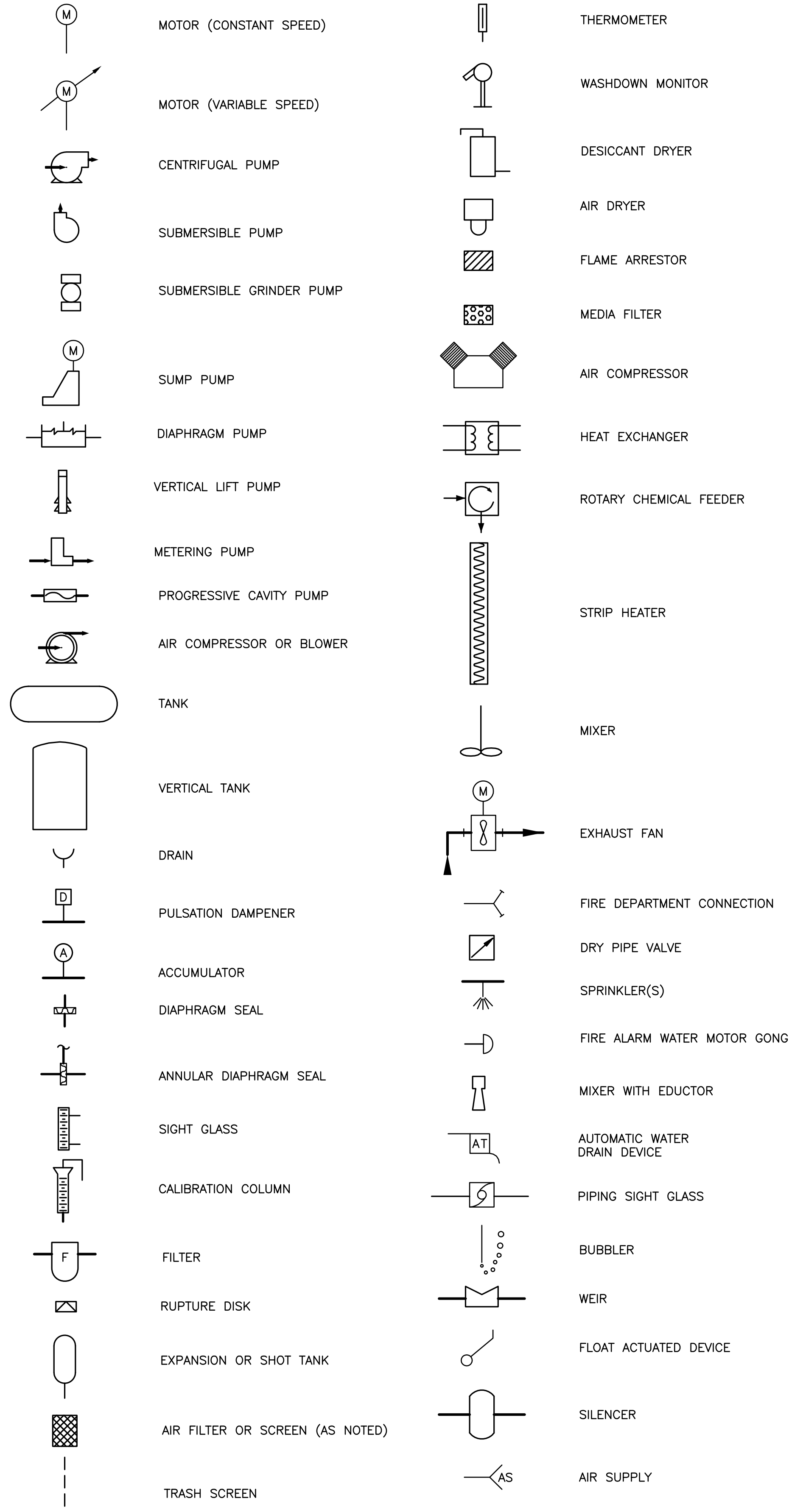
MISCELLANEOUS SYMBOLS



MOTOR (CONSTANT SPEED)
MOTOR (VARIABLE SPEED)
CENTRIFUGAL PUMP
SUBMERSIBLE PUMP
SUBMERSIBLE GRINDER PUMP
SUMP PUMP
DIAPHRAGM PUMP
VERTICAL LIFT PUMP
METERING PUMP
PROGRESSIVE CAVITY PUMP
AIR COMPRESSOR OR BLOWER
TANK
VERTICAL TANK
DRAIN
PULSATION DAMPENER
ACCUMULATOR
DIAPHRAGM SEAL
ANNULAR DIAPHRAGM SEAL
SIGHT GLASS
CALIBRATION COLUMN
FILTER
RUPTURE DISK
EXPANSION OR SHOT TANK
AIR FILTER OR SCREEN (AS NOTED)
TRASH SCREEN

THERMOMETER
WASHDOWN MONITOR
DESICCANT DRYER
AIR DRYER
FLAME ARRESTOR
MEDIA FILTER
AIR COMPRESSOR
HEAT EXCHANGER
ROTARY CHEMICAL FEEDER
STRIP HEATER
MIXER
EXHAUST FAN
FIRE DEPARTMENT CONNECTION
DRY PIPE VALVE
SPRINKLER(S)
FIRE ALARM WATER MOTOR GONG
MIXER WITH EDUCTOR
AUTOMATIC WATER DRAIN DEVICE
PIPING SIGHT GLASS
BUBBLER
WEIR
FLOAT ACTUATED DEVICE
SILENCER
AIR SUPPLY

EQUIPMENT ABBREVIATIONS

ALR PNL	ALARM PANEL
BAC	BACKFLOW PREVENTER
BAT	BATTERY
BC	BATTERY CHARGER
CPR	COMPRESSOR
EF	EXHAUST FAN
F	FAN
FA	FLAME ARRESTOR
HB	HEAT BLANKET
HMI	HUMAN/MACHINE INTERFACE
HTR	HEATER
ME	MISCELLANEOUS EQUIPMENT
MIX	MIXER
OD	ODOR CONTROL
P	PUMP
PCP	PILOT CONTROL PANEL
PLC	PROGRAMMABLE LOGIC CONTROLLER (LOCATED IN PCP)
SF	SUPPLY FAN
T	TANK
VSA	VACUUM SWING ADSORBTION SYSTEM
WGB	WASTE GAS BURNER

MECHANICAL EQUIPMENT CODE

EXAMPLES:

P–101	PUMP NUMBERED 101
MIX–101	MIXER NUMBERED 101

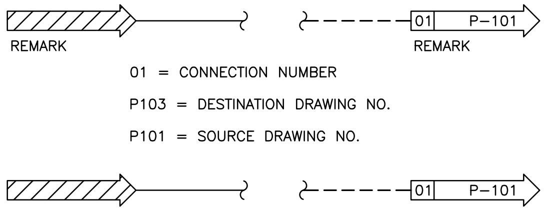
EQUIPMENT NUMBERS ARE SEQUENTIAL STARTING AT 101 FOR EACH TYPE OF EQUIPMENT.

FLOW STREAM IDENTIFICATION

AHP	AIR, HIGH PRESSURE PROCESS
ALP	AIR, LOW PRESSURE PROCESS
ASP	AIR, SUPPLY
CW	CITY WATER
DF	DIGESTER FEED
DG	DIGESTER GAS
DOF	DIGESTER OVERFLOW
DR	DRAIN, PROCESS
DS	DIGESTED SLUDGE
DST	DIGESTED SLUDGE TRANSFER
FA	FOUL AIR
T	TELEPHONE

INTERFACE SYMBOLS

OFF PAGE CONNECTORS



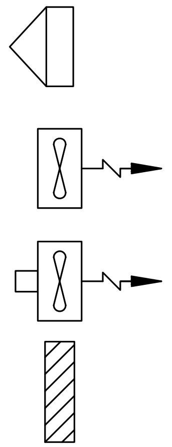
01 = CONNECTION NUMBER

P103 = DESTINATION DRAWING NO.

P101 = SOURCE DRAWING NO.

INTERFACE TO OR FROM PROCESS EXTERNAL TO PROJECT.

HVAC SYMBOLS



STORM HOOD
WALL FAN
UNIT HEATER
WALL LOUVER

ADDTIONAL ABBREVIATIONS

BV	BALL VALVE
HV	HAND VALVE
FV	FOOT VALVE
LCV	LOCAL CONTROL VALVE
NC	NORMALLY OPEN
NO	NORMALLY CLOSED
NV	NEEDLE VALVE
PCV	PRESSURE CONTROLLING VALVE
PRV	PRESSURE RELIEF VALVE
SV	SOLENOID VALVE

REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: C. McPHERSON
DRAWN BY: J. WEINER
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: APRIL 2011

LINE IS 1 INCH
AT FULL SIZE
(34X22)
SCALE ACCORDINGLY

CDM
Camp Dresser & McKee Inc.
1218 3rd Avenue, Suite 100
Seattle, CA 98101
Phone: 206-336-4900
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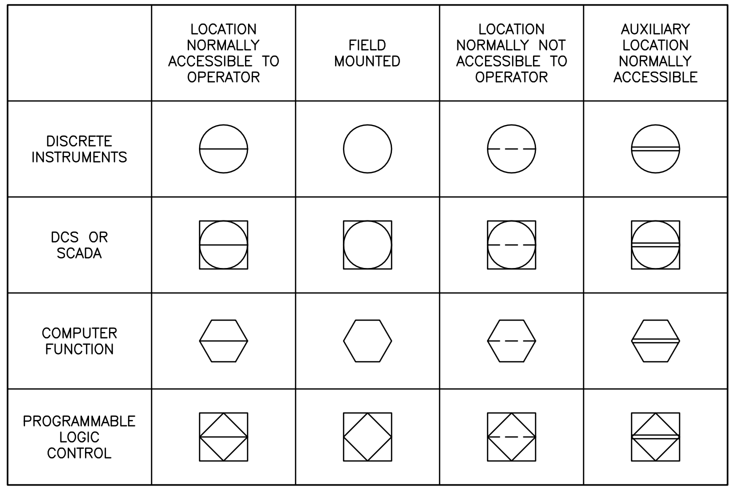
Renewable Energy Production from
DoD Installation Solid Waste by
Anaerobic Digestion

LEGEND - P&ID 2

PROJECT NO. 50957–73968
FILE NAME: G104LGPD
DRAWING NO.
GI04
SHEET NO.
4 OF 28

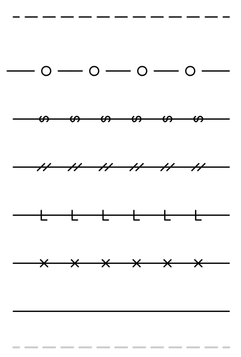
GENERAL INSTRUMENT OR FUNCTION SYMBOLS


LOCATION NORMALLY ACCESSIBLE TO OPERATOR
FIELD MOUNTED
LOCATION NORMALLY NOT ACCESSIBLE TO OPERATOR
AUXILIARY LOCATION NORMALLY ACCESSIBLE
DISCRETE INSTRUMENTS
DCS OR SCADA
COMPUTER FUNCTION
PROGRAMMABLE LOGIC CONTROL

◯◯	INDICATES A SINGLE INSTRUMENT OR OTHER COMPONENT HAVING MULTIPLE FUNCTIONS
MCC	INDICATES INTERLOCK OR LOGIC AT MOTOR CONTROL CENTER OR MOTOR STARTER
I	INDICATES GENERAL OR MISCELLANEOUS HARDWIRED INTERLOCK
SCR	SILICON CONTROLLED RECTIFIER
VFD	VARIABLE FREQUENCY DRIVE
SS	SOLID STATE SOFT STARTER

INSTRUMENT LINE SYMBOLS

MAJOR PROCESS LINES SHOWN BOLD, MINOR LINES SHOWN NONBOLD



ELECTRICAL SIGNAL

LOGICAL SIGNAL PATH (SOFTWARE LINK)

ELECTROMAGNETIC OR SONIC SIGNAL

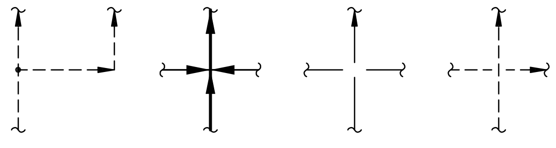
PNEUMATIC SIGNAL

HYDRAULIC SIGNAL

CAPILLARY TUBE

INSTRUMENT SUPPLY OR CONNECTION TO PROCESS

SCREENED INSTRUMENT LINES INDICATE EXISTING LINES TO REMAIN AS IS (ELECTRIC SIGNAL SHOWN—TYPICAL FOR OTHER SIGNALS)


CONNECTING LINES
NON—CONNECTING LINES

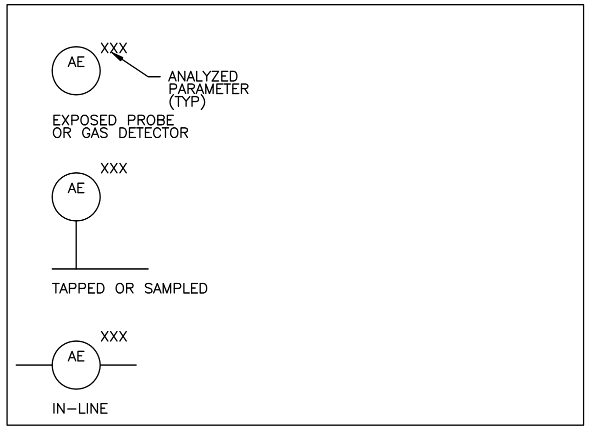
INSTRUMENTATION FUNCTIONAL CODE

	FIRST LETTER		SUCCEEDING LETTERS		
	MEASURED OR INITIATING VARIABLE	(MODIFIER)	READOUT OR PASSIVE FUNCTION	OUTPUT FUNCTION	(MODIFIER)
A	ANALYSIS		ALARM		
B			(1)	(1)	(1)
C	(1)			CONTROL	
D	DENSITY(1)	DIFFERENTIAL			
E	VOLTAGE		SENSOR (PRIMARY ELEMENT)		
F	FLOW RATE	RATIO			
G	(1)		GLASS OR VIEWING DEVICE		
H	HAND (MANUAL)				HIGH (OPENED)
I	CURRENT		INDICATE		
J	POWER	SCAN			
K	TIME	TIME RATE OF CHANGE		CONTROL STATION	
L	LEVEL		PILOT LIGHT		LOW (CLOSED)
M	(1)	MOMENTARY		(1)	MIDDLE OR INTERMEDIATE
N	(1)		(1)	(1)	(1)
O	(1)		ORIFICE		(1)
P	PRESSURE OR VACUUM		POINT (TEST CONNECTION)		
Q	QUANTITY	INTEGRATE OR TOTALIZE			
R			RECORD		
S	SPEED OR FREQUENCY	SAFETY		SWITCH	
T	TEMPERATURE			TRANSMIT	
U	MULTIVARIABLE (2)		MULTIFUNCTION (2)	MULTIFUNCTION (2)	MULTIFUNCTION (2)
V	VIBRATION, MECH ANAL.			VALVE, DAMPER OR LOUVER	
W	WEIGHT OR FORCE		WELL		
X	STATUS (3)				
Y	EVENT, STATE OR PRESENCE			RELAY, COMPUTE OR CONVERT	
Z	POSITION			DRIVE, ACTUATE OR UNCLASSIFIED FINAL ELEMENT	

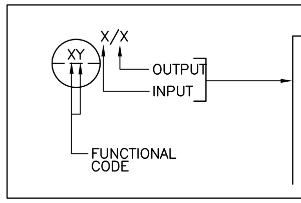
TABLE NOTES:

1. USER'S CHOICE.
2. WHEN USED SYMBOL OR SIGNAL LINE IS ANNOTATED.
3. PROJECT SPECIFIC FUNCTION.

ANALYSIS INSTRUMENTS

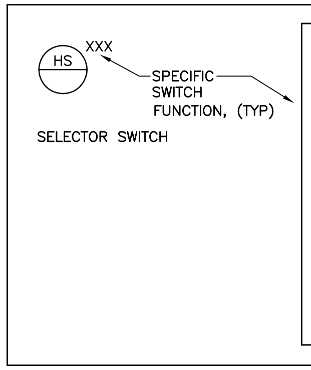

AE
XXX
ANALYZED PARAMETER (TYP)
EXPOSED PROBE OR GAS DETECTOR
AE
XXX
TAPPED OR SAMPLED
AE
XXX
IN—LINE

SIGNAL CONVERTERS


XY
X/X
OUTPUT
INPUT
FUNCTIONAL CODE

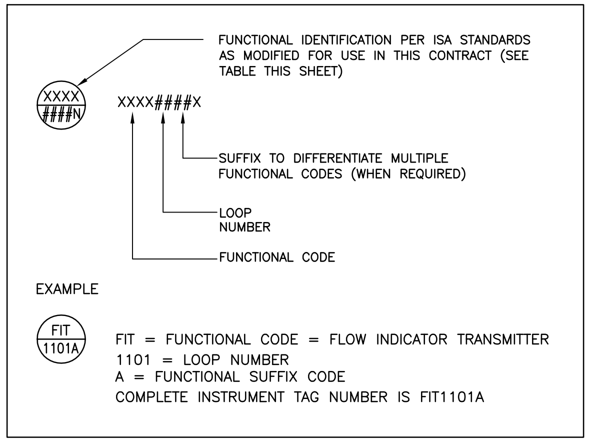
E = VOLTAGE
F = FREQUENCY
H = HYDRAULIC
I = CURRENT
P = PNEUMATIC
PF = PULSE FREQUENCY
PD = PULSE DURATION
R = RESISTANCE
☑ = SQUARE ROOT EXTRACTION
Σ = SUM

HAND SWITCHES


HS
XXX
SPECIFIC SWITCH FUNCTION, (TYP)
SELECTOR SWITCH

AO = AUTO/OFF
AM = AUTO/MANUAL
CM = COMPUTER/MANUAL
CL = COMPUTER/LOCAL
FR = FORWARD/REVERSE
FOR = FORWARD/OFF/REVERSE
FS = FAST/SLOW
FOS = FAST/OFF/SLOW
HOA = HAND/OFF/AUTO
LLS = LEAD/LAG/STANDBY
LOR = LOCAL/OFF/REMOTE
LOS = LOCKOUT/STOP
LR = LOCAL/REMOTE
OC = OPEN/CLOSE
OCA = OPEN/CLOSE/AUTO
OO = ON/OFF
OSC = OPEN/STOP/CLOSE
SS = START/STOP
SOR = START/OFF/RESET

INSTRUMENTATION TAGGING

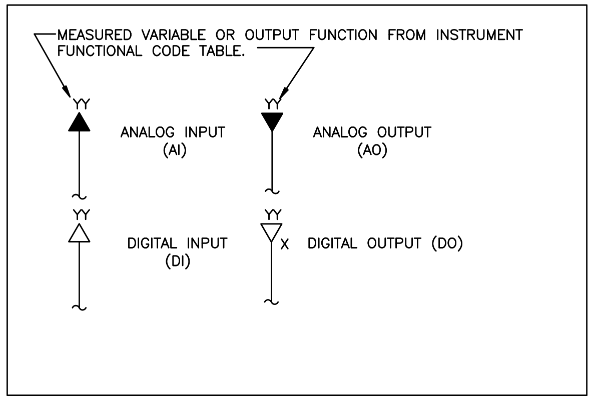

XXXX
####N
XXXX####X
FUNCTIONAL IDENTIFICATION PER ISA STANDARDS AS MODIFIED FOR USE IN THIS CONTRACT (SEE TABLE THIS SHEET)
SUFFIX TO DIFFERENTIATE MULTIPLE FUNCTIONAL CODES (WHEN REQUIRED)
LOOP NUMBER
FUNCTIONAL CODE
EXAMPLE
FIT
1101A

FIT = FUNCTIONAL CODE = FLOW INDICATOR TRANSMITTER
1101 = LOOP NUMBER
A = FUNCTIONAL SUFFIX CODE
COMPLETE INSTRUMENT TAG NUMBER IS FIT1101A

GENERAL NOTES

1. REFER TO DRAWING G103 FOR ADDITIONAL NOTES.

I/O SIGNALS


MEASURED VARIABLE OR OUTPUT FUNCTION FROM INSTRUMENT FUNCTIONAL CODE TABLE.
YY
ANALOG INPUT (AI)
YY
ANALOG OUTPUT (AO)
YY
DIGITAL INPUT (DI)
YY
X
DIGITAL OUTPUT (DO)

COLOR CODES

1. UNLESS OTHERWISE NOTED, THE FOLLOWING COLOR CODE SHALL BE USED FOR LENSES OF ALL INDICATING LIGHTS.

FUNCTION	COLOR
ON	RED
OFF	GREEN
CLOSED	GREEN
OPEN	RED
LOW	AMBER
FAIL	AMBER
HIGH	AMBER
AUTOMATIC	WHITE
MANUAL	BLUE
LOCAL	BLUE
REMOTE	WHITE

2. UNLESS OTHERWISE NOTED, THE FOLLOWING COLOR CODE SHALL BE USED FOR PUSHBUTTONS.

FUNCTION	COLOR
STOP	BLACK
RESET	BLACK
EMERGENCY STOP	RED
OPEN	RED
CLOSE	GREEN
ON	RED
OFF	GREEN
FAULT	AMBER
HIGH PRESSURE	AMBER

REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: C. McPHERSON
DRAWN BY: J. WEINER
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: APRIL 2011

LINE IS 1 INCH
AT FULL SIZE
(34X22)
SCALE ACCORDINGLY

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DoD Installation Solid Waste by
Anaerobic Digestion

LEGEND - P&ID 3

PROJECT NO. 50957—73968
FILE NAME: G105
DRAWING NO.
GI05
SHEET NO.
5 OF 28

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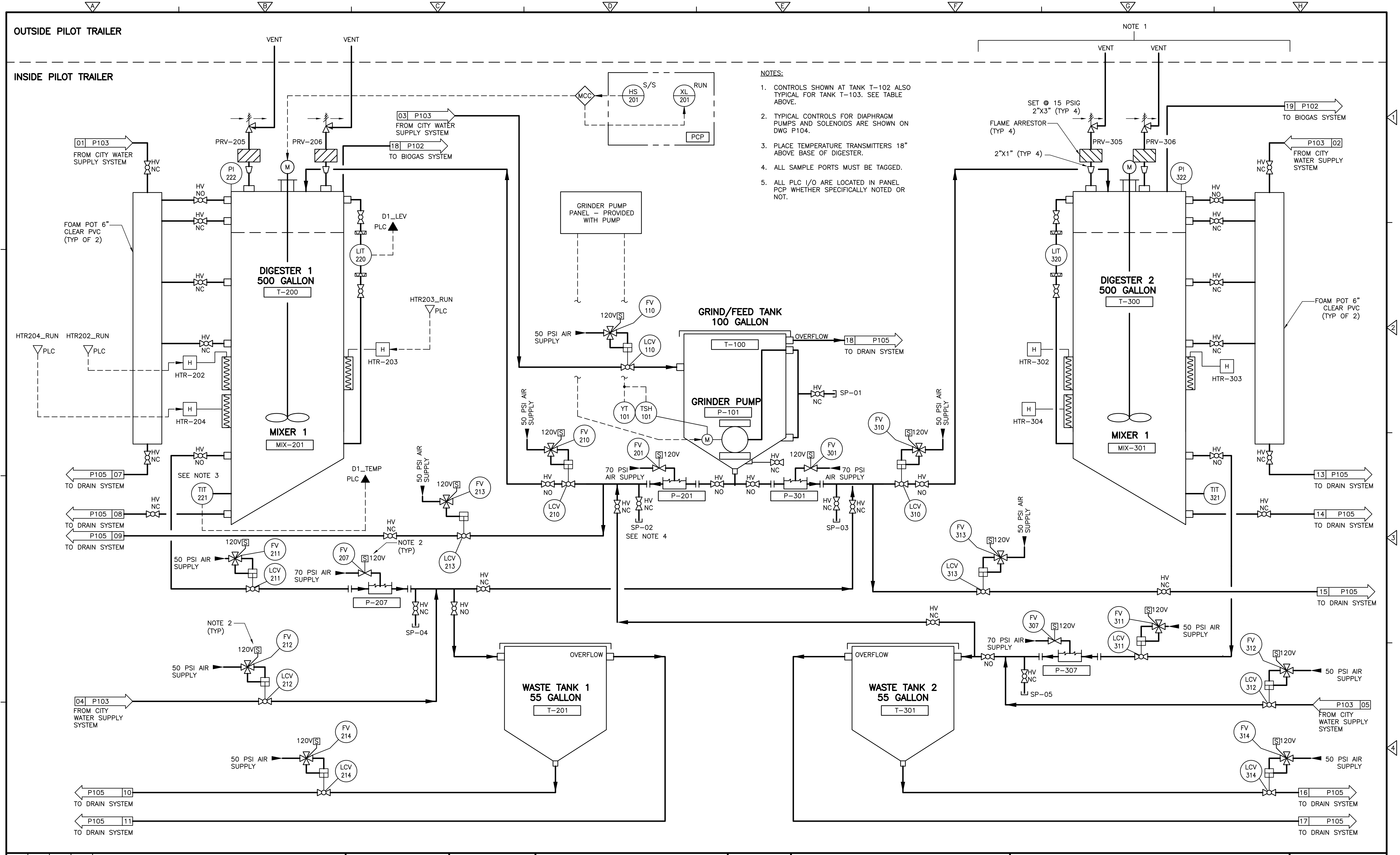
A
B
C
D
E
F
G
H
1
2
3
4
OUTSIDE PILOT TRAILER
INSIDE PILOT TRAILER
VENT
VENT
NOTE 1
VENT
VENT
S/S
HS 201
XL 201
RUN
MCC
PCP
01 P103 FROM CITY WATER SUPPLY SYSTEM
03 P103 FROM CITY WATER SUPPLY SYSTEM
18 P102 TO BIOGAS SYSTEM
19 P102 TO BIOGAS SYSTEM
P103 02 FROM CITY WATER SUPPLY SYSTEM
PRV-205
PRV-206
PRV-305
PRV-306
SET @ 15 PSIG
2"X3" (TYP 4)
FLAME ARRESTOR (TYP 4)
2"X1" (TYP 4)
PI 222
PI 322
M
HV NO
HV NC
FOAM POT 6" CLEAR PVC (TYP OF 2)
DIGESTER 1
500 GALLON
T-200
DIGESTER 2
500 GALLON
T-300
D1_LEV
PLC
LIT 220
LIT 320
HTR203_RUN
PLC
HTR-203
HTR204_RUN
HTR202_RUN
PLC
HTR-202
HTR-204
HTR-302
HTR-303
HTR-304
H
MIXER 1
MIX-201
MIXER 1
MIX-301
D1_TEMP
PLC
SEE NOTE 3
TIT 221
TIT 321
P105 07 TO DRAIN SYSTEM
P105 08 TO DRAIN SYSTEM
P105 09 TO DRAIN SYSTEM
13 P105 TO DRAIN SYSTEM
14 P105 TO DRAIN SYSTEM
15 P105 TO DRAIN SYSTEM
GRINDER PUMP PANEL – PROVIDED WITH PUMP
GRIND/FEED TANK
100 GALLON
T-100
OVERFLOW
18 P105 TO DRAIN SYSTEM
GRINDER PUMP
P-101
50 PSI AIR SUPPLY
120V S
FV 110
LCV 110
YT 101
TSH 101
SP-01
FV 210
LCV 210
FV 201
P-201
FV 301
P-301
FV 310
LCV 310
70 PSI AIR SUPPLY
SP-02
SEE NOTE 4
SP-03
FV 213
LCV 213
NOTE 2 (TYP)
FV 211
LCV 211
FV 207
P-207
SP-04
FV 313
LCV 313
NOTE 2 (TYP)
FV 212
LCV 212
04 P103 FROM CITY WATER SUPPLY SYSTEM
WASTE TANK 1
55 GALLON
T-201
OVERFLOW
FV 214
LCV 214
P105 10 TO DRAIN SYSTEM
P105 11 TO DRAIN SYSTEM
FV 307
FV 311
LCV 311
P-307
SP-05
FV 312
LCV 312
P103 05 FROM CITY WATER SUPPLY SYSTEM
WASTE TANK 2
55 GALLON
T-301
FV 314
LCV 314
16 P105 TO DRAIN SYSTEM
17 P105 TO DRAIN SYSTEM

NOTES:

1. CONTROLS SHOWN AT TANK T-102 ALSO TYPICAL FOR TANK T-103. SEE TABLE ABOVE.
2. TYPICAL CONTROLS FOR DIAPHRAGM PUMPS AND SOLENOIDS ARE SHOWN ON DWG P104.
3. PLACE TEMPERATURE TRANSMITTERS 18" ABOVE BASE OF DIGESTER.
4. ALL SAMPLE PORTS MUST BE TAGGED.
5. ALL PLC I/O ARE LOCATED IN PANEL PCP WHETHER SPECIFICALLY NOTED OR NOT.

C:\cdmxm\clarkcd\d0566183\P101PPID.DWG 8/29/2012 3:06:29 PM

REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: C. McPHERSON
DRAWN BY: K. TALBOT
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: AUGUST 2012

LINE IS 1 INCH
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(34X22)
SCALE ACCORDINGLY

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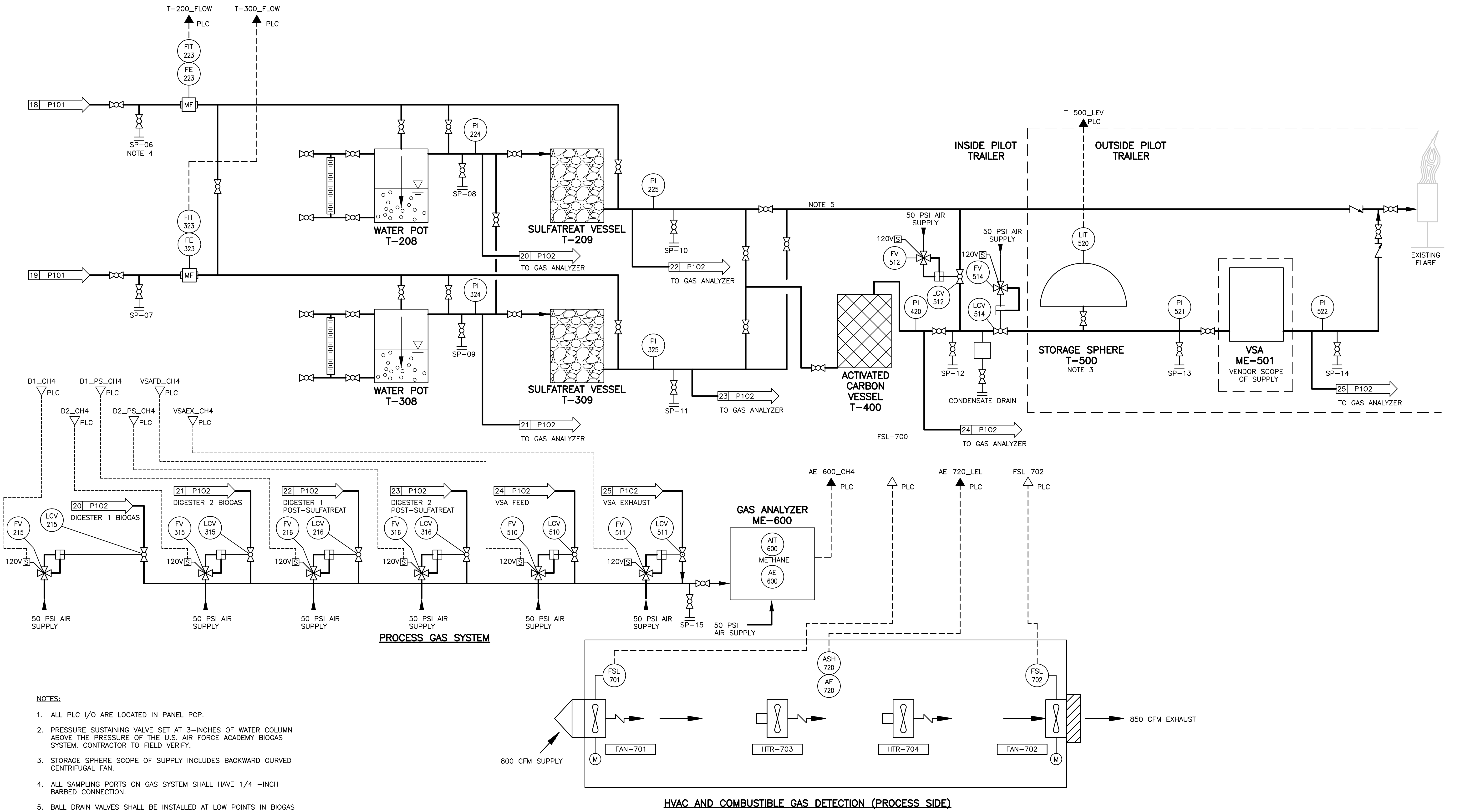
Renewable Energy Production from DoD Installation Solid Waste by Anaerobic Digestion

PROCESS PIPING AND INSTRUMENTATION DIAGRAM

PROJECT NO. 50957-73968
FILE NAME: P101PPID
DRAWING NO.
P101
SHEET NO.
6 OF 28


T-200_FLOW
T-300_FLOW
PLC
PLC
FIT 223
FE 223
MF
18 P101
SP-06
NOTE 4
FIT 323
FE 323
MF
19 P101
SP-07
PI 224
SP-08
WATER POT
T-208
SULFATREAT VESSEL
T-209
20 P102
TO GAS ANALYZER
PI 225
SP-10
22 P102
TO GAS ANALYZER
PI 324
SP-09
WATER POT
T-308
SULFATREAT VESSEL
T-309
21 P102
TO GAS ANALYZER
PI 325
SP-11
23 P102
TO GAS ANALYZER
NOTE 5
ACTIVATED
CARBON
VESSEL
T-400
50 PSI AIR
SUPPLY
120V S
FV 512
LCV 512
PI 420
50 PSI AIR
SUPPLY
120V S
FV 514
LCV 514
SP-12
CONDENSATE DRAIN
24 P102
TO GAS ANALYZER
FSL-700
INSIDE PILOT
TRAILER
OUTSIDE PILOT
TRAILER
T-500_LEV
PLC
LIT 520
STORAGE SPHERE
T-500
NOTE 3
PI 521
SP-13
VSA
ME-501
VENDOR SCOPE
OF SUPPLY
PI 522
SP-14
25 P102
TO GAS ANALYZER
EXISTING
FLARE
D1_CH4
PLC
D1_PS_CH4
PLC
VSAFD_CH4
PLC
D2_CH4
PLC
D2_PS_CH4
PLC
VSAEX_CH4
PLC
20 P102
DIGESTER 1 BIOGAS
FV 215
LCV 215
120V S
21 P102
DIGESTER 2 BIOGAS
FV 315
LCV 315
120V S
22 P102
DIGESTER 1
POST-SULFATREAT
FV 216
LCV 216
120V S
23 P102
DIGESTER 2
POST-SULFATREAT
FV 316
LCV 316
120V S
24 P102
VSA FEED
FV 510
LCV 510
120V S
25 P102
VSA EXHAUST
FV 511
LCV 511
120V S
50 PSI AIR
SUPPLY
50 PSI AIR
SUPPLY
50 PSI AIR
SUPPLY
50 PSI AIR
SUPPLY
50 PSI AIR
SUPPLY
50 PSI AIR
SUPPLY
SP-15
50 PSI
AIR SUPPLY
PROCESS GAS SYSTEM
GAS ANALYZER
ME-600
AIT 600
METHANE
AE 600
AE-600_CH4
PLC
PLC
AE-720_LEL
PLC
FSL-702
PLC
FSL 701
ASH 720
AE 720
FSL 702
FAN-701
HTR-703
HTR-704
FAN-702
M
M
800 CFM SUPPLY
850 CFM EXHAUST
HVAC AND COMBUSTIBLE GAS DETECTION (PROCESS SIDE)

NOTES:

1. ALL PLC I/O ARE LOCATED IN PANEL PCP.
2. PRESSURE SUSTAINING VALVE SET AT 3-INCHES OF WATER COLUMN ABOVE THE PRESSURE OF THE U.S. AIR FORCE ACADEMY BIOGAS SYSTEM. CONTRACTOR TO FIELD VERIFY.
3. STORAGE SPHERE SCOPE OF SUPPLY INCLUDES BACKWARD CURVED CENTRIFUGAL FAN.
4. ALL SAMPLING PORTS ON GAS SYSTEM SHALL HAVE 1/4 -INCH BARBED CONNECTION.
5. BALL DRAIN VALVES SHALL BE INSTALLED AT LOW POINTS IN BIOGAS CONVEYANCE SYSTEM; LOCATIONS TO BE FIELD-SITED BY INSTALLATION CONTRACTOR

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REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: C. McPHERSON
DRAWN BY: K. TALBOT
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: AUGUST 2012

LINE IS 1 INCH
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SCALE ACCORDINGLY

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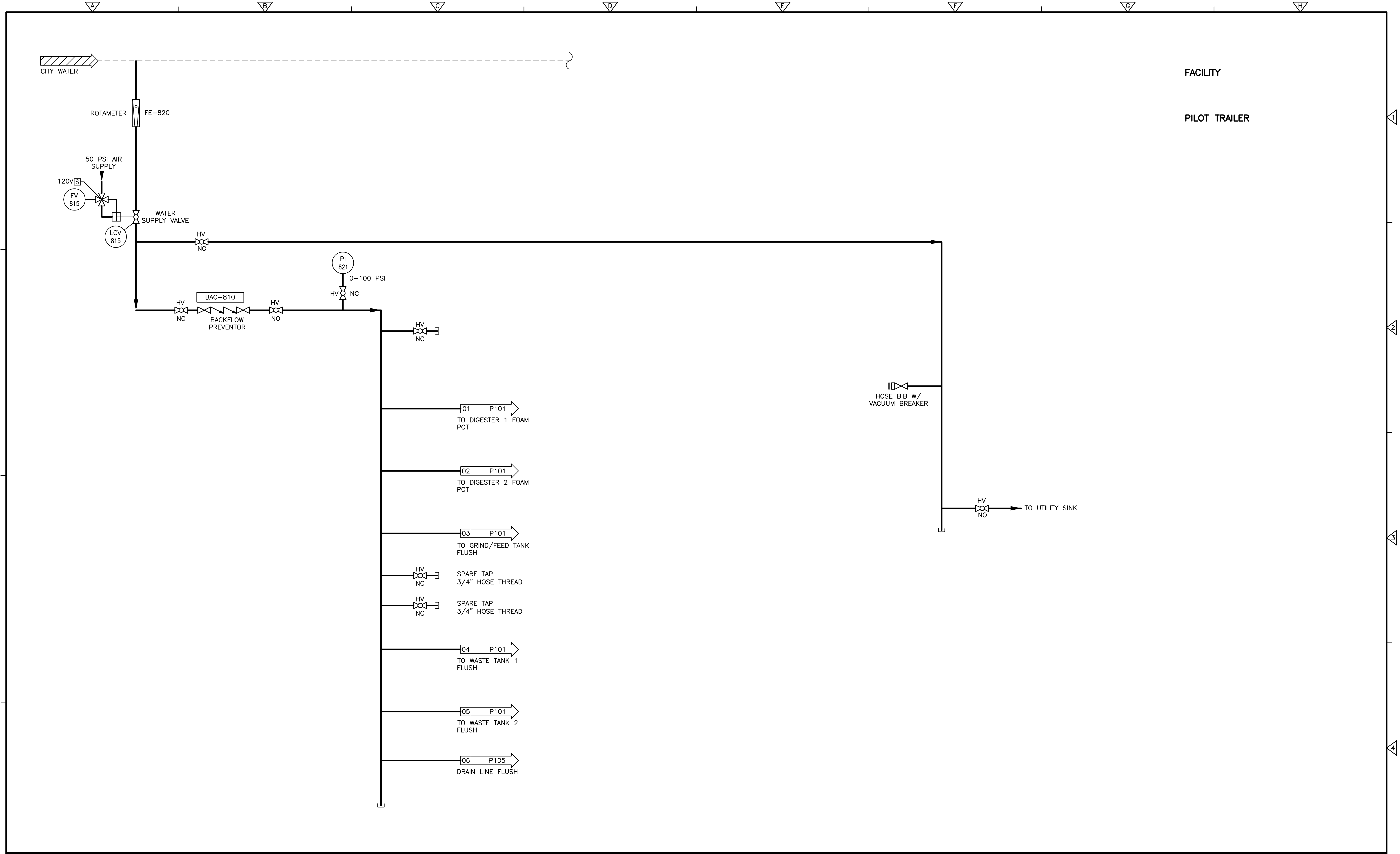
Renewable Energy Production from
DoD Installation Solid Waste by
Anaerobic Digestion

PROCESS GAS SYSTEM
HVAC AND COMBUSTIBLE GAS DETECTION

PROJECT NO. 50957-73968
FILE NAME: P102PRGS
DRAWING NO.
P102
SHEET NO.
7 OF 28



A
B
C
D
E
F
G
H
1
2
3
4
CITY WATER
FACILITY
PILOT TRAILER
ROTAMETER
FE–820
50 PSI AIR SUPPLY
120V
S
FV 815
LCV 815
WATER SUPPLY VALVE
HV
NO
PI 821
0–100 PSI
HV
NC
HV
NO
BAC–810
BACKFLOW PREVENTOR
HV
NO
HV
NC
01
P101
TO DIGESTER 1 FOAM POT
02
P101
TO DIGESTER 2 FOAM POT
03
P101
TO GRIND/FEED TANK FLUSH
HV
NC
SPARE TAP 3/4" HOSE THREAD
HV
NC
SPARE TAP 3/4" HOSE THREAD
04
P101
TO WASTE TANK 1 FLUSH
05
P101
TO WASTE TANK 2 FLUSH
06
P105
DRAIN LINE FLUSH
HOSE BIB W/ VACUUM BREAKER
HV
NO
TO UTILITY SINK

REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: C. McPHERSON
DRAWN BY: K. TALBOT
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: AUGUST 2012

LINE IS 1 INCH
AT FULL SIZE
(34X22)
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Renewable Energy Production from
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Anaerobic Digestion

WATER SUPPY & PLUMBING SYSTEM

PROJECT NO. 50957–73968
FILE NAME: P103WSPS
DRAWING NO.
P103
SHEET NO.
8 OF 28

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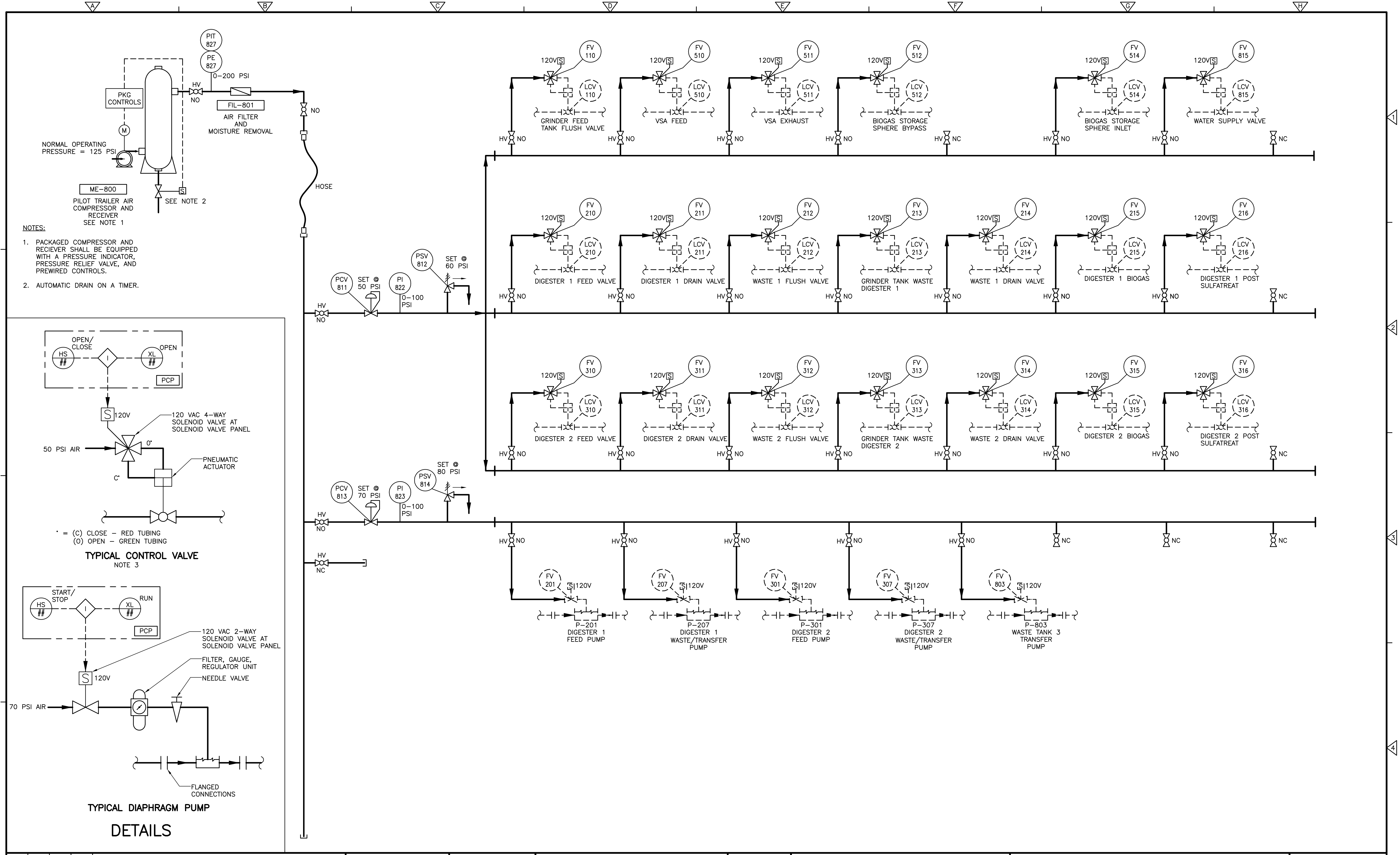
PIT 827
PE 827
0–200 PSI
PKG CONTROLS
HV NO
FIL–801
AIR FILTER AND MOISTURE REMOVAL
NO
M
NORMAL OPERATING PRESSURE = 125 PSI
ME–800
PILOT TRAILER AIR COMPRESSOR AND RECEIVER SEE NOTE 1
SEE NOTE 2
HOSE
NOTES:
1. PACKAGED COMPRESSOR AND RECIEVER SHALL BE EQUIPPED WITH A PRESSURE INDICATOR, PRESSURE RELIEF VALVE, AND PREWIRED CONTROLS.
2. AUTOMATIC DRAIN ON A TIMER.
FV 110
LCV 110
GRINDER FEED TANK FLUSH VALVE
FV 510
LCV 510
VSA FEED
FV 511
LCV 511
VSA EXHAUST
FV 512
LCV 512
BIOGAS STORAGE SPHERE BYPASS
FV 514
LCV 514
BIOGAS STORAGE SPHERE INLET
FV 815
LCV 815
WATER SUPPLY VALVE
120V S
HV NO
NC
PSV 812
SET @ 60 PSI
PCV 811
SET @ 50 PSI
PI 822
0–100 PSI
FV 210
LCV 210
DIGESTER 1 FEED VALVE
FV 211
LCV 211
DIGESTER 1 DRAIN VALVE
FV 212
LCV 212
WASTE 1 FLUSH VALVE
FV 213
LCV 213
GRINDER TANK WASTE DIGESTER 1
FV 214
LCV 214
WASTE 1 DRAIN VALVE
FV 215
LCV 215
DIGESTER 1 BIOGAS
FV 216
LCV 216
DIGESTER 1 POST SULFATREAT
FV 310
LCV 310
DIGESTER 2 FEED VALVE
FV 311
LCV 311
DIGESTER 2 DRAIN VALVE
FV 312
LCV 312
WASTE 2 FLUSH VALVE
FV 313
LCV 313
GRINDER TANK WASTE DIGESTER 2
FV 314
LCV 314
WASTE 2 DRAIN VALVE
FV 315
LCV 315
DIGESTER 2 BIOGAS
FV 316
LCV 316
DIGESTER 2 POST SULFATREAT
PSV 814
SET @ 80 PSI
PCV 813
SET @ 70 PSI
PI 823
0–100 PSI
HV NC
FV 201
P–201 DIGESTER 1 FEED PUMP
FV 207
P–207 DIGESTER 1 WASTE/TRANSFER PUMP
FV 301
P–301 DIGESTER 2 FEED PUMP
FV 307
P–307 DIGESTER 2 WASTE/TRANSFER PUMP
FV 803
P–803 WASTE TANK 3 TRANSFER PUMP
OPEN/ CLOSE
HS ##
I
XL ##
OPEN
PCP
S 120V
120 VAC 4–WAY SOLENOID VALVE AT SOLENOID VALVE PANEL
50 PSI AIR
O*
C*
PNEUMATIC ACTUATOR
* = (C) CLOSE – RED TUBING
(O) OPEN – GREEN TUBING
TYPICAL CONTROL VALVE
NOTE 3
START/ STOP
RUN
120 VAC 2–WAY SOLENOID VALVE AT SOLENOID VALVE PANEL
FILTER, GAUGE, REGULATOR UNIT
NEEDLE VALVE
70 PSI AIR
FLANGED CONNECTIONS
TYPICAL DIAPHRAGM PUMP
DETAILS
A B C D E F G H
1 2 3 4

REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: C. McPHERSON
DRAWN BY: K. TALBOT
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: AUGUST 2012

LINE IS 1 INCH
AT FULL SIZE
(34X22)
SCALE ACCORDINGLY

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Renewable Energy Production from DoD Installation Solid Waste by Anaerobic Digestion

INSTRUMENT & SERVICE
AIR SYSTEM DIAGRAM

PROJECT NO. 50957–73968
FILE NAME: P104ISAD
DRAWING NO.
P104
SHEET NO.
9 OF 28

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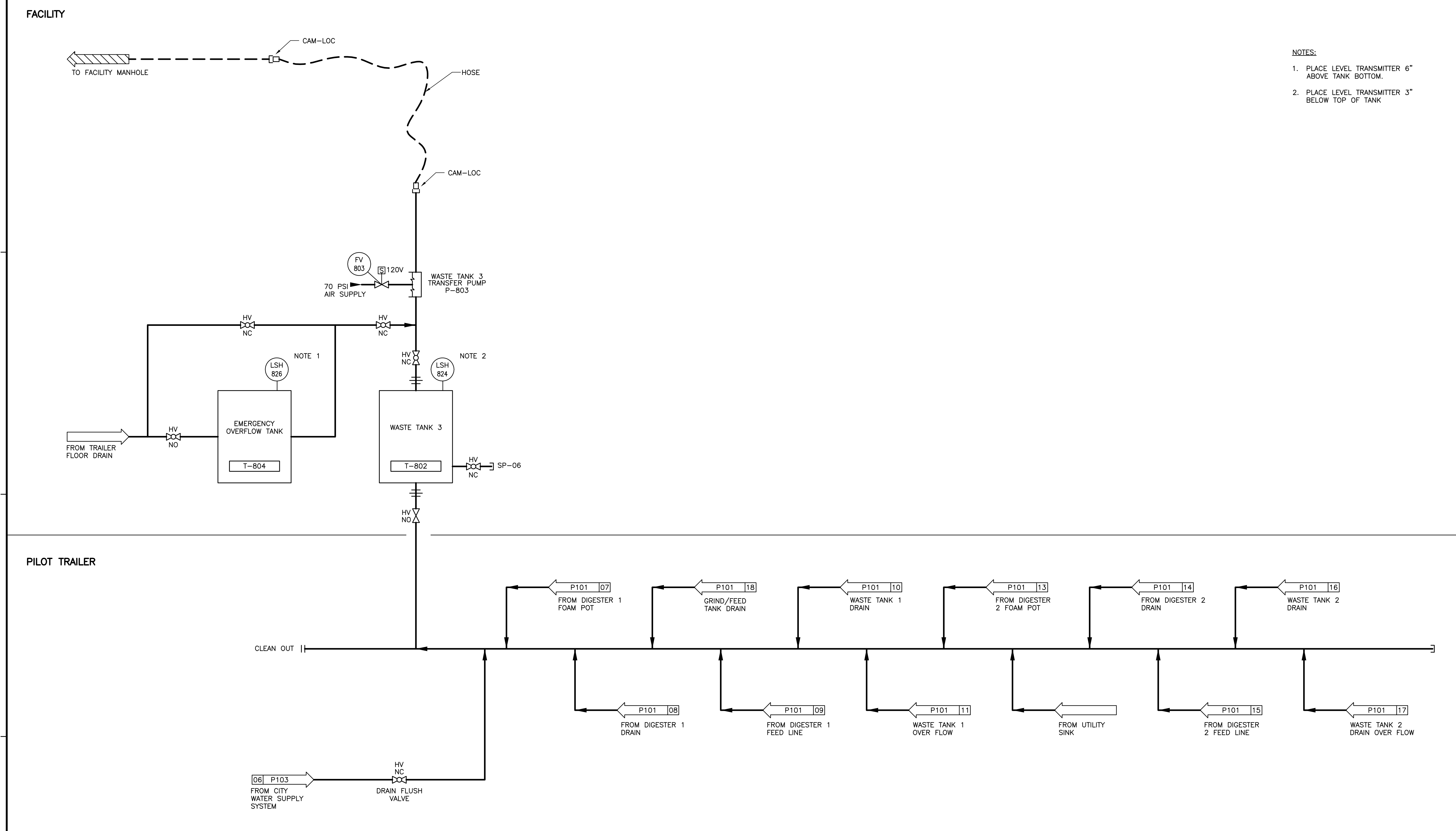
A
B
C
D
E
F
G
H
1
2
3
4
FACILITY
CAM-LOC
TO FACILITY MANHOLE
HOSE
CAM-LOC
FV 803
S 120V
70 PSI AIR SUPPLY
WASTE TANK 3 TRANSFER PUMP P-803
HV NC
HV NC
HV NC
NOTE 1
LSH 826
NOTE 2
LSH 824
EMERGENCY OVERFLOW TANK
T-804
WASTE TANK 3
T-802
HV NO
FROM TRAILER FLOOR DRAIN
HV NC
SP-06
HV NO
PILOT TRAILER
P101 07
FROM DIGESTER 1 FOAM POT
P101 18
GRIND/FEED TANK DRAIN
P101 10
WASTE TANK 1 DRAIN
P101 13
FROM DIGESTER 2 FOAM POT
P101 14
FROM DIGESTER 2 DRAIN
P101 16
WASTE TANK 2 DRAIN
CLEAN OUT
P101 08
FROM DIGESTER 1 DRAIN
P101 09
FROM DIGESTER 1 FEED LINE
P101 11
WASTE TANK 1 OVER FLOW
FROM UTILITY SINK
P101 15
FROM DIGESTER 2 FEED LINE
P101 17
WASTE TANK 2 DRAIN OVER FLOW
06 P103
FROM CITY WATER SUPPLY SYSTEM
HV NC
DRAIN FLUSH VALVE

NOTES:

1. PLACE LEVEL TRANSMITTER 6" ABOVE TANK BOTTOM.
2. PLACE LEVEL TRANSMITTER 3" BELOW TOP OF TANK

Xref's: [CDM_2234] Images: []
Last saved by: TALBOTWK Time: 4/19/2011 1:04:19 PM

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REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: C. McPHERSON
DRAWN BY: K. TALBOT
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: AUGUST 2012

LINE IS 1 INCH
AT FULL SIZE
(34X22)
SCALE ACCORDINGLY

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Seattle, CA 98101
Phone: 206-336-4900
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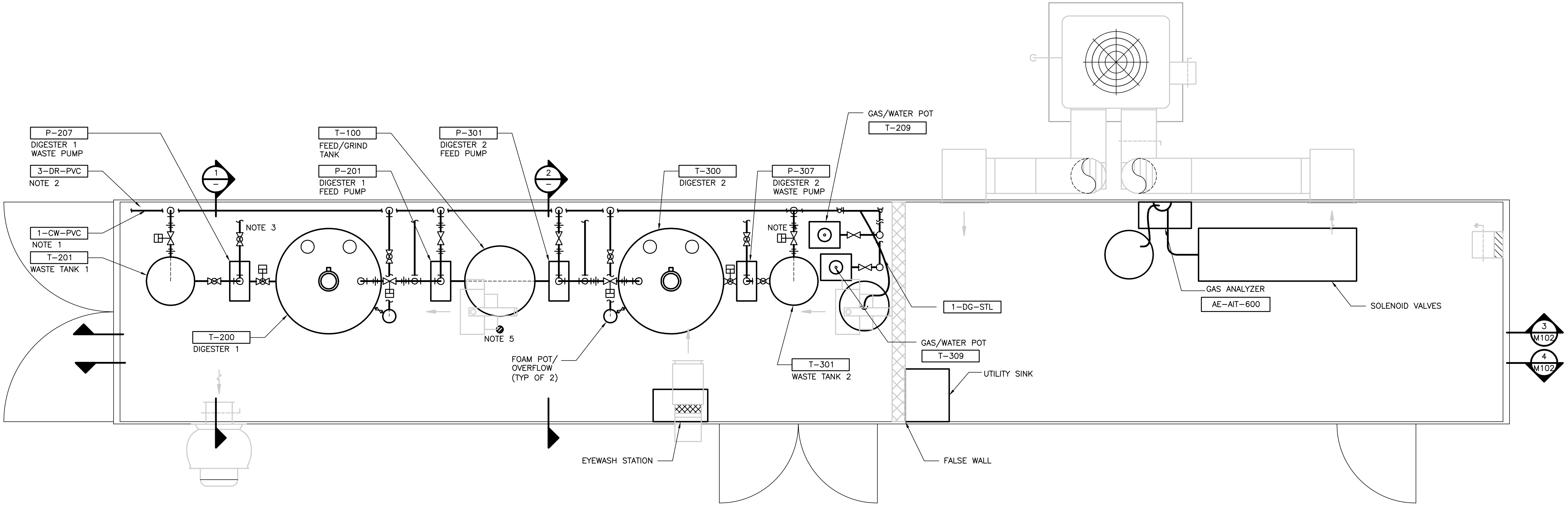
Renewable Energy Production from DoD Installation Solid Waste by Anaerobic Digestion

PROCESS DRAIN SYSTEM DIAGRAM

PROJECT NO. 50957-73968
FILE NAME: P105PRSD

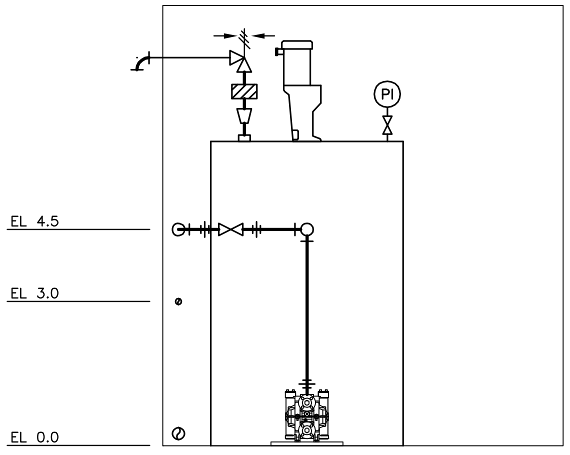
DRAWING NO.
P105

SHEET NO.
10 OF 28


P–207
DIGESTER 1
WASTE PUMP
3–DR–PVC
NOTE 2
1–CW–PVC
NOTE 1
T–201
WASTE TANK 1
T–100
FEED/GRIND
TANK
P–201
DIGESTER 1
FEED PUMP
P–301
DIGESTER 2
FEED PUMP
1
–
2
–
T–300
DIGESTER 2
P–307
DIGESTER 2
WASTE PUMP
GAS/WATER POT
T–209
NOTE 3
NOTE 3
T–200
DIGESTER 1
NOTE 5
FOAM POT/
OVERFLOW
(TYP OF 2)
T–301
WASTE TANK 2
1–DG–STL
GAS/WATER POT
T–309
UTILITY SINK
GAS ANALYZER
AE–AIT–600
SOLENOID VALVES
EYEWASH STATION
FALSE WALL
3
M102
4
M102

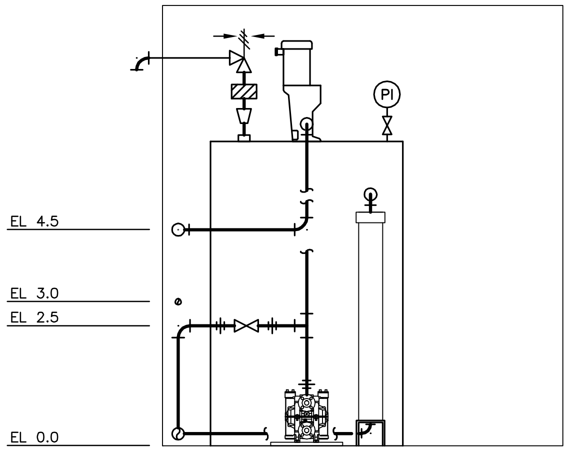
PLAN

1/2" = 1'–0"


PI
EL 4.5
EL 3.0
EL 0.0

SECTION 1

1/2" = 1'–0"


PI
EL 4.5
EL 3.0
EL 2.5
EL 0.0

SECTION 2

1/2" = 1'–0"

1/2" = 1'– 0"
1 0 1 2

NOTES:

1. CITY WATER SUPPLY LINE FOR SYSTEM FLUSHES AND UTILITY SINK. SUPPORTED OFF OF NORTH WALL AT EL 3.0. FIELD CONNECTIONS/ROUTING AS SHOWN ON P101.
2. DRAIN PIPE AT BASE OF NORTH WALL AT EL 0.2. CONNECTIONS AS SHOWN ON P101 AND P105.
3. SLUDGE TRANSFER LINE FROM DIGESTER 1 WASTE PUMP TO DIGESTER 2 FEED LINE ALONG NORTH WALL AT EL 4.3 AS SHOWN ON P101.
4. SLUDGE TRANSFER LINE FROM DIGESTER 2 WASTE PUMP TO DIGESTER 1 FEED LINE ALONG NORTH WALL AT EL 4.5 AS SHOWN ON P101.
5. PROVIDE 3–INCH FLOOR DRAIN WITH CONNECTION TO EMERGENCY OVERFLOW TANK AS SHOWN ON P105. SLOPE PILOT TRAILER TO CENTRAL DRAIN.
6. WALLS OF TRAILER SHALL BE STRUCTURALLY REINFORCED AS NEEDED TO SUPPORT EQUIPMENT PIPING AND APPURTENANCES.
7. DRAIN LINE SHALL BE MOUNTED UNDERNEATH TRAILER.

REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: C. McPHERSON
DRAWN BY: K. TALBOT
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: AUGUST 2012

LINE IS 1 INCH
AT FULL SIZE
(34X22)
SCALE ACCORDINGLY

CDM
Camp Dresser & McKee Inc.
1218 3rd Avenue, Suite 100
Seattle, CA 98101
Phone: 206-336-4900
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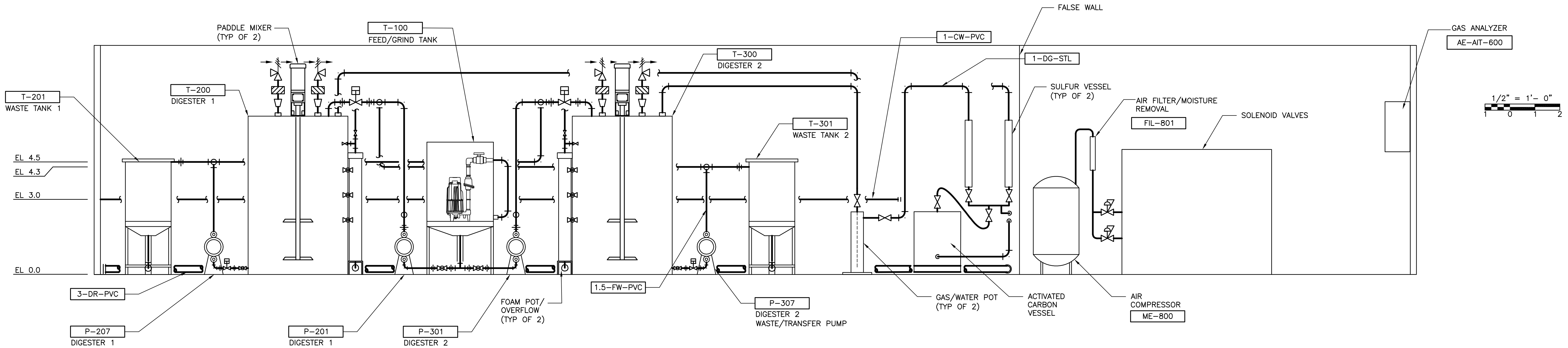
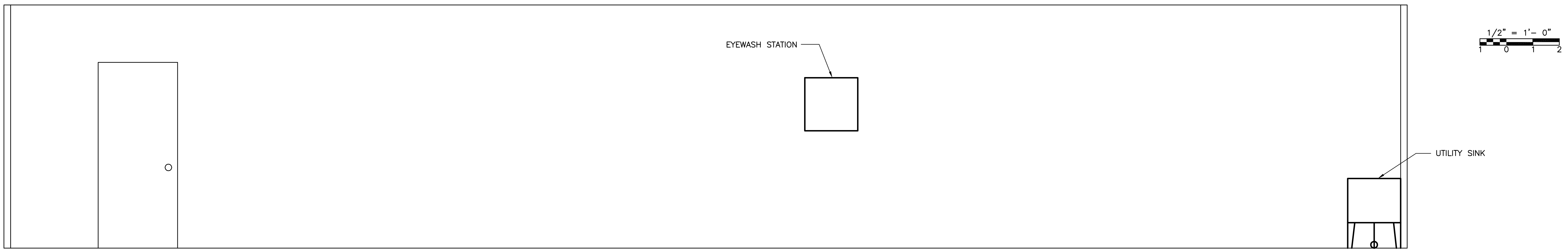
Renewable Energy Production from
DoD Installation Solid Waste by
Anaerobic Digestion

PILOT EQUIPMENT
PLAN AND SECTION

PROJECT NO. 50957–73968
FILE NAME: M101PEPL
DRAWING NO.
M101
SHEET NO.
12 OF 28


PADDLE MIXER (TYP OF 2)
T-100
FEED/GRIND TANK
FALSE WALL
GAS ANALYZER
AE-AIT-600
1-CW-PVC
T-300
DIGESTER 2
1-DG-STL
T-201
WASTE TANK 1
T-200
DIGESTER 1
SULFUR VESSEL (TYP OF 2)
AIR FILTER/MOISTURE REMOVAL
FIL-801
SOLENOID VALVES
1/2" = 1'- 0"
1 0 1 2
T-301
WASTE TANK 2
EL 4.5
EL 4.3
EL 3.0
EL 0.0
3-DR-PVC
1.5-FW-PVC
FOAM POT/ OVERFLOW (TYP OF 2)
P-307
DIGESTER 2 WASTE/TRANSFER PUMP
GAS/WATER POT (TYP OF 2)
ACTIVATED CARBON VESSEL
AIR COMPRESSOR
ME-800
P-207
DIGESTER 1 WASTE/TRANSFER PUMP
P-201
DIGESTER 1 FEED PUMP
P-301
DIGESTER 2 FEED PUMP

SECTION 3
M101
1/2" = 1'-0"


1/2" = 1'- 0"
1 0 1 2
EYEWASH STATION
UTILITY SINK

SECTION 4
M101
1/2" = 1'-0"

NOTES:

PIPE MATERIAL AND SERVICE SHALL BE AS FOLLOWS:

Service	Size	Symbol	Material	Rating
City Water	1"	CW	PVC	SCH 80
Digester Gas	1"	DG	STEEL	ASTM A53
Food Waste	1"	FW	PVC	SCH 80
Drain	3"	DR	PVC	SCH 40
Service Air	1/4" Tubing	SA	Nylon	200 psi minimum
Service Air	1"	SA	Copper	ASTM B88

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REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: C. McPHERSON
DRAWN BY: K. TALBOT
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: AUGUST 2012

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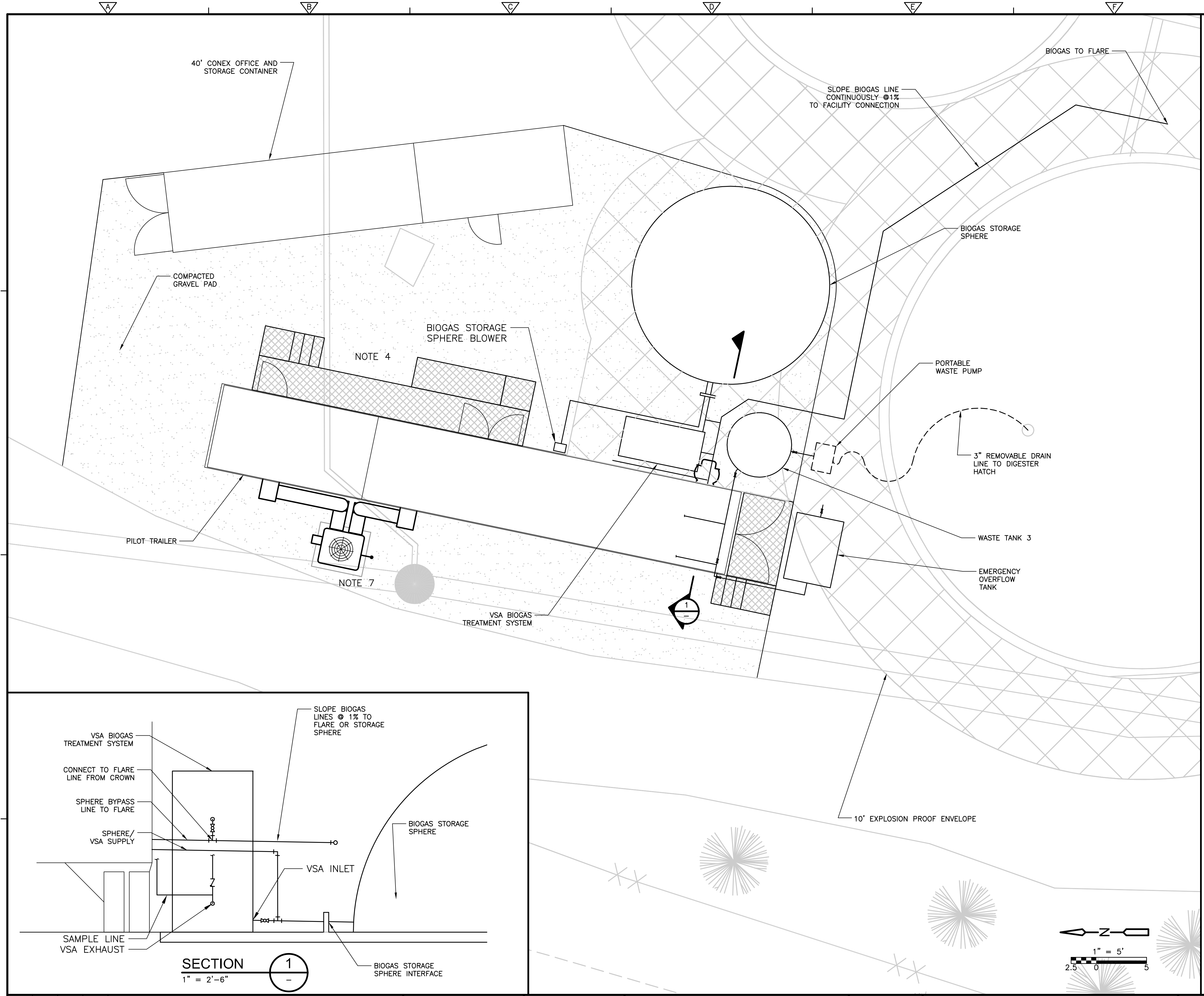
Renewable Energy Production from
DoD Installation Solid Waste by
Anaerobic Digestion

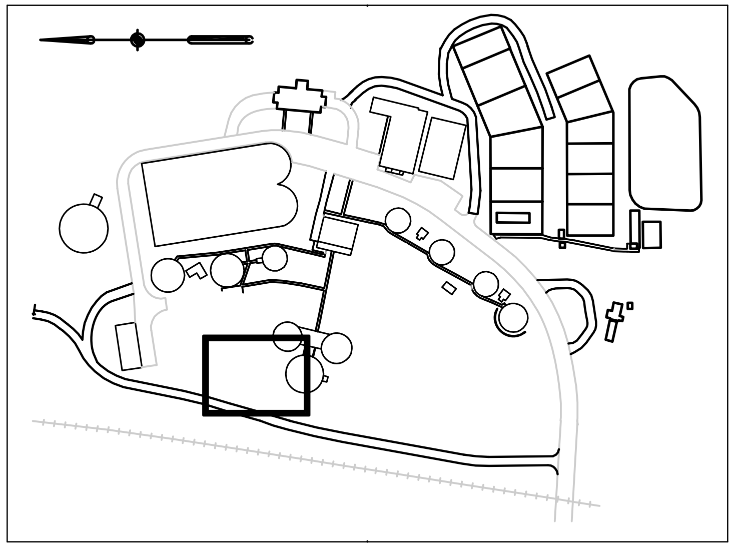
PILOT EQUIPMENT
SECTIONS

PROJECT NO. 50957-73968
FILE NAME: M102PESC
DRAWING NO.
M102
SHEET NO.
13 OF 28



40' CONEX OFFICE AND STORAGE CONTAINER
BIOGAS TO FLARE
SLOPE BIOGAS LINE CONTINUOUSLY @1% TO FACILITY CONNECTION
COMPACTED GRAVEL PAD
BIOGAS STORAGE SPHERE
BIOGAS STORAGE SPHERE BLOWER
NOTE 4
PORTABLE WASTE PUMP
3" REMOVABLE DRAIN LINE TO DIGESTER HATCH
PILOT TRAILER
WASTE TANK 3
EMERGENCY OVERFLOW TANK
NOTE 7
VSA BIOGAS TREATMENT SYSTEM
1
–
10' EXPLOSION PROOF ENVELOPE
N
1" = 5'
2.5
0
5
SLOPE BIOGAS LINES @ 1% TO FLARE OR STORAGE SPHERE
VSA BIOGAS TREATMENT SYSTEM
CONNECT TO FLARE LINE FROM CROWN
SPHERE BYPASS LINE TO FLARE
SPHERE/ VSA SUPPLY
VSA INLET
BIOGAS STORAGE SPHERE
SAMPLE LINE
VSA EXHAUST
BIOGAS STORAGE SPHERE INTERFACE

SECTION 1
–
1" = 2'-6"



KEY MAP

NOTES:

1. UNDERGROUND UTILITIES ARE SHOWN BASED ON PLANT RECORD DRAWINGS WHICH REPRESENT THE BEST INFORMATION AVAILABLE. THE TYPE, SIZE, LOCATION, AND NUMBER ARE APPROXIMATE AS SHOWN BY THESE DRAWINGS.
2. PRIOR TO COMMENCEMENT OF ANY EXCAVATION, CONTRACTOR SHALL LOCATE AND MARK THE ACTUAL LOCATION OF UNDERGROUND UTILITIES.
3. PROVIDE 1" CITY WATER CONNECTION FROM DIGESTER CONTROL BUILDING HOSE BIB. FREEZE PROTECT AND INSULATE AS NECESSARY.
4. PROVIDE STAIR ACCESS TO THE TRAILER ON THE NORTH END AND RAMPED ACCESS TO THE TRAILER ON THE SOUTH END.
5. ALL EXPOSED LINES AND TANKS SHALL BE INSULATED AND FREEZE PROTECTED.
6. CONTRACTOR SHALL LEVEL SITE AS NECESSARY AND PROVIDE EQUIPMENT PIPE LINE.
7. HEAT PUMP SHALL BE PROTECTED FROM SNOW AND WIND LOAD USING A PREFABRICATED OR CUSTOM SHELTER.

ANCHORAGE AS NECESSARY

REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY:
DRAWN BY:
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: AUGUST 2012

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Renewable Energy Production from
DoD Installation Solid Waste by
Anaerobic Digestion

MECHANICAL SITE PLAN

PROJECT NO. 50957-73968
FILE NAME: M103
DRAWING NO.
M103
SHEET NO.
OF 28

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PACKAGED AIR CONDITIONING UNIT SCHEDULE

MARK	SERVES	AIRFLOW (CFM)	OUTSIDE AIR (CFM)	EXTERNAL STATIC PRESSURE (IN WG)	TYPE	COOLING DATA						HEATING CAPACITY (MBH)	ELECTRIC RESISTANCE HEATER					ELECTRICAL DATA									BASIS OF DESIGN	NOTES
						TONS	TOTAL CAP (MBH)	SENS CAP (MBH)	ENT DB (DEG F)	ENT WB (DEG F)	LVG AIR TEMP DB/WB (DEG F)		MODEL	CAPACITY (KW)	STAGES	VOLTS/PHASE	MCA	EVAP FAN HP	CONDENSER FAN(S)		COMPRESSOR(S)		MCA	MAX OVER CURRENT (AMPS)	VOLTS/PHASE	EER		
																			QTY	(HP) EACH	QTY	RLA (EACH)						
AC-1	ESTCP	1200	300	0.5	PACKAGED HEAT PUMP	3	26.5	22.8	80.0	67.0	61/60	51.2	BAYHTRV115	15	2	240/1	78	0.5	1	0.2	1	15.4	25.5	40	230/1	11	TRANE 4WCC3036A1000	1, 2, 3, 4

NOTES:

1. PROVIDE PLEATED FILTERS WITH MERV 8 EFFICIENCY.
2. PROVIDE OUTSIDE AIR DAMPER.
3. PROVIDE THERMOSTAT AND LOW AMBIENT CONTROL TO 0°F.
4. PROVIDE MANUAL OUTSIDE AIR HOOD.

FAN SCHEDULE

MARK	SERVES	FAN DATA				CFM	ESP (IN WG)	FAN (RPM)	MOTOR			BASIS OF DESIGN	NOTES
		FAN TYPE	WHEEL TYPE	WHEEL DIA	BLADE TYPE				DRIVE TYPE	HP	VOLTS/ PHASE		
SF-1	ESTCP	INLINE	CENTRIFUGAL	8	BI	750	0.11	1725	BELT	0.25	460/3	COOK 80SQN-B	1, 3, 4
EF-1	ESTCP	WALL MOUNTED	CENTRIFUGAL	12	BI	850	0.125	1140	DIRECT	0.25	460/3	COOK 120W11D	4

NOTES:

1. PROVIDE BELT GUARD AND OUTLET GUARD.
2. BI=BACKWARDS INCLINED.
3. PROVIDE VIBRATION ISOLATION SPRINGS.
4. EXPLOSION PROOF ASSEMBLY.

UNIT HEATER SCHEDULE

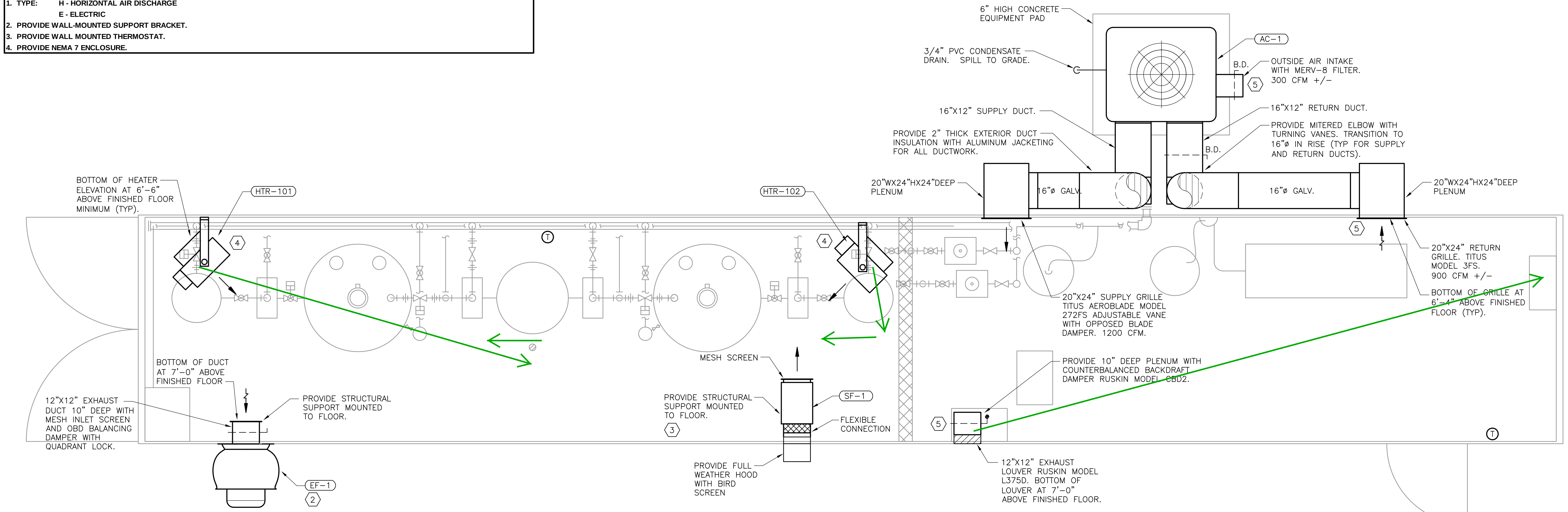
MARK	SERVES	TYPE (NOTE 1)	CAPACITY (KW)	NOMINAL CFM	MOTOR HP	VOLTAGE/ PHASE	BASIS OF DESIGN	NOTES
HTR-101	ESTCP	H, E	15	1200	1/4	480/3	OUELLET OHX15034	2, 3, 4
HTR-102	ESTCP	H, E	15	1200	1/4	480/3	OUELLET OHX15034	2, 3, 4

NOTES:

1. TYPE: H - HORIZONTAL AIR DISCHARGE
   E - ELECTRIC
2. PROVIDE WALL-MOUNTED SUPPORT BRACKET.
3. PROVIDE WALL MOUNTED THERMOSTAT.
4. PROVIDE NEMA 7 ENCLOSURE.

NOTES:

1. ALL EQUIPMENT SHALL BE SUPPORTED BY STRUCTURAL FRAME. DO NOT SUPPORT FROM TRAILER ROOF/WALL UNLESS RATED FOR LOAD.
2. EF-1 IS A DIRECT DRIVE EXHAUST FAN. SET BALANCE DAMPER TO DELIVER 850 CFM. SET QUADRANT LOCK AND PIN TO THIS SETTING.
3. ADJUST VARIABLE SHEAVE ON SUPPLY FAN TO MAINTAIN −0.10" W.G. ROOM STATIC PRESSURE WITH ALL DOORS CLOSED.
4. INSTALL PER MANUFACTURER'S INSTRUCTIONS FOR CLEARANCES REQUIRED.
5. BALANCE OUTSIDE AIR, RETURN AIR AND BAROMETRIC RELIEF TO MAINTAIN ROOM PRESSURE OF +0.10" W.G.


6" HIGH CONCRETE EQUIPMENT PAD
AC−1
3/4" PVC CONDENSATE DRAIN. SPILL TO GRADE.
B.D.
OUTSIDE AIR INTAKE WITH MERV−8 FILTER. 300 CFM +/−
5
16"X12" SUPPLY DUCT.
16"X12" RETURN DUCT.
PROVIDE 2" THICK EXTERIOR DUCT INSULATION WITH ALUMINUM JACKETING FOR ALL DUCTWORK.
PROVIDE MITERED ELBOW WITH TURNING VANES. TRANSITION TO 16"ø IN RISE (TYP FOR SUPPLY AND RETURN DUCTS).
B.D.
20"WX24"HX24"DEEP PLENUM
16"ø GALV.
16"ø GALV.
20"WX24"HX24"DEEP PLENUM
BOTTOM OF HEATER ELEVATION AT 6'−6" ABOVE FINISHED FLOOR MINIMUM (TYP).
HTR−101
4
T
HTR−102
4
5
20"X24" RETURN GRILLE. TITUS MODEL 3FS. 900 CFM +/−
20"X24" SUPPLY GRILLE TITUS AEROBLADE MODEL 272FS ADJUSTABLE VANE WITH OPPOSED BLADE DAMPER. 1200 CFM.
BOTTOM OF GRILLE AT 6'−4" ABOVE FINISHED FLOOR (TYP).
BOTTOM OF DUCT AT 7'−0" ABOVE FINISHED FLOOR
MESH SCREEN
PROVIDE 10" DEEP PLENUM WITH COUNTERBALANCED BACKDRAFT DAMPER RUSKIN MODEL CBD2.
12"X12" EXHAUST DUCT 10" DEEP WITH MESH INLET SCREEN AND OBD BALANCING DAMPER WITH QUADRANT LOCK.
PROVIDE STRUCTURAL SUPPORT MOUNTED TO FLOOR.
PROVIDE STRUCTURAL SUPPORT MOUNTED TO FLOOR.
3
SF−1
FLEXIBLE CONNECTION
5
T
EF−1
2
PROVIDE FULL WEATHER HOOD WITH BIRD SCREEN
12"X12" EXHAUST LOUVER RUSKIN MODEL L375D. BOTTOM OF LOUVER AT 7'−0" ABOVE FINISHED FLOOR.

HVAC PLAN
1/2" = 1'−0"

1/2" = 1'− 0"
1 0 1 2

REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: DHL
DRAWN BY: ALP
SHEET CHK'D BY: GJS
CROSS CHK'D BY: CC
APPROVED BY: GJS
DATE: AUGUST 2012

LINE IS 1 INCH
AT FULL SIZE
(34X22)
SCALE ACCORDINGLY

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Renewable Energy Production from DoD Installation Solid Waste by Anaerobic Digestion

PILOT EQUIPMENT
HVAC PLAN

PROJECT NO. 50957−73968
FILE NAME: H001
DRAWING NO.
H-1
SHEET NO.

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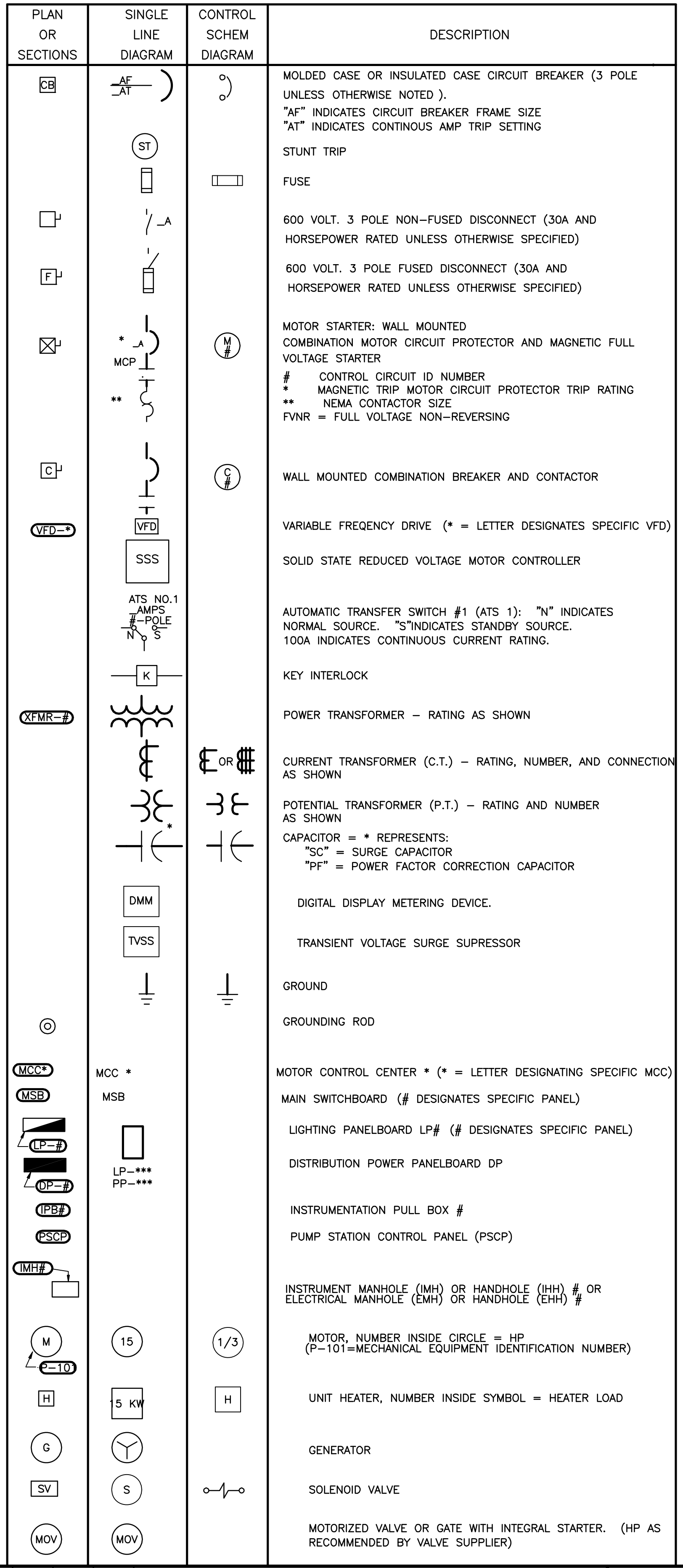
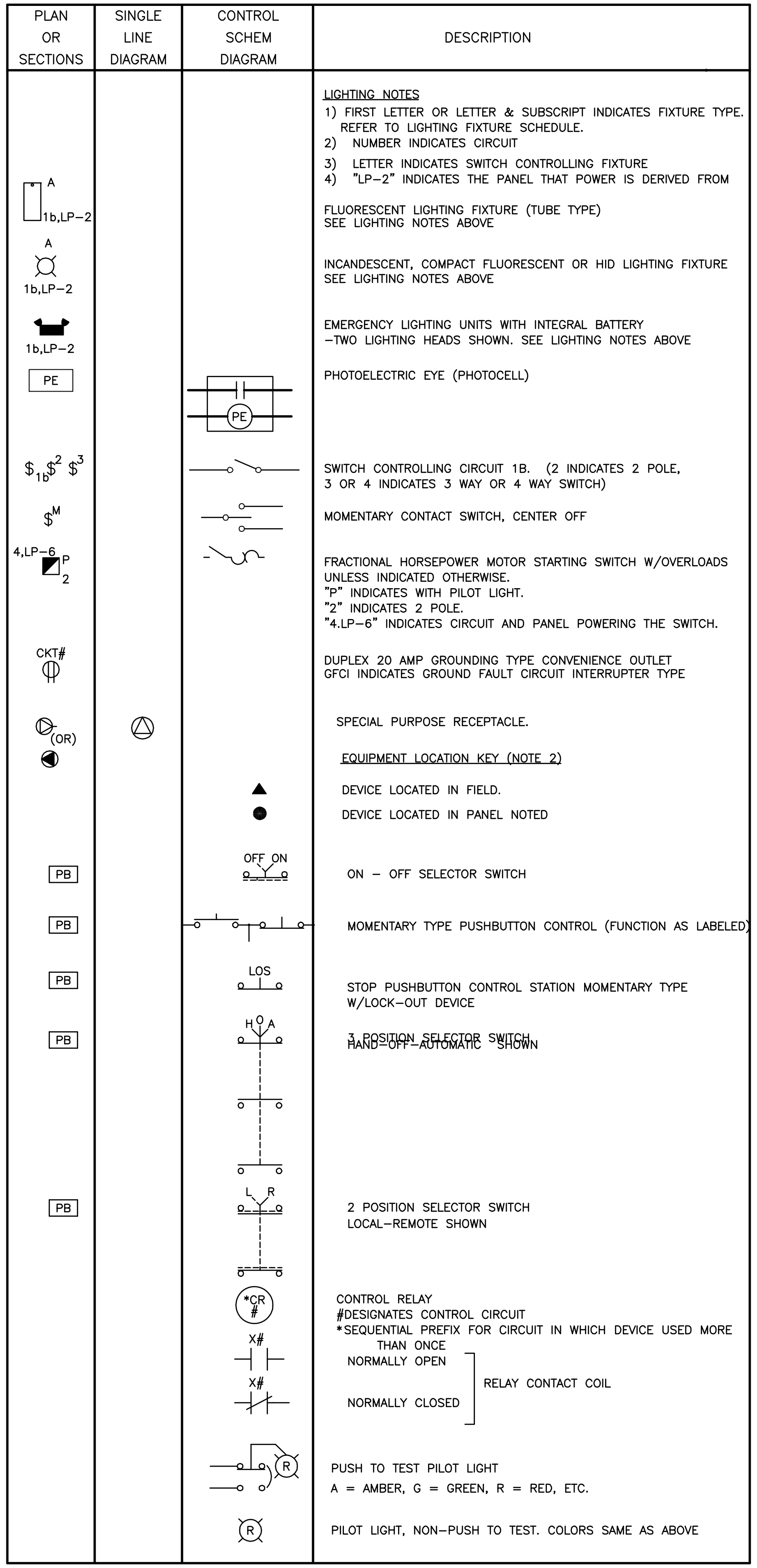
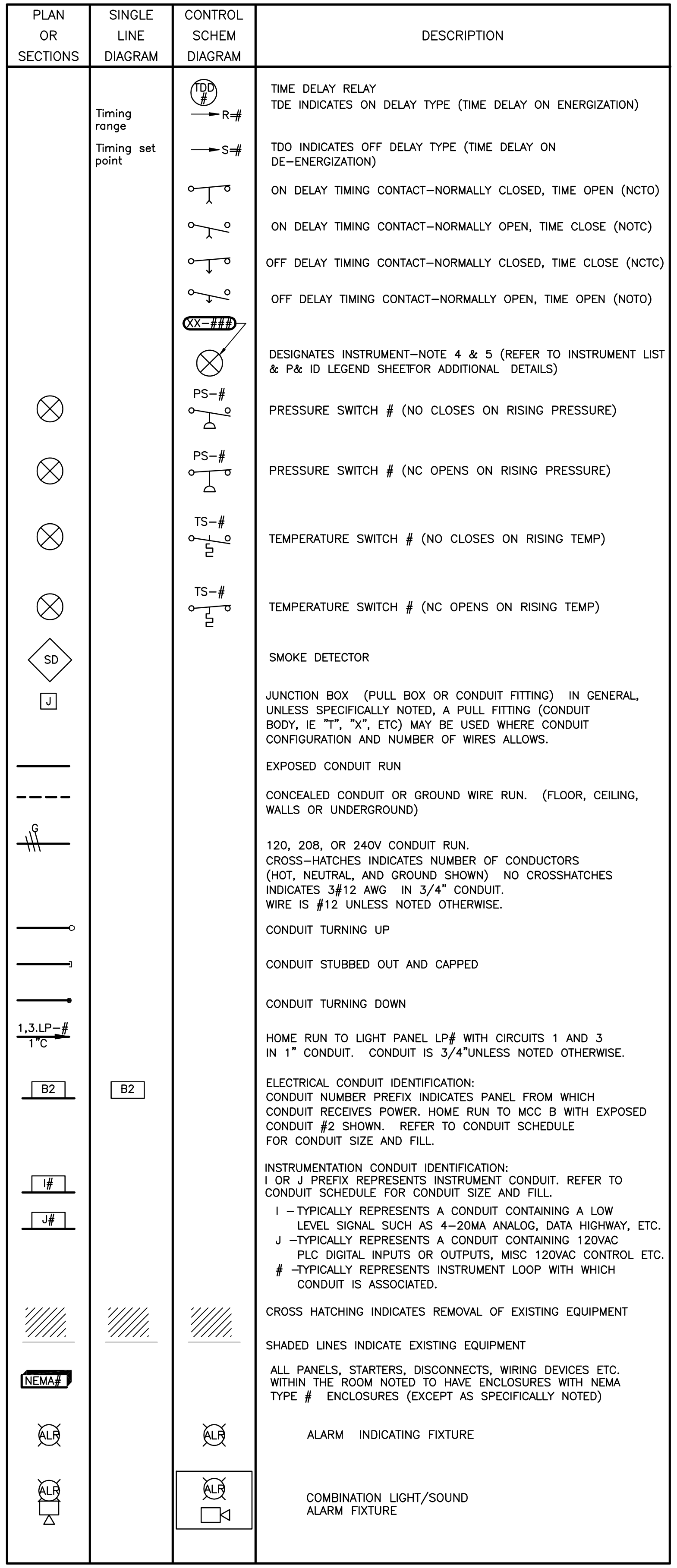


PLAN OR SECTIONS	SINGLE LINE DIAGRAM	CONTROL SCHEM DIAGRAM	DESCRIPTION
CB	_AF _AT		MOLDED CASE OR INSULATED CASE CIRCUIT BREAKER (3 POLE UNLESS OTHERWISE NOTED). "AF" INDICATES CIRCUIT BREAKER FRAME SIZE "AT" INDICATES CONTINOUS AMP TRIP SETTING
	ST		STUNT TRIP
			FUSE
	_A		600 VOLT. 3 POLE NON–FUSED DISCONNECT (30A AND HORSEPOWER RATED UNLESS OTHERWISE SPECIFIED)
F			600 VOLT. 3 POLE FUSED DISCONNECT (30A AND HORSEPOWER RATED UNLESS OTHERWISE SPECIFIED)
	* _A MCP **	M #	MOTOR STARTER: WALL MOUNTED COMBINATION MOTOR CIRCUIT PROTECTOR AND MAGNETIC FULL VOLTAGE STARTER # CONTROL CIRCUIT ID NUMBER * MAGNETIC TRIP MOTOR CIRCUIT PROTECTOR TRIP RATING ** NEMA CONTACTOR SIZE FVNR = FULL VOLTAGE NON–REVERSING
C		C #	WALL MOUNTED COMBINATION BREAKER AND CONTACTOR
VFD–*	VFD		VARIABLE FREQENCY DRIVE (* = LETTER DESIGNATES SPECIFIC VFD)
	SSS		SOLID STATE REDUCED VOLTAGE MOTOR CONTROLLER
	ATS NO.1 _AMPS #–POLE N S		AUTOMATIC TRANSFER SWITCH #1 (ATS 1): "N" INDICATES NORMAL SOURCE. "S"INDICATES STANDBY SOURCE. 100A INDICATES CONTINUOUS CURRENT RATING.
	K		KEY INTERLOCK
XFMR–#			POWER TRANSFORMER – RATING AS SHOWN
		OR	CURRENT TRANSFORMER (C.T.) – RATING, NUMBER, AND CONNECTION AS SHOWN
			POTENTIAL TRANSFORMER (P.T.) – RATING AND NUMBER AS SHOWN
	*		CAPACITOR = * REPRESENTS: "SC" = SURGE CAPACITOR "PF" = POWER FACTOR CORRECTION CAPACITOR
	DMM		DIGITAL DISPLAY METERING DEVICE.
	TVSS		TRANSIENT VOLTAGE SURGE SUPRESSOR
			GROUND
			GROUNDING ROD
MCC*	MCC *		MOTOR CONTROL CENTER * (* = LETTER DESIGNATING SPECIFIC MCC)
MSB	MSB		MAIN SWITCHBOARD (# DESIGNATES SPECIFIC PANEL)
LP–#	LP–*** PP–***		LIGHTING PANELBOARD LP# (# DESIGNATES SPECIFIC PANEL)
DP–#			DISTRIBUTION POWER PANELBOARD DP
IPB#			INSTRUMENTATION PULL BOX #
PSCP			PUMP STATION CONTROL PANEL (PSCP)
IMH#			INSTRUMENT MANHOLE (IMH) OR HANDHOLE (IHH) # OR ELECTRICAL MANHOLE (EMH) OR HANDHOLE (EHH) #
M P–101	15	1/3	MOTOR, NUMBER INSIDE CIRCLE = HP (P–101=MECHANICAL EQUIPMENT IDENTIFICATION NUMBER)
H	15 KW	H	UNIT HEATER, NUMBER INSIDE SYMBOL = HEATER LOAD
G			GENERATOR
SV	S		SOLENOID VALVE
MOV	MOV		MOTORIZED VALVE OR GATE WITH INTEGRAL STARTER. (HP AS RECOMMENDED BY VALVE SUPPLIER)



PLAN OR SECTIONS	SINGLE LINE DIAGRAM	CONTROL SCHEM DIAGRAM	DESCRIPTION
			LIGHTING NOTES 1) FIRST LETTER OR LETTER & SUBSCRIPT INDICATES FIXTURE TYPE. REFER TO LIGHTING FIXTURE SCHEDULE. 2) NUMBER INDICATES CIRCUIT 3) LETTER INDICATES SWITCH CONTROLLING FIXTURE 4) "LP–2" INDICATES THE PANEL THAT POWER IS DERIVED FROM
A 1b,LP–2			FLUORESCENT LIGHTING FIXTURE (TUBE TYPE) SEE LIGHTING NOTES ABOVE
A 1b,LP–2			INCANDESCENT, COMPACT FLUORESCENT OR HID LIGHTING FIXTURE SEE LIGHTING NOTES ABOVE
1b,LP–2			EMERGENCY LIGHTING UNITS WITH INTEGRAL BATTERY –TWO LIGHTING HEADS SHOWN. SEE LIGHTING NOTES ABOVE
PE		PE	PHOTOELECTRIC EYE (PHOTOCELL)
$\$_{1b}$ $\$^{2}$ $\$^{3}$			SWITCH CONTROLLING CIRCUIT 1B. (2 INDICATES 2 POLE, 3 OR 4 INDICATES 3 WAY OR 4 WAY SWITCH)
$\$^{M}$			MOMENTARY CONTACT SWITCH, CENTER OFF
4,LP–6 P 2			FRACTIONAL HORSEPOWER MOTOR STARTING SWITCH W/OVERLOADS UNLESS INDICATED OTHERWISE. "P" INDICATES WITH PILOT LIGHT. "2" INDICATES 2 POLE. "4.LP–6" INDICATES CIRCUIT AND PANEL POWERING THE SWITCH.
CKT#			DUPLEX 20 AMP GROUNDING TYPE CONVENIENCE OUTLET GFCI INDICATES GROUND FAULT CIRCUIT INTERRUPTER TYPE
(OR)			SPECIAL PURPOSE RECEPTACLE.
			EQUIPMENT LOCATION KEY (NOTE 2)
		▲	DEVICE LOCATED IN FIELD.
		●	DEVICE LOCATED IN PANEL NOTED
PB		OFF ON	ON – OFF SELECTOR SWITCH
PB			MOMENTARY TYPE PUSHBUTTON CONTROL (FUNCTION AS LABELED)
PB		LOS	STOP PUSHBUTTON CONTROL STATION MOMENTARY TYPE W/LOCK–OUT DEVICE
PB		H O A	3 POSITION SELECTOR SWITCH HAND–OFF–AUTOMATIC SHOWN
PB		L R	2 POSITION SELECTOR SWITCH LOCAL–REMOTE SHOWN
		*CR #	CONTROL RELAY #DESIGNATES CONTROL CIRCUIT *SEQUENTIAL PREFIX FOR CIRCUIT IN WHICH DEVICE USED MORE THAN ONCE
		X#	NORMALLY OPEN — RELAY CONTACT COIL
		X#	NORMALLY CLOSED — RELAY CONTACT COIL
		R	PUSH TO TEST PILOT LIGHT A = AMBER, G = GREEN, R = RED, ETC.
		R	PILOT LIGHT, NON–PUSH TO TEST. COLORS SAME AS ABOVE



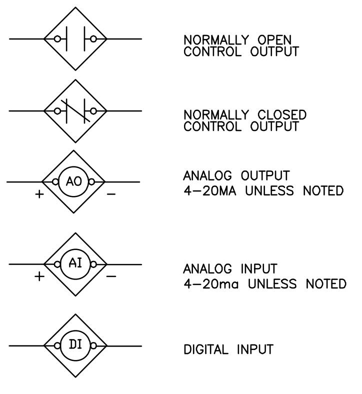
PLAN OR SECTIONS	SINGLE LINE DIAGRAM	CONTROL SCHEM DIAGRAM	DESCRIPTION
		TDD #	TIME DELAY RELAY
	Timing range	R=#	TDE INDICATES ON DELAY TYPE (TIME DELAY ON ENERGIZATION)
	Timing set point	S=#	TDO INDICATES OFF DELAY TYPE (TIME DELAY ON DE–ENERGIZATION)
			ON DELAY TIMING CONTACT–NORMALLY CLOSED, TIME OPEN (NCTO)
			ON DELAY TIMING CONTACT–NORMALLY OPEN, TIME CLOSE (NOTC)
			OFF DELAY TIMING CONTACT–NORMALLY CLOSED, TIME CLOSE (NCTC)
			OFF DELAY TIMING CONTACT–NORMALLY OPEN, TIME OPEN (NOTO)
		XX–###	DESIGNATES INSTRUMENT–NOTE 4 & 5 (REFER TO INSTRUMENT LIST & P& ID LEGEND SHEETFOR ADDITIONAL DETAILS)
		PS–#	PRESSURE SWITCH # (NO CLOSES ON RISING PRESSURE)
		PS–#	PRESSURE SWITCH # (NC OPENS ON RISING PRESSURE)
		TS–#	TEMPERATURE SWITCH # (NO CLOSES ON RISING TEMP)
		TS–#	TEMPERATURE SWITCH # (NC OPENS ON RISING TEMP)
SD			SMOKE DETECTOR
J			JUNCTION BOX (PULL BOX OR CONDUIT FITTING) IN GENERAL, UNLESS SPECIFICALLY NOTED, A PULL FITTING (CONDUIT BODY, IE "T", "X", ETC) MAY BE USED WHERE CONDUIT CONFIGURATION AND NUMBER OF WIRES ALLOWS.
			EXPOSED CONDUIT RUN
			CONCEALED CONDUIT OR GROUND WIRE RUN. (FLOOR, CEILING, WALLS OR UNDERGROUND)
G			120, 208, OR 240V CONDUIT RUN. CROSS–HATCHES INDICATES NUMBER OF CONDUCTORS (HOT, NEUTRAL, AND GROUND SHOWN) NO CROSSHATCHES INDICATES 3#12 AWG IN 3/4" CONDUIT. WIRE IS #12 UNLESS NOTED OTHERWISE.
			CONDUIT TURNING UP
			CONDUIT STUBBED OUT AND CAPPED
			CONDUIT TURNING DOWN
1,3.LP–# 1"C			HOME RUN TO LIGHT PANEL LP# WITH CIRCUITS 1 AND 3 IN 1" CONDUIT. CONDUIT IS 3/4"UNLESS NOTED OTHERWISE.
B2	B2		ELECTRICAL CONDUIT IDENTIFICATION: CONDUIT NUMBER PREFIX INDICATES PANEL FROM WHICH CONDUIT RECEIVES POWER. HOME RUN TO MCC B WITH EXPOSED CONDUIT #2 SHOWN. REFER TO CONDUIT SCHEDULE FOR CONDUIT SIZE AND FILL.
I# J#			INSTRUMENTATION CONDUIT IDENTIFICATION: I OR J PREFIX REPRESENTS INSTRUMENT CONDUIT. REFER TO CONDUIT SCHEDULE FOR CONDUIT SIZE AND FILL. I –TYPICALLY REPRESENTS A CONDUIT CONTAINING A LOW LEVEL SIGNAL SUCH AS 4–20MA ANALOG, DATA HIGHWAY, ETC. J –TYPICALLY REPRESENTS A CONDUIT CONTAINING 120VAC PLC DIGITAL INPUTS OR OUTPUTS, MISC 120VAC CONTROL ETC. # –TYPICALLY REPRESENTS INSTRUMENT LOOP WITH WHICH CONDUIT IS ASSOCIATED.
▨	▨	▨	CROSS HATCHING INDICATES REMOVAL OF EXISTING EQUIPMENT
			SHADED LINES INDICATE EXISTING EQUIPMENT
NEMA#			ALL PANELS, STARTERS, DISCONNECTS, WIRING DEVICES ETC. WITHIN THE ROOM NOTED TO HAVE ENCLOSURES WITH NEMA TYPE # ENCLOSURES (EXCEPT AS SPECIFICALLY NOTED)
ALR		ALR	ALARM INDICATING FIXTURE
ALR		ALR	COMBINATION LIGHT/SOUND ALARM FIXTURE

NOTES:

1. THIS SHEET IS A GENERAL ELECTRICAL LEGENDS; ALL SYMBOLS INCLUDED HERE MAY NOT NECESSARILY BE USED ON THE CONTRACT DRAWINGS.
2. THE SYMBOLS ARE USED ON THE CONTROL SCHEMATIC DRAWINGS TO INDICATE THE PHYSICAL LOCATION OF DEVICES. REFER TO THE CONTROL SCHEMATICS FOR SPECIFIC DETAILS.
3. ⊗ SYMBOL DENOTES AN INSTRUMENTATION DEVICE
4. XX–### INSTRUMENT IDENTIFICATION TAG NUMBER.
   XX DENOTES FUNCTIONAL IDENTIFICATION. (REFER TO P & ID LEGEND FOR INSTRUMENT TAGGING ABBREVIATIONS).
   ## DENOTES LOOP NUMBER.

PLC INPUT/OUTPUT DEVICES–

AS SHOWN ON CONTROL SCHEMATICS



NORMALLY OPEN CONTROL OUTPUT
NORMALLY CLOSED CONTROL OUTPUT
AO
+
–
ANALOG OUTPUT 4–20MA UNLESS NOTED
AI
+
–
ANALOG INPUT 4–20ma UNLESS NOTED
DI
DIGITAL INPUT

30% SUBMITTAL - NOT FOR CONSTRUCTION

REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: RRR
DRAWN BY: WKT
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: APRIL 2011

LINE IS 1 INCH
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SCALE ACCORDINGLY

CDM
Camp Dresser & McKee Inc.
1218 3rd Avenue, Suite 100
Seattle, CA 98101
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consulting • engineering • construction • operations

Renewable Energy Production from DoD Installation Solid Waste by Anaerobic Digestion

ELECTRICAL LEGEND

PROJECT NO. 50957–73968
FILE NAME: E001
DRAWING NO. E-1
SHEET NO. OF 30

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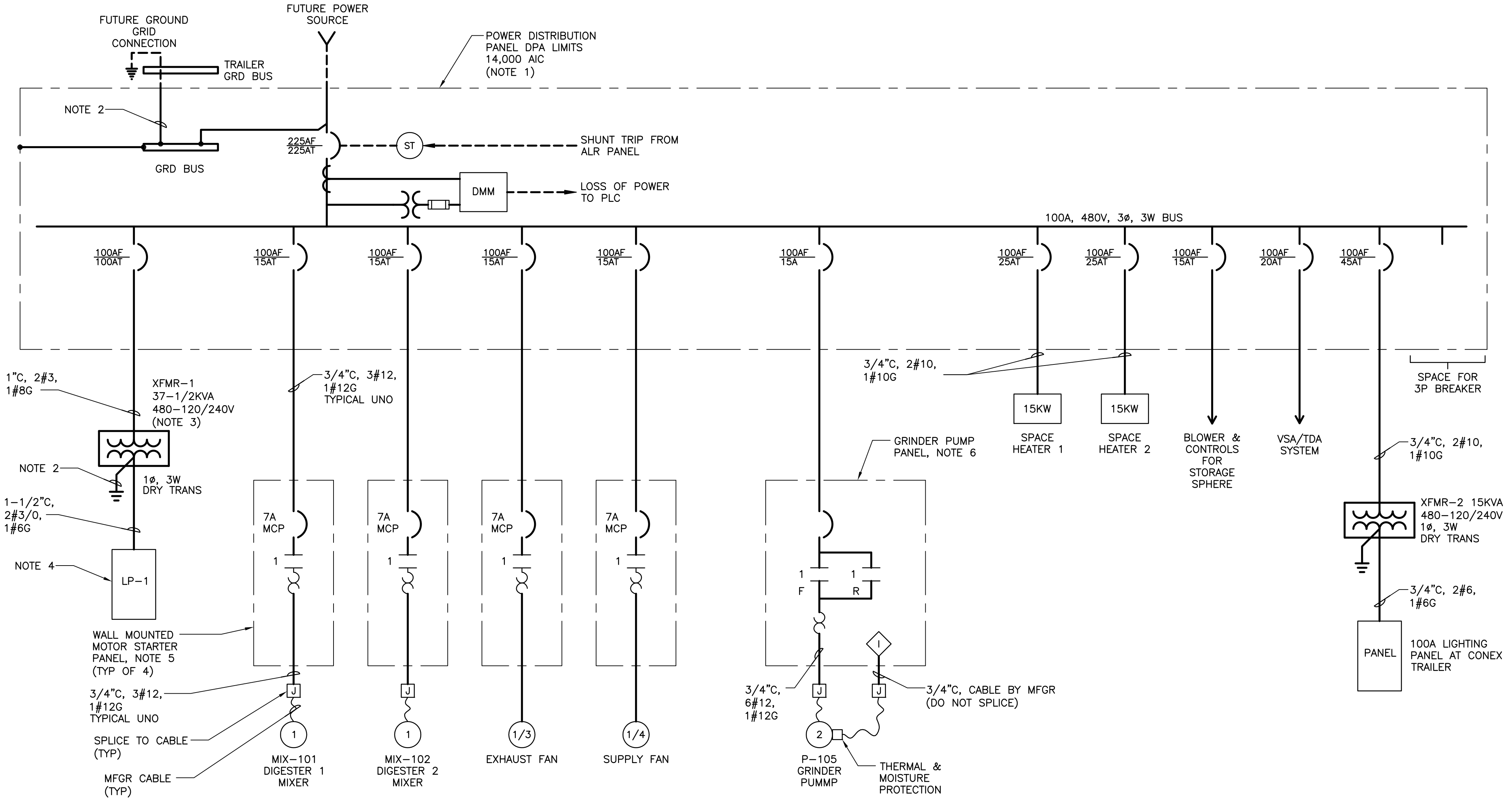
FUTURE GROUND GRID CONNECTION
FUTURE POWER SOURCE
TRAILER GRD BUS
POWER DISTRIBUTION PANEL DPA LIMITS 14,000 AIC (NOTE 1)
NOTE 2
GRD BUS
225AF 225AT
ST
SHUNT TRIP FROM ALR PANEL
DMM
LOSS OF POWER TO PLC
100A, 480V, 3ø, 3W BUS
100AF 100AT
100AF 15AT
100AF 15AT
100AF 15AT
100AF 15AT
100AF 15A
100AF 25AT
100AF 25AT
100AF 15AT
100AF 20AT
100AF 45AT
1"C, 2#3, 1#8G
XFMR-1 37-1/2KVA 480-120/240V (NOTE 3)
3/4"C, 3#12, 1#12G TYPICAL UNO
3/4"C, 2#10, 1#10G
15KW
15KW
SPACE HEATER 1
SPACE HEATER 2
BLOWER & CONTROLS FOR STORAGE SPHERE
VSA/TDA SYSTEM
SPACE FOR 3P BREAKER
GRINDER PUMP PANEL, NOTE 6
3/4"C, 2#10, 1#10G
NOTE 2
1ø, 3W DRY TRANS
1-1/2"C, 2#3/0, 1#6G
7A MCP
7A MCP
7A MCP
7A MCP
1
F
R
XFMR-2 15KVA 480-120/240V 1ø, 3W DRY TRANS
NOTE 4
LP-1
3/4"C, 2#6, 1#6G
PANEL
100A LIGHTING PANEL AT CONEX TRAILER
WALL MOUNTED MOTOR STARTER PANEL, NOTE 5 (TYP OF 4)
3/4"C, 3#12, 1#12G TYPICAL UNO
3/4"C, 6#12, 1#12G
3/4"C, CABLE BY MFGR (DO NOT SPLICE)
J
I
SPLICE TO CABLE (TYP)
MFGR CABLE (TYP)
1
1
1/3
1/4
2
MIX-101 DIGESTER 1 MIXER
MIX-102 DIGESTER 2 MIXER
EXHAUST FAN
SUPPLY FAN
P-105 GRINDER PUMMP
THERMAL & MOISTURE PROTECTION

SINGLE LINE DIAGRAM

NOTES:

1. DP-A: NEMA 3R 480 VOLT DISTRIBUTION PANEL MOUNTED TO EXTERIOR OF TRAILER, WITH NEMA 3R ENCLOSURE, BOLT-ON MOLDED CASE BREAKERS, SHUNT TRIP ON MAIN BREAKER, OTHER FEATURES AS SHOWN. EATON-CUTLER HAMMER POW-R-LINE 2A OR EQUAL.
2. #6 BARE COPPER TO TRAILER GROUND BUS OR GROUND LUG.
3. XFMR-1: DRY-TYPE TWO-WINDING TRANSFORMER, VENTILATED, NEMA 2 DRIP-PROOF, WITH WEATHER SHIELD SUITABLE FOR OUTDOOR MOUNTING. NEMA TP-1 TYPE, COMPLIANT WITH THE DEPARTMENT OF ENERGY (DOE), 10 CFR PART 431, "ENERGY CONSERVATION PROGRAM FOR COMMERCIAL EQUIPMENT: DISTRIBUTION TRANSFORMERS ENERGY CONSERVATION STANDARDS; FINAL RULE" DATED OCT 2007. PROVIDE BRACKET MOUNTING TO BOLT TRANSFORMER TO EXTERIOR OF TRAILER. EATON-CUTLER HAMMER OR EQUAL.
4. LP-1: NEMA 3R 120-240 VOLT LIGHTING PANEL MOUNTED TO EXTERIOR OF TRAILER, WITH NEMA 3R ENCLOSURE, BOLT-ON MOLDED CASE BREAKERS, OTHER FEATURES AS SHOWN. EATON-CUTLER HAMMER POW-R-LINE 1A OR EQUAL.
5. INDIVIDUAL WALL MOUNTED FULL VOLTAGE NON-REVERSING COMBINATION MOTOR STARTER
    A. MOTOR CIRCUIT PROTECTOR WITH DOOR MOUNTED, PADLOCKABLE OPERATING HANDLE INTERLOCKED WITH COVER
    B. NEMA RATED CONDUCTOR
    C. OVERLOAD HEATERS SIZED FOR MOTOR FURNISHED
    D. AUXILIARY CONTACTS AS SHOWN ON THE CONTROL SCHEMATICS
    E. APPLETON OR EQUAL
6. GRINDER PUMP PANEL FURNISHED WITH PUMP, INCLUDES CLASS I, DIV 1 RATED ENCLOSURE, REVERSING STARTER, PUMP CONTROLS AND PROTECTIONS.
7. DIGITAL ENERGY METER, LCD DISPLAY, WATT-HR METER WITH DEMAND, MONITORING VOLTAGE, CURRENT, PF & FREQUENCY: DRY ALARM CONTACT PROGRAMMED TO DETECT LOSS OF VOLTAGE (POWER FAIL ALARM TO AUTODIALER). EATON IQ 35M OR EQUAL.

PANELBOARD LP-1

100 AMP MAIN BREAKER
100 AMP BUS RATING
32 POLES
120/240 VOLTS **1** PHASE **3** WIRE **60 Hz.**
10 KA SHORT CIRCUIT RATING
ELECTRONIC GRADE: **NO**
LOCATION: **outside trailer**
ENCLOSURE RATING: **NEMA 3R**
MOUNTING: **SURFACE**

CIRCUIT NO.	DESCRIPTION	LOAD KVA LINE 1	LOAD KVA LINE 2	BREAKER AMPS/ POLES	NOTES	CIRCUIT NO.	DESCRIPTION	LOAD KVA LINE 1	LOAD KVA LINE 2	BREAKER AMPS/ POLES	NOTES
1	Lighting	0.4	▨	15 /1	5	2	Receptacles	1.44	▨	15 /1	5
3	Alarm panel ALR PNL	▨	1	15 /1	1, 5	4	Tank Heater 2A	▨	0.22	15 /1	3, 5
5	Pilot Control panel PCP	0.5	▨	15 /1	5	6	Tank Heater 2B	0.22	▨	15 /1	3, 5
7	Tank Heater 1A	▨	0.22	15 /1	3, 5	8	AE/AIT-131A&B	▨	0.01	15 /1	
9	Tank Heater 1B	0.22	▨	15 /1	3, 5	10	Single Phase 120 volt Circuit		▨	15 /1	
11	Single Phase 120 volt Circuit	▨		15 /1		12	flow meter FIT-111	▨		15 /1	5
13	Single Phase 120 volt Circuit		▨	15 /1		14	flow meter FIT-112		▨	15 /1	5
15	Solenoid panel	▨	0.68	20 /1	5	16	Single Phase 120 volt Circuit	▨		15 /1	
17	compressor	1.8	▨	20 /2		18	Single Phase 120 volt Circuit		▨	15 /1	
19		▨	1.8			20	Single Phase 120 volt Circuit	▨		15 /1	
21	Single Phase 120 volt Circuit		▨	15 /1		22	Single Phase 120 volt Circuit		▨	15 /1	
23	Single Phase 120 volt Circuit	▨		15 /1		24	Single Phase 120 volt Circuit	▨		15 /1	
25	Single Phase 120 volt Circuit		▨	15 /1		26	Single Phase 120 volt Circuit		▨	15 /1	
27	Single Phase 120 volt Circuit	▨		15 /1		28	Single Phase 120 volt Circuit	▨		15 /1	
29	Single Phase 120 volt Circuit		▨	15 /1		30	Single Phase 120 volt Circuit		▨	15 /1	
31	Single Phase 120 volt Circuit	▨		15 /1		32	Single Phase 120 volt Circuit	▨		15 /1	
		▨						▨			
	TOTAL LINE KVA THIS SIDE	2.92	3.7				TOTAL LINE KVA THIS SIDE	1.66	0.23		
							TOTAL KVA PER LINE	4.58	3.93		
							TOTAL KVA	8.51			

NOTES:		NOTES CONT.:	
1.	PROVIDE LOCKING HARDWARE	2.	5 ma GROUND FAULT INTERRUPTER (GFI) CIRCUIT BREAKER
3.	30 ma GFI CIRCUIT BREAKER FOR EQUIPMENT PROTECTION ONLY (HEAT TRACE)	4.	PROVIDE LOCKING HARDWARE & PAINT BREAKER HANDLE RED (FACP)
5.	BRANCH CIRCUIT WIRING: 3/4"C, 2#12 & 1#12G	6.	

SEE REVISED SCHEDULE ON FOLLOWING PAGE

LP-1 PANEL SCHEDULE

REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: RRR
DRAWN BY: JAW
SHEET CHK'D BY: GNM
CROSS CHK'D BY:
APPROVED BY:
DATE: AUGUST 2012

LINE IS 1 INCH
AT FULL SIZE (34X22)
SCALE ACCORDINGLY

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Renewable Energy Production from DoD Installation Solid Waste by Anaerobic Digestion

SINGLE LINE DIAGRAM AND PANEL SCHEDULE

PROJECT NO. 50957-73968
FILE NAME: E002
DRAWING NO.
E-2
SHEET NO.
10 OF 28

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200 AMP MAIN BREAKER
200 AMP BUS RATING **32** POLES
120/240 VOLTS **1** PHASE **3** WIRE **60 Hz.**

PANELBOARD LP-1

10 KA SHORT CIRCUIT RATING
ELECTRONIC GRADE: **NO**

LOCATION: **outside trailer**
ENCLOSURE RATING: **NEMA 3R**
MOUNTING: **SURFACE**

CIRCUIT NO.	DESCRIPTION	LOAD KVA		BREAKER AMPS/ POLES	NOTES	CIRCUIT NO.	DESCRIPTION	LOAD KVA		BREAKER AMPS/ POLES	NOTES
		LINE 1	LINE 2					LINE 1	LINE 2		
1	Lighting	0.4	▨	15 /1	5	2	Receptacles	1.44	▨	15 /1	5
3	Alarm panel ALR PNL	▨	1	15 /1	1, 5	4	Tank Heater 2A	▨	0.22	15 /1	3, 5
5	Pilot Control/metering panel PCP	0.5	▨	15 /1	5	6	Tank Heater 2B	0.22	▨	15 /1	3, 5
7	Tank Heater 1A	▨	0.22	15 /1	3, 5	8	AE/AIT-151-A&B	▨	0.01	15 /1	
9	Tank Heater 1B	0.22	▨	15 /1	3, 5	10	Single Phase 120 volt Circuit	0	▨	15 /1	
11	Tank Heaters 1C, D, E, F	▨	0.88	15 /1	3, 5	12	flow meter FIT-111	▨	0.5	15 /1	5
13	Single Phase 120 volt Circuit		▨	15 /1		14	flow meter FIT-112	0.5	▨	15 /1	5
15	Solenoid panel	▨	0.68	20 /1	5	16	heat pump AC-1	▨	11.73	110 /2	6
17	compressor	1.8	▨	20 /2		18		11.73	▨		
19		▨	1.8			20	Tank Heaters 2C, D, E, F	▨	0.88	15 /1	3, 5
21	Single Phase 120 volt Circuit	0.11	▨	15 /1		22	Single Phase 120 volt Circuit		▨	15 /1	
23	Single Phase 120 volt Circuit	▨	0.11	15 /1		24	Single Phase 120 volt Circuit	▨		15 /1	
25	heat tracing	1.285	▨	20 /1	3, 5	26	Single Phase 120 volt Circuit		▨	15 /1	
27	heat tracing	▨	1.285	20 /1	3, 5	28	Single Phase 120 volt Circuit	▨		15 /1	
29	Single Phase 120 volt Circuit		▨	15 /1		30	Single Phase 120 volt Circuit		▨	15 /1	
31	Single Phase 120 volt Circuit	▨		15 /1		32	Single Phase 120 volt Circuit	▨		15 /1	
		▨						▨			
	TOTAL LINE KVA THIS SIDE	4.315	5.975				TOTAL LINE KVA THIS SIDE	13.89	13.34		
							TOTAL KVA PER LINE	18.205	19.315		
							TOTAL KVA	37.52			

NOTES:		NOTES CONT.:	
1.	PROVIDE LOCKING HARDWARE	2.	5 ma GROUND FAULT INTERRUPTER (GFI) CIRCUIT BREAKER
3.	30 ma GFI CIRCUIT BREAKER FOR EQUIPMENT PROTECTION ONLY (HEAT TRACE)	4.	PROVIDE LOCKING HARDWARE & PAINT BREAKER HANDLE RED (FACP)
5.	BRANCH CIRCUIT WIRING: 3/4"C, 2#12 & 1#12G	6.	BRANCH CIRCUIT WIRING: 1"C, 2#2, 1#6G
7.		8.	
9.		10.	
11.		12.	
13.		14.	
15.		16.	
17.		18.	
19.		20.	

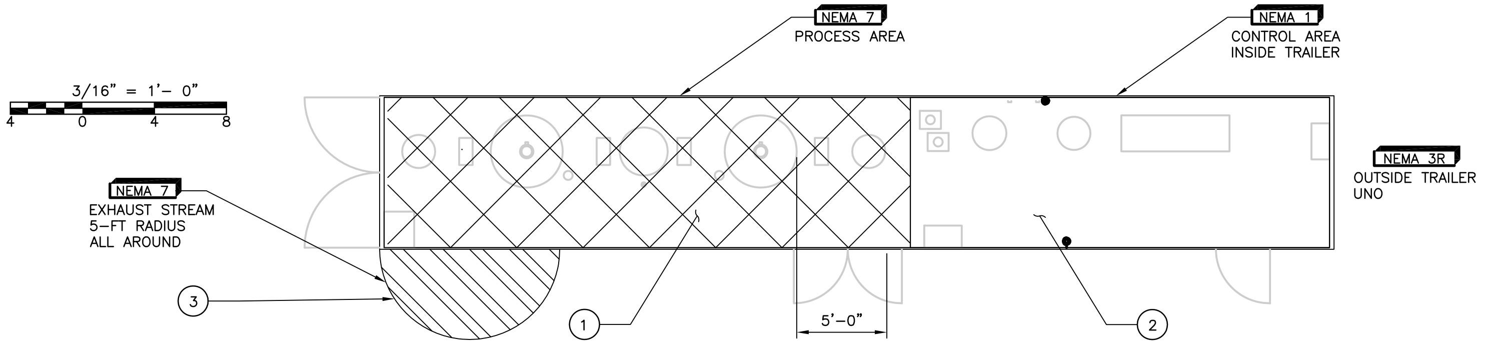
480 V DP-A at trailer

08/23/12

NO.		DESCRIPTION	LOAD			QUANTITY			FEEDER SIZING FACTOR	DEM FAC	VOLT KV	CONN	OPER DEMAND	EMERG	FEEDER SIZING	FEEDER SIZING	FEEDER SIZING
			SIZE	UNIT	MOTOR RPM	CONN	OPER	EMER				KVA	KVA	KVA	CONN. KVA	DEM. KVA	E. KVA
1	-	P-105 grinder pump	2	HP	1800 RPM @ 60Hz	1	1	0	1	1	0.48	2.8	2.8	0.0	2.8	2.8	0.0
2	-	space heater 1	15	KW	1800 RPM @ 60Hz	1	1	0	1.25	1	0.48	15.0	15.0	0.0	18.8	18.8	0.0
3	-	space heater 2	15	KW	1800 RPM @ 60Hz	1	1	0	1.25	1	0.48	15.0	15.0	0.0	18.8	18.8	0.0
4	-	37.5 kva XFMR	78	FLA	1800 RPM @ 60Hz	1	0.75	0	1.25	1	0.48	64.8	48.6	0.0	81.0	60.8	0.0
5	-	MIX-101	1	HP	1800 RPM @ 60Hz	1	1	0	1	1	0.48	1.7	1.7	0.0	1.7	1.7	0.0
6	-	MIX-102	1	HP	1800 RPM @ 60Hz	1	1	0	1	1	0.48	1.7	1.7	0.0	1.7	1.7	0.0
7	-	supply fan	0.25	HP	1800 RPM @ 60Hz	1	1	0	1	1	0.48	0.9	0.9	0.0	0.9	0.9	0.0
8	-	exhaust fan	0.33	HP	1800 RPM @ 60Hz	1	1	0	1	1	0.48	0.9	0.9	0.0	0.9	0.9	0.0
9	-	VSA/TDA system	2	HP	1800 RPM @ 60Hz	1	1	0	1	1	0.48	2.8	2.8	0.0	2.8	2.8	0.0
10	-	storage sphere blower + controls	10	FLA	1800 RPM @ 60Hz	1	1	0	1.25	1	0.48	8.3	8.3	0.0	10.4	10.4	0.0
11	-	15 kva XFMR for conex trailer	31	FLA	1800 RPM @ 60Hz	1	0.75	0	1.25	1	0.48	25.8	19.3	0.0	32.3	24.1	0.0
		SPARE CAPACITY	0	%								0.0	0.0	0.0	0.0	0.0	0.0
TOTAL		**DP-A at trailer**									**0.48**	**139.7**	**117.0**	**0.0**	**172.1**	**143.7**	**0.0**
		CONNECTED LOAD				STARTER		LARGEST MOTOR					MIN BREAKER TRIP =				218.6
		LARGEST MOTOR CONNECTED	2	HP		FV		MAX BREAKER TRIP =			15	A	MIN FEEDER AMPS =				207.9
		TOTAL MOTOR HP	7	HP				MAIN BREAKER		80 %		RATED	MAX BREAKER TRIP =				225.0
		TOTAL VFD LOAD	0	KVA													
		DEMAND LOAD				STARTER		LARGEST MOTOR					MIN BREAKER TRIP =				184.4
		LARGEST MOTOR CONNECTED	2	HP		FV		MAX BREAKER TRIP =			15	A	MIN FEEDER AMPS =				173.7
		TOTAL MOTOR HP	7	HP				MAIN BREAKER		80 %		RATED	MAX BREAKER TRIP =				200.0
		TOTAL VFD LOAD	0	KVA													
		EMERGENCY LOAD				STARTER		LARGEST MOTOR					MIN BREAKER TRIP =				0.0
		LARGEST MOTOR CONNECTED	0	HP		FV		MAX BREAKER TRIP =			0	A	MIN FEEDER AMPS =				0.0
		TOTAL MOTOR HP	0	HP				MAIN BREAKER		80 %		RATED	MAX BREAKER TRIP =				0.0
		TOTAL VFD LOAD	0	KVA													
		COMMENTS:															

NOTES:

1. SEE SHEET E-4 FOR GENERAL AND SHEET NOTES.


3/16" = 1'- 0"
4 0 4 8
NEMA 7
PROCESS AREA
NEMA 1
CONTROL AREA
INSIDE TRAILER
NEMA 3R
OUTSIDE TRAILER
UNO
NEMA 7
EXHAUST STREAM
5-FT RADIUS
ALL AROUND
3
1
5'-0"
2

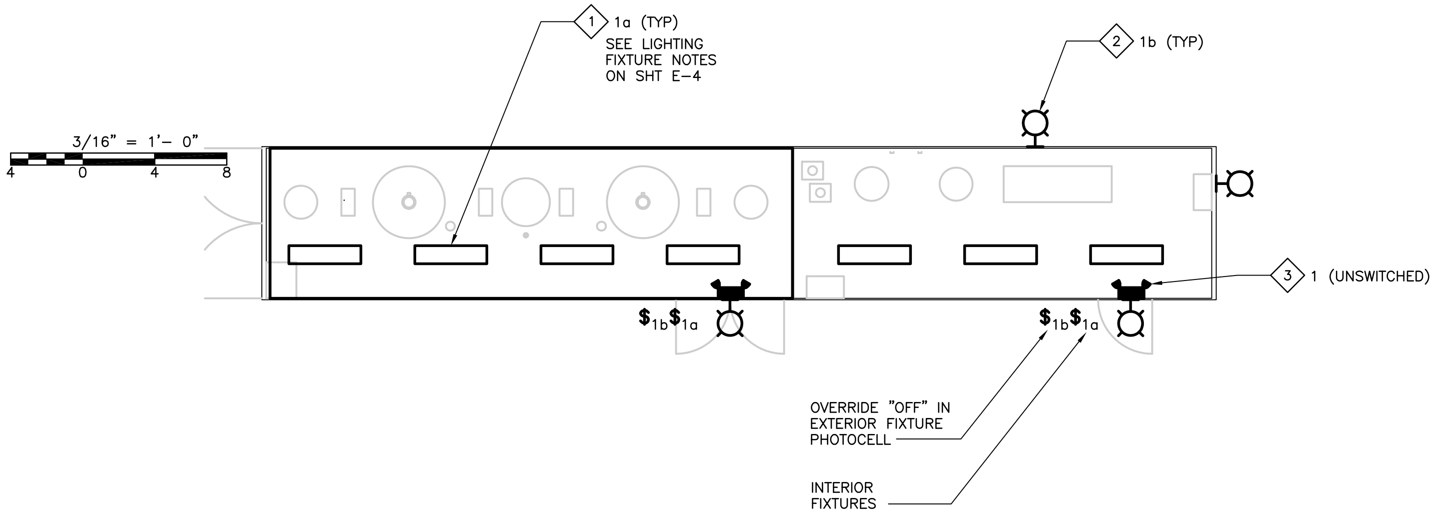
① CLASS I, DIV 1, GRP C&D: LEFT SIDE OF TRAILER FALSE WALL

② UNCLASSIFIED: REMAINDER OF TRAILER

③ CLASS I, DIV 2, GRP C&D: 5-FT RADIUS AROUND EXHAUST FAN OUTLET

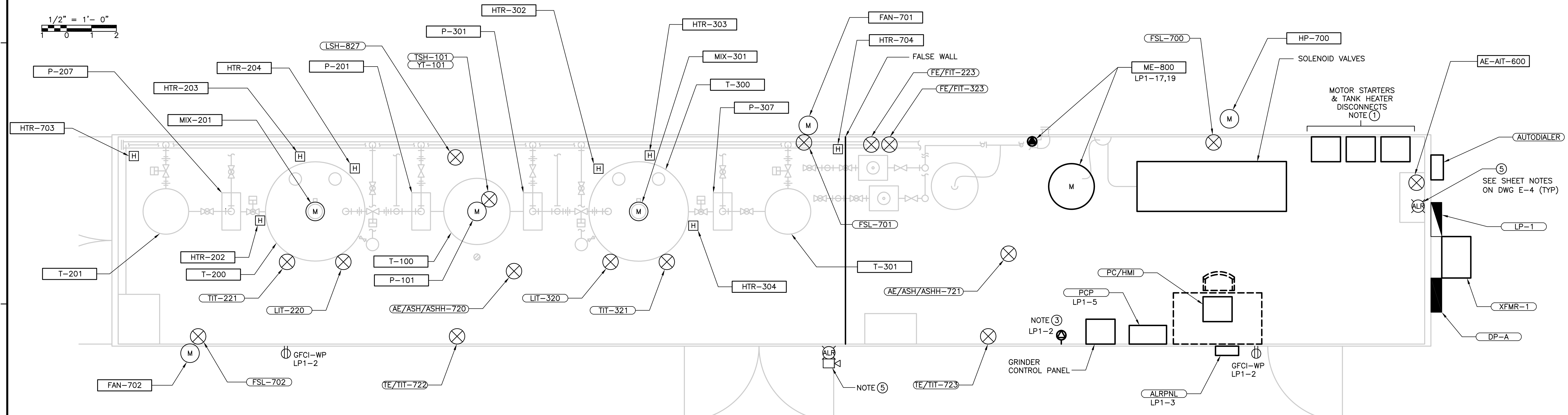
ELECTRICAL CLASSIFICATION PLAN

3/16" = 1'-0"


1 1a (TYP)
SEE LIGHTING
FIXTURE NOTES
ON SHT E-4
2 1b (TYP)
3/16" = 1'- 0"
4 0 4 8
3 1 (UNSWITCHED)
$1b$1a
$1b$1a
OVERRIDE "OFF" IN
EXTERIOR FIXTURE
PHOTOCELL
INTERIOR
FIXTURES

LIGHTING PLAN

3/16" = 1'-0"


1/2" = 1'- 0"
1 0 1 2
HTR-302
P-301
LSH-827
TSH-101
YT-101
P-201
HTR-204
P-207
HTR-203
MIX-201
HTR-703
HTR-303
MIX-301
T-300
P-307
FAN-701
HTR-704
FALSE WALL
FE/FIT-223
FE/FIT-323
ME-800
LP1-17,19
FSL-700
HP-700
SOLENOID VALVES
MOTOR STARTERS
& TANK HEATER
DISCONNECTS
NOTE 1
AE-AIT-600
AUTODIALER
5
SEE SHEET NOTES
ON DWG E-4 (TYP)
LP-1
XFMR-1
DP-A
H
M
ALR
T-201
HTR-202
T-200
TIT-221
LIT-220
T-100
P-101
AE/ASH/ASHH-720
LIT-320
TIT-321
HTR-304
FSL-701
T-301
AE/ASH/ASHH-721
PC/HMI
PCP
LP1-5
NOTE 3
LP1-2
GRINDER
CONTROL PANEL
GFCI-WP
LP1-2
ALRPNL
LP1-3
FAN-702
FSL-702
GFCI-WP
LP1-2
TE/TIT-722
NOTE 5
TE/TIT-723

POWER & INSTRUMENT PLAN

1/2" = 1'-0"

REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: RRR
DRAWN BY: JAW
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: AUGUST 2012

LINE IS 1 INCH
AT FULL SIZE
(34X22)
SCALE ACCORDINGLY

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Renewable Energy Production from
DoD Installation Solid Waste by
Anaerobic Digestion

PILOT EQUIPMENT
ELECTRICAL PLANS

PROJECT NO. 50957-73968
FILE NAME: E003
DRAWING NO.
E-3
SHEET NO.
OF 28

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GENERAL NOTES

1. REMOVE ALL EXISTING ELECTRICAL ITEMS (NOT SHOWN) FROM THE TRAILER. EQUIPMENT REMOVED SHALL BECOME THE CONTRACTOR'S PROPERTY AND SHALL BE DISPOSED OF OFF THE SITE BY THE CONTRACTOR
2. PROVIDE ALL LABOR, MATERIALS, EQUIPMENT, TOOLS, APPURTENANCES, AND TESTING NECESSARY FOR COMPLETE AND PROPERLY OPERATING ELECTRICAL/INSTRUMENTATION SYSTEM AS INDICATED ON THE DRAWINGS. ALL MATERIAL THAT CAN REASONABLY INFERRED TO BE A PART OF THE ELECTRICAL AND INSTRUMENTATION SYSTEMS AND NECESSARY TO ITS PROPER OPERATION SHALL BE FURNISHED AND INSTALLED WHETHER OR NOT SPECIFICALLY CALLED OUT ON THE DRAWINGS.
3. MATERIALS AND EQUIPMENT FURNISHED UNDER THIS CONTRACT SHALL BE NEW. PROVIDE UL LABELED OR LISTED MATERIALS WHERE UL STANDARDS APPLY. WORK AND MATERIALS SHALL BE IN ACCORDANCE WITH NFPA AND NATIONAL ELECTRICAL CODE.
4. EQUIPMENT, MATERIALS AND INSTALLATION IN AREAS DESIGNATED AS HAZARDOUS ON THE DRAWINGS SHALL COMPLY WITH NEC ARTICLES 500, 501, AND 502. EQUIPMENT AND MATERIALS INSTALLED IN HAZARDOUS AREAS SHALL BE UL LISTED FOR THE APPROPRIATE HAZARDOUS AREA CLASSIFICATION
5. UNLESS SPECIFICALLY DIMENSIONED, THE DRAWINGS ARE NOT INTENDED TO SHOW THE EXACT INSTALLATION LOCATIONS OF CONDUIT OR EQUIPMENT. COORDINATE THE INSTALLATION WITH OTHER TRADES AND THE ACTUAL SUPPLIED EQUIPMENT.
6. TEST SYSTEMS AND EQUIPMENT AND REPAIR OR REPLACE ALL DEFECTIVE WORK AND EQUIPMENT AT NO ADDITIONAL COST TO THE OWNER. TESTS SHALL INCLUDE THE FOLLOWING:
    - a. CHECK AND RECORD THE FULL LOAD CURRENT DRAW OF EACH MOTOR. CHECK MOTOR NAMEPLATES FOR CORRECT PHASE AND VOLTAGE. CHECK ROTATION OF MOTORS PRIOR TO TESTING THE DRIVEN LOAD.
    - b. CHECK AMPERE RATING OF THERMAL OVERLOADS FOR MOTORS.
    - c. CHECK SETTINGS OF THE MOTOR CIRCUIT PROTECTORS. ADJUST SETTINGS TO LOWEST SETTING THAT WILL ALLOW THE MOTOR TO BE STARTED WHEN UNDER LOAD CONDITIONS'
    - d. CHECK INTERLOCKING, CONTROL AND INSTRUMENT WIRING FOR EACH SYSTEM AND/OR PART OF A SYSTEM TO PROVE THAT THE SYSTEM WILL FUNCTION PROPERLY AS INDICATED BY CONTROL SCHEMATIC AND WIRING DIAGRAMS.
    - e. MEGGER TEST ALL LOW VOLTAGE POWER SYSTEM CABLE. MINIMUM WIRE INSULATION RESISTANCE SHALL NOT BE LESS THAN 250 MEGOHMS.
    - f. CHECK OPERATION OF THE PCP UPS AND THE AUTO–DIALER BATTERY BACKUP FOR OPERATION UNDER POWER FAIL CONDITIONS.
    - g. SUBMIT WRITTEN TEST RESULTS
7. IDENTIFY MOTOR STARTERS, CONTROL STATIONS, ETC. WITH THE NAME OF THE EQUIPMENT IT SERVES. CONTROL PANELS, PANELBOARDS, ETC, SHALL HAVE NAMEPLATE DESIGNATIONS AS SHOWN ON THE DRAWINGS. PROVIDE ANSI Z535.4 COMPLIANT WARNING SIGNS FOR POWER EQUIPMENT.
8. CONDUIT AND CONDUIT FITTINGS NOTES:
    - a. CONDUIT SHALL BE GALVANIZED RIGID STEEL CONSISTING OF HEAVY WALL STEEL TUBING WITH A HOT–DIPPED GALVANIZED FINISH INSIDE AND OUT AFTER THREADING AND SHALL COMPLY WITH ANSI C 80.1 AND UL/6. LIQUID–TIGHT FLEXIBLE METAL CONDUIT SHALL BE USED FOR ALL MOTOR TERMINATIONS, THE PRIMARY AND SECONDARY OF TRANSFORMERS, AND OTHER EQUIPMENT WHERE VIBRATION IS PRESENT OR MAY REQUIRE REMOVAL. THE LENGTH OF LIQUID–TIGHT FLEXIBLE METAL CONDUIT SHALL NOT EXCEED 36". LIQUID–TIGHT FLEXIBLE METAL CONDUIT SHALL BE SQUARE LOCKED, GALVANIZED STEEL FLEXIBLE CONDUIT WITH A MOISTURE PROOF, FLAME RESISTANT, POLYVINYL CHLORIDE JACKET, FOR USE WITH RIGID METAL CONDUIT SYSTEMS. SEALTITE, TYPE UA, OR EQUAL.
    - b. CONDUIT SEALING AND DRAIN FITTINGS SHALL BE INSTALLED IN THE HAZARDOUS (CLASSIFIED) AREAS DESIGNATED CLASS 1, DIVISION 1, AND CLASS 1, DIVISION 2 AS REQUIRED BY NEC ARTICLE 501 AND 502. CONDUITS TERMINATING AT BOXES ENCLOSING CIRCUIT OPENING EQUIPMENT SHALL BE SEALED AT THE ENTRANCE TO THE ENCLOSURE WITH APPROVED COMPOUND FILLED SEALING FITTINGS TO PREVENT PASSAGE OF EXPLOSIVE OR COMBUSTIBLE GASES THROUGH THE CONDUITS. ALL CONDUITS LEADING FROM OR ENTERING HAZARDOUS LOCATIONS SHALL BE SIMILARLY SEALED AT POINTS OF EXIT OR ENTRANCE. EXPOSED CONDUITS PASSING THROUGH HAZARDOUS LOCATIONS SHALL BE SEALED AT BOTH THE ENTRANCE TO AND THE EXIT FROM THE HAZARDOUS LOCATIONS. SEAL FITTINGS SHALL BE APPLETON "EYS" TYPE OR EQUAL WITH APPROVED SEALING COMPOUND.
    - c. DRAWINGS DO NOT SHOW CONDUIT RUNS. PROVIDE AS REQUIRED BY THE SINGLE LINES, INTERCONNECTION DIAGRAM, PANEL SCHEDULE AND GENERAL NOTES. COORDINATE CONDUIT INSTALLATION WITH OTHER TRADES AND THE ACTUAL SUPPLIED EQUIPMENT. PROVIDE ALL NECESSARY FITTINGS, SUPPORTS, AND BOXES FOR A COMPLETE RACEWAY INSTALLATION.
    - d. WALL OPENINGS SHALL BE SEALED WITH A UL APPROVED EXPENDING MATERIAL TO PROVIDE WEATHER TIGHT SEAL.
    - e. EXPLOSION PROOF BOXES SHALL BE DESIGNED FOR THE SPECIFIC HAZARDOUS LOCATIONS SHOWN ON THE DRAWINGS. THEY SHALL BE CAST IRON WITH CADMIUM ZINC OR HOT DIPPED GALVANIZED FINISH, STAINLESS STEEL OR HOT DIPPED GALVANIZED BOLTS; TYPE EJB OR EJB_N4 AS MANUFACTURED BY THE CROUSE HINDS COMPANY; APPLETON ELECTRIC CO,. OR EQUAL.
    - f. NO CONDUIT SMALLER THAN 3/4 INCH ELECTRICAL TRADE SIZE SHALL BE USED, NOR SHALL ANY HAVE MORE THAN THE EQUIVALENT OF THREE 90 DEGREE BENDS IN ANY ONE RUN.
9. WIRE AND CABLE NOTES:
    - a. ALL WIRE SHALL BE INSTALLED IN CONDUIT.
    - b. WIRES AND CABLES SHALL BE OF ANNEALED, 98 PERCENT CONDUCTIVITY, SOFT DRAWN COPPER. ALL CONDUCTORS SHALL BE STRANDED, EXCEPT THAT LIGHTING AND RECEPTACLE WIRING MAY BE SOLID. SHALL HAVE 600 VOLT INSULATION EXCEPT WHERE INDICATED OTHERWISE.
    - c. EXCEPT FOR CONTROL, SIGNAL AND INSTRUMENTATION CIRCUITS, WIRE SMALLER THAN NO. 12 AWG SHALL NOT BE USED.
    - d. POWER WIRE SHALL BE NEC TYPE XHHW OR XHHW–2.
    - e. CONTROL, STATUS AND ALARM WIRE SHALL BE NO.14 AWG NEC TYPE THWN.
    - f. WIRE FOR PROCESS INSTRUMENTATION SIGNALS (I.E. 1–5 VDC, 4–20 MADC), R.T.D., POTENTIOMETER AND SIMILAR SIGNALS SHALL BE SINGLE PAIR CABLE: 2 NO. 16 STRANDED AND TWISTED CONDUCTORS ON 2 IN LAY, 100% ALUMINUM/POLYESTER FOIL SHIELD WITH DRAIN WIRE, PVC JACKET. BELDEN NO. 1030A OR EQUAL.
    - g. WIRE SHALL BE COLOR CODED OR CODED USING ELECTRICAL TAPE, FOLLOWING UL COLOR CODING SCHEME.
    - h. SHIELDED INSTRUMENTATION WIRE AND CONTROL CONDUCTORS SHALL BE RUN WITHOUT SPLICES BETWEEN INSTRUMENTS, TERMINAL BOXES, OR PANELS. TERMINAL BLOCKS SHALL BE PROVIDED FOR ALL INSTRUMENT AND CONTROL CABLE TERMINATIONS. GROUND SHIELD ON INSTRUMENTATION WIRES AT ONE END ONLY AS RECOMMENDED BY THE INSTRUMENT MANUFACTURER AND ISOLATED AT ALL OTHER LOCATIONS. TERMINAL BLOCKS SHALL BE PROVIDED FOR INTER_CONNECTING SHIELD DRAIN WIRES AT ALL JUNCTION BOXES. WHERE INDIVIDUAL CIRCUIT SHIELDING IS REQUIRED, EACH SHIELD CIRCUIT SHALL BE PROVIDED WITH ITS OWN BLOCK.
    - i. INSTALL EACH 480 VOLT FEED IN ITS OWN CONDUIT.
    - j. 120 VOLT CONDUCTORS MAY BE GROUPED INTO MULTI WIRE HOMERUNS OF UP TO 3 CIRCUITS.
    - k. CONTROL WIRES MAY BE GROUPED INTO MULTI WIRE HOMERUNS BUT MAY NOT BE MIXED WITH OTHER SIGNAL OR POWER CONDUCTORS.
    - l. INSTRUMENTATION LOW VOLTAGE SIGNAL CABLES MAY BE GROUPED INTO MULTI CIRCUIT HOMERUNS BUT MAY NOT BE MIXED WITH OTHER CONTROL OR POWER CONDUCTORS.

GENERAL NOTES (CONTD)

10. CONTROL PANEL NOTES:
    - a. EACH CONTROL PANEL SHALL BEAR THE UL LABEL. THE UL LABEL SHALL APPLY TO THE ENCLOSURE, THE SPECIFIC EQUIPMENT SUPPLIED WITH THE ENCLOSURE, AND THE INSTALLATION AND WIRING OF THE EQUIPMENT WITHIN AND ON THE ENCLOSURE.
    - b. ALL COMPONENTS SHALL BE MOUNTED IN A MANNER THAT SHALL PERMIT SERVICING, ADJUSTMENT, TESTING, AND REMOVAL WITHOUT DISCONNECTING, MOVING, OR REMOVING ANY OTHER COMPONENT. COMPONENTS MOUNTED ON THE INSIDE OF PANELS SHALL BE MOUNTED ON REMOVABLE PLATES UNLESS NOTED. COMPONENT MOUNTING SHALL BE ORIENTED IN ACCORDANCE WITH MANUFACTURER'S RECOMMENDATIONS. THE INTERNAL COMPONENTS SHALL BE IDENTIFIED WITH SUITABLE PLASTIC OR METAL ENGRAVED NAMETAGS MOUNTED ADJACENT TO EACH COMPONENT IDENTIFYING THE COMPONENT IN ACCORDANCE WITH THE DRAWINGS.
    - c. ALL PANELS IN OUTDOOR ENVIRONMENTS SHALL BE NEMA 4X UNLESS OTHERWISE NOTED. ALL PANELS LOCATED IN A HAZARDOUS LOCATION SHALL BE RATED FOR THE TYPE OF HAZARD (E.G., NEMA 7 FOR CLASS 1, DIVISION 2). ENCLOSURES SHALL BE SIZED AS REQUIRED FOR THE COMPONENTS INSTALLED.
    - d. EXPLOSION PROOF PANELS SHALL BE GASKETED CAST ALUMINUM CONTROL CENTERS, FACTORY INSTALLED COVER MOUNTED CONTROL DEVICES AND FACTORY TAPPED FOR THE CONDUIT ENTRIES REQUIRED. APPLETON ACSEW OR EQUAL.
    - e. POWER DISTRIBUTION WIRING ON THE LINE SIDE OF FUSES OR BREAKERS SHALL BE 12 AWG MINIMUM. CONTROL WIRING ON THE SECONDARY SIDE OF FUSES SHALL BE 16 AWG MINIMUM. ELECTRONIC ANALOG CIRCUITS SHALL UTILIZE 18 AWG SHIELDED, TWISTED PAIR, CABLE INSULATED FOR NOT LESS THAN 600 VOLTS.
    - f. POWER AND LOW VOLTAGE DC WIRING SYSTEMS SHALL BE ROUTED IN SEPARATE WIREWAYS. WIRING TROUGHS SHALL NOT BE FILLED TO MORE THAN 60 PERCENT VISIBLE FILL.
    - g. DIFFERENT WIRING SYSTEMS SHALL TERMINATE ON SEPARATE TERMINAL BLOCK.TERMINAL BLOCKS SHALL BE ARRANGED IN VERTICAL ROWS AND SEPARATED INTO GROUPS (POWER, AC CONTROL, DC SIGNAL). ONLY ONE SIDE OF A TERMINAL BLOCK ROW SHALL BE USED FOR INTERNAL WIRING.
    - h. EACH PANEL SHALL BE PROVIDED WITH A CIRCUIT BREAKER TO INTERRUPT INCOMING POWER.
    - i. PILOT TYPE INDICATING LIGHTS SHALL BE PUSH TO TEST TYPE, PROVIDED WITH LOW VOLTAGE LED LAMPS SUITABLE FOR THE VOLTAGE SUPPLIED, NEMA RATING TO MAINTAIN OVERALL PANEL RATING.PROVIDE NAMEPLATES AS SHOWN ON THE DRAWINGS.
    - j. SELECTOR SWITCHES AND PUSHBUTTONS: HEAVY–DUTY, FULL SIZE TYPE WITH CONTACT ARRANGEMENT AND SWITCHING ACTION AS REQUIRED, NEMA RATING TO MAINTAIN OVERALL PANEL RATING. PROVIDE NAMEPLATES AS SHOWN ON THE DRAWINGS
    - k. GENERAL PURPOSE RELAYS AND TIME DELAY RELAYS: PLUG_IN TYPE, VOLTAGE RATING AND CONTACT ARRANGEMENT/FUNCTION AS REQUIRED, RATED FOR CONTINUOUS OPERATION. IDEC OR EQUAL.
    - l. PROVIDE CORROSION INHIBITORS IN ALL OUTDOOR PANELS AND ENCLOSURES

SHEET NOTES (DRAWING E–3)

① BOLTED COMBINATION MOTOR STARTERS AND TANK HEATER DISCONNECTS AS SHOWN ON THE SINGLE LINE. MOUNT IN 2 ROWS SO THAT THE OPERATING HANDLES ARE NOT HIGHER THAN 6 FT ABOVE FLOOR. STARTERS SHALL BE EXPLOSION PROOF, CAST ALUMINUM, WITH MOTOR CIRCUIT PROTECTOR UTILIZING A COVER MOUNTED, PAD LOCKABLE BREAKER OPERATOR INTERLOCKED WITH THE COVER DOOR. SEPARATE FUSED 120 VOLT CONTROL CIRCUIT IN PANEL PCP WILL BE USED. NO PILOT DEVICES REQUIRED. APPLETON AEB SERIES OR EQUAL. TANK HEATER DISCONNECTS ARE DESCRIBED ON DWG E–5.

② TEMPORARY LOCATION FOR COMPRESSOR AND COMPRESSOR RECEPTACLE INSIDE TRAILER FOR TRANSPORT AND TESTING. COMPRESSOR AND RECEPTACLE TO BE RELOCATED OUTSIDE TRAILER BEFORE PILOT PLANT OPERATION. RECEPTACLE TO BE SIMPLEX, 20A, 2W3P, 250 VOLT, NON–HAZARDOUS, HEAVY DUTY, NEMA 4X WATER TIGHT, MECHANICALLY INTERLOCKED, WITH BACK BOX. COOPER–CROUSE HINDS GH320MI6W OR EQUAL.

③ RECEPTACLE FOR INSIDE TRAILER: SIMPLEX, CLASS I DIV 2 GRP D RATED, DEAD FRONT, SPRING DOOR, INTERLOCKED CIRCUIT BREAKING TYPE, 15A, 125 V, COOPER–CROUSE HINDS ENR5151 OR EQUAL WITH BACK BOX AND MATCHING PLUG.

④ OUTDOOR RECEPTACLES: SPECIFICATION GRADE, WEATHER RESISTANT, DUPLEX, 15A, 125V, GFCI TYPE WITH HEAVY DUTY, DIE CAST ALUMINUM WP WHILE IN USE COVER, T&B RED DOT CODE KEEPER WET LOCATION COVER AND BACK BOX, OR EQUAL.

⑤ ALARM BEACONS AND HORN FOR COMBUSTIBLE GAS LEAK/VENTILATION FAILURE NOTIFICATION. INDOOR UNIT SHALL BE EXPLOSION PROOF BEACON ONLY, CLASS I DIV 2 GRP D RATED, WITH STROBE TUBE; FEDERAL SIGNAL FIREBALL 2 OR EQUAL. PROVIDE A NAMEPLATE ON WALL BELOW: "ALARM LIGHT INDICATES COMBUSTIBLE GAS LEAK/VENTILATION FAILURE". OUTDOOR UNIT SHALL BE COMBINATION STROBE BEACON AND HORN UNIT, NEMA 4X, FEDERAL SIGNAL STREAMLINE LOW PROFILE OR EQUAL. : "ALARM LIGHT INDICATES COMBUSTIBLE GAS LEAK/VENTILATION FAILURE. DO NOT ENTER". BOTH UNITS SHALL BE WALL MOUNT TYPE, 12 VDC, WITH AMBER LENS.

⑥ PILOT CONTROL PANEL "PCP": COMPLY WITH CONTROL PANEL SPECIFICATIONS UNDER "GENERAL NOTES". COVER MOUNTED PILOT DEVICES ARE SHOWN ON THE PIDS AND CONTROL SCHEMATIC DIAGRAMS. INTERIOR DEVICES, INCLUDING RELAYS AND THE PLC, SHALL BE AS SHOWN ON THE INTERCONNECT AND CONTROL SCHEMATIC DIAGRAMS AND AS REQUIRED BY THE SPECIFICATION NOTES. EXPLOSION PROOF ENCLOSURE SHALL BE APPROXIMATELY 48"HX24"WX12"D, AS REQUIRED.

⑦ COMBUSTIBLE GAS LEAK/VENTILATION FAILURE ALARM PANEL "ALR PNL": COMPLY WITH CONTROL PANEL SPECIFICATIONS UNDER "GENERAL NOTES". COVER MOUNTED PILOT DEVICES AND INTERIOR DEVICES, INCLUDING RELAYS AND UPS FOR POWER BACKUP, SHALL BE AS SHOWN ON CONTROL SCHEMATIC DIAGRAM AND AS REQUIRED BY THE SPECIFICATION NOTES. ARRANGE INTERNAL DEVICES TO MINIMIZE PANEL DEPTH. HINGE COVER, STEEL NEMA 3R ENCLOSURE SHALL BE APPROXIMATELY 24"HX20"WX8"D, AS REQUIRED. HOFFMAN OR EQUAL.

LIGHTING FIXTURE NOTES (DRAWING E–3)

◇1 EXPLOSION PROOF FLUORESCENT FIXTURE, CLASS I DIV 1GRP D RATED, 120 V, NOMINAL 12"X48", 2–32 WATT LAMPS, ELECTRONIC BALLAST, COOPER–CROUSE HINDS EVF SERIES OR EQUAL.

◇2 CUTOFF WALLPACK FIXTURE, 120 V, 70W MH, PHOTOCELL, DIE CAST HOUSING GLASS REFRACTOR, RAB WP1C OR EQUAL.

◇3 COMBINATION EXIT AND EMERGENCY LIGHT, , CLASS I DIV 2GRP D RATED, 120 V, LED EXIT LIGHT WITH RED LETTERING, 2–6W HALOGEN EMERGENCY LIGHT HEADS, LEAD CALCIUM BATTERY AND SOLID STATE CHARGING SYSTEM. THE EXIT LIGHT COMPANY "COMBO–C1D2" OR EQUAL.

30% SUBMITTAL - NOT FOR CONSTRUCTION

REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: RRR
DRAWN BY: JAW
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: APRIL 2011

LINE IS 1 INCH
AT FULL SIZE
(34X22)
SCALE ACCORDINGLY

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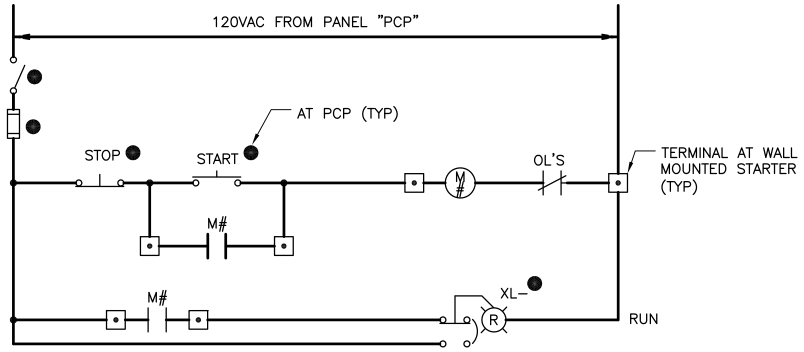
Renewable Energy Production from
DoD Installation Solid Waste by
Anaerobic Digestion

ELECTRICAL NOTES

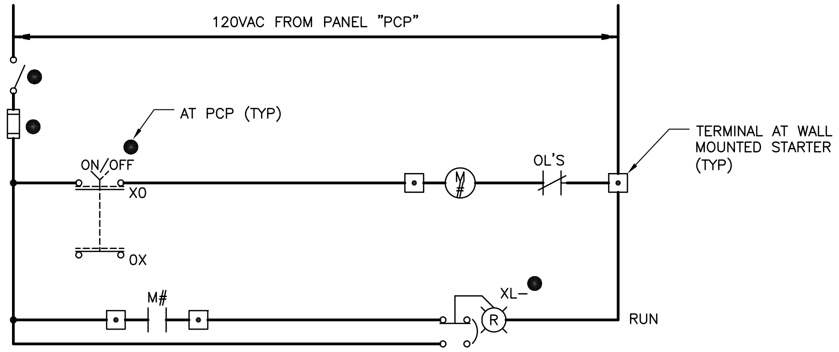
PROJECT NO. 50957–73968
FILE NAME: E004
DRAWING NO.
E-4
SHEET NO.
OF 30


120VAC FROM PANEL "PCP"
AT PCP (TYP)
STOP
START
M#
OL'S
TERMINAL AT WALL MOUNTED STARTER (TYP)
M#
XL-
R
RUN

NOTES:

1. DEVICES WITHOUT LOCATION SYMBOL LOCATED AT WALL MOUNTED STARTER

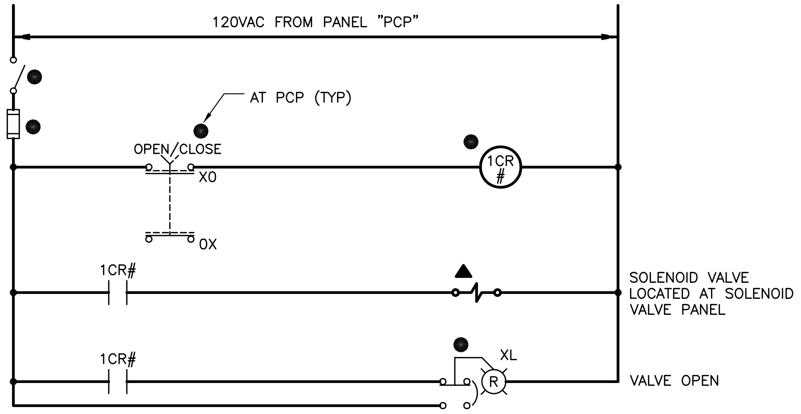
MIX-201 & 301 DIGESTER MIXERS


120VAC FROM PANEL "PCP"
AT PCP (TYP)
ON/OFF
XO
OX
M#
OL'S
TERMINAL AT WALL MOUNTED STARTER (TYP)
M#
XL-
R
RUN

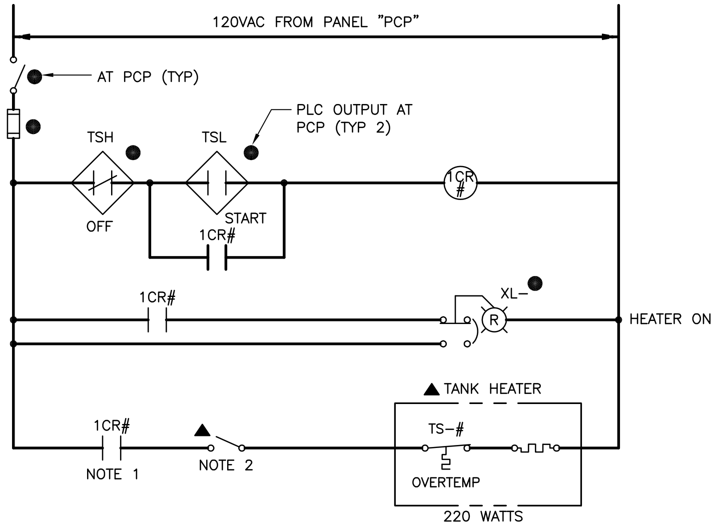
NOTES:

1. DEVICES WITHOUT LOCATION SYMBOL LOCATED AT WALL MOUNTED STARTER

EXHAUST & SUPPLY FANS


120VAC FROM PANEL "PCP"
AT PCP (TYP)
OPEN/CLOSE
XO
OX
1CR #
1CR#
SOLENOID VALVE LOCATED AT SOLENOID VALVE PANEL
1CR#
XL
R
VALVE OPEN

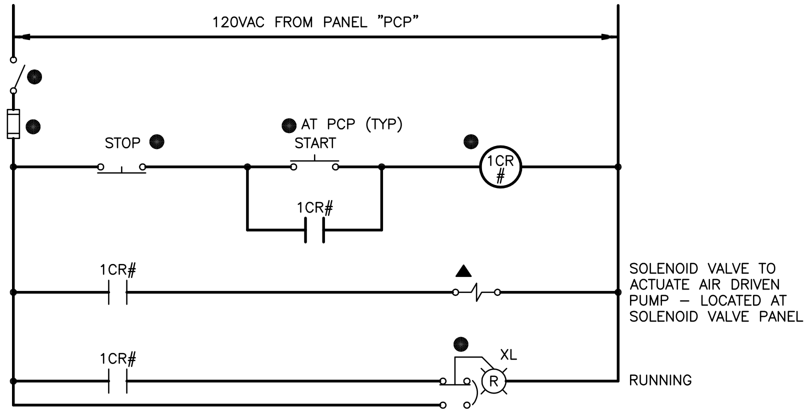
TYPICAL SOLENOID VALVE


120VAC FROM PANEL "PCP"
AT PCP (TYP)
PLC OUTPUT AT PCP (TYP 2)
TSH
TSL
OFF
START
1CR#
1CR #
1CR#
XL-
R
HEATER ON
TANK HEATER
1CR#
NOTE 1
NOTE 2
TS-#
OVERTEMP
220 WATTS

DIGESTER TANK HEATERS
HTR-202,203,204,302,303&304

NOTES:

1. RELAY CONTACTS RATED FOR CONTINUOUS LOAD.
2. WALL MOUNTED LOCKABLE DISCONNECT, FRONT OPERATED, FACTORY SEALED, CLASS I, DIV 2, 20 AMP, APPLETON EDS OR EQUAL.


120VAC FROM PANEL "PCP"
STOP
AT PCP (TYP)
START
1CR #
1CR#
1CR#
SOLENOID VALVE TO ACTUATE AIR DRIVEN PUMP – LOCATED AT SOLENOID VALVE PANEL
1CR#
XL
R
RUNNING

METERING PUMP
P-201,207,301,307&803

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REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: RRR
DRAWN BY: WKT
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: AUGUST 2012

LINE IS 1 INCH
AT FULL SIZE
(34X22)
SCALE ACCORDINGLY

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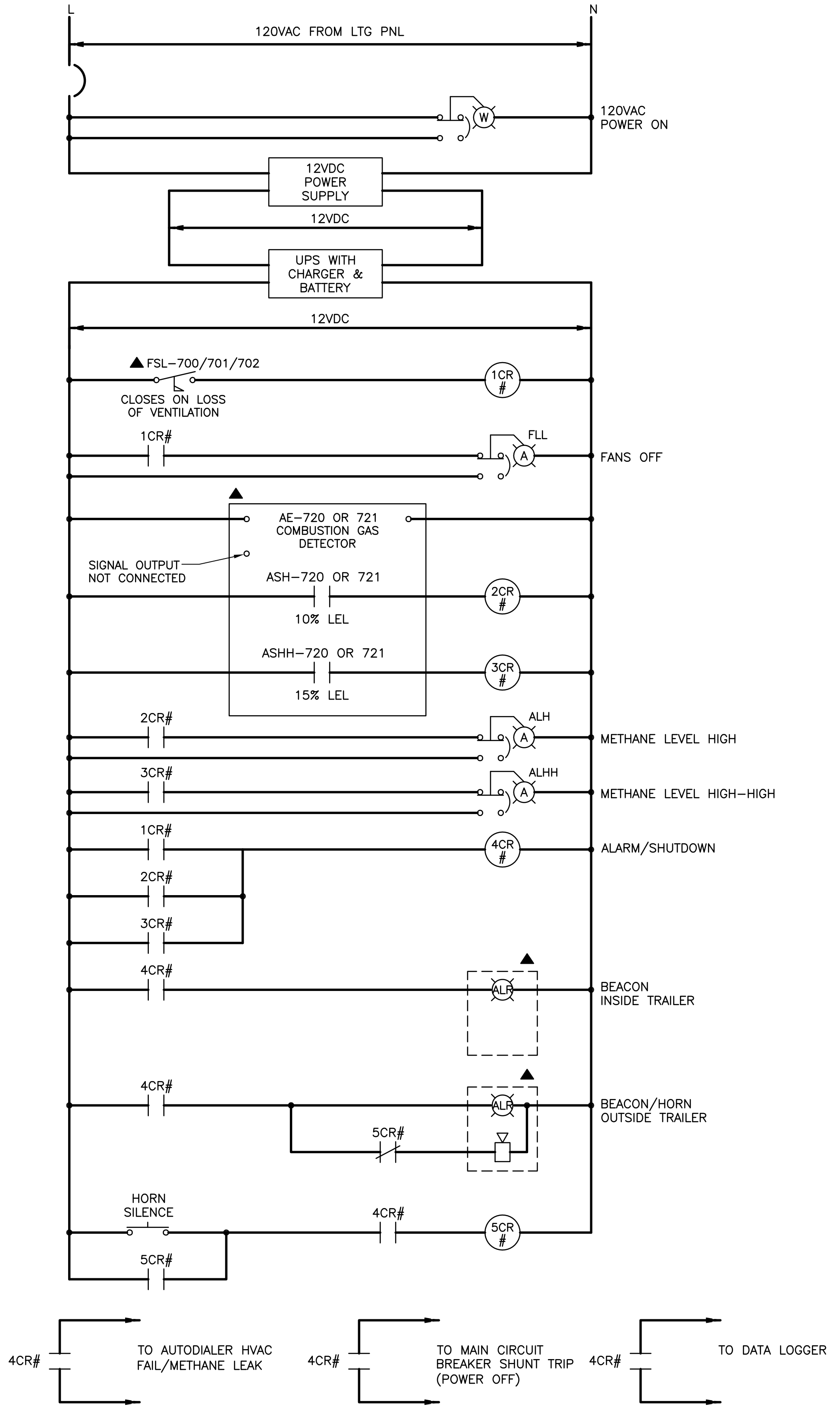
Renewable Energy Production from DoD Installation Solid Waste by Anaerobic Digestion

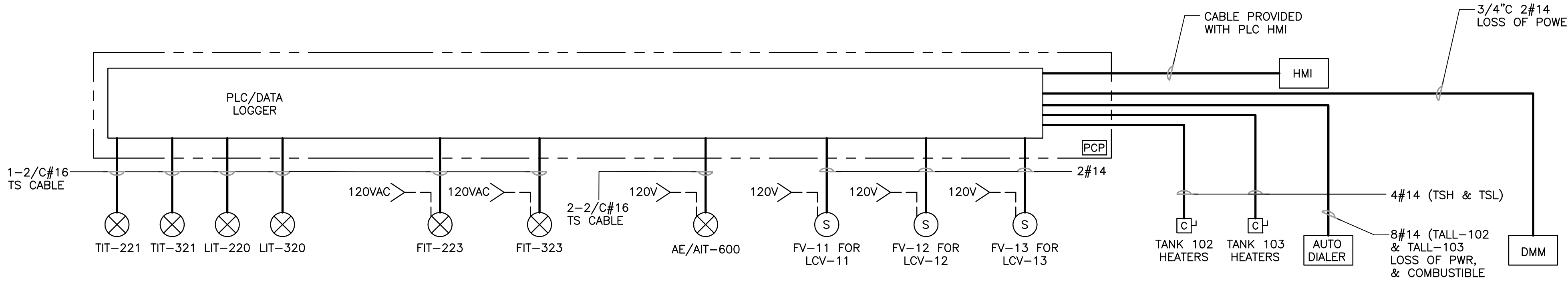
CONTROL DIAGRAMS
1 OF 2

PROJECT NO. 50957-73968
FILE NAME: E005
DRAWING NO.
E-5
SHEET NO.
OF 28


L
N
120VAC FROM LTG PNL
W
120VAC POWER ON
12VDC POWER SUPPLY
12VDC
UPS WITH CHARGER & BATTERY
12VDC
FSL-700/701/702
CLOSES ON LOSS OF VENTILATION
1CR#
1CR#
FLL
A
FANS OFF
AE-720 OR 721 COMBUSTION GAS DETECTOR
SIGNAL OUTPUT NOT CONNECTED
ASH-720 OR 721
10% LEL
2CR#
ASHH-720 OR 721
15% LEL
3CR#
2CR#
ALH
A
METHANE LEVEL HIGH
3CR#
ALHH
A
METHANE LEVEL HIGH-HIGH
1CR#
4CR#
ALARM/SHUTDOWN
2CR#
3CR#
4CR#
ALR
BEACON INSIDE TRAILER
4CR#
ALR
5CR#
BEACON/HORN OUTSIDE TRAILER
HORN SILENCE
4CR#
5CR#
5CR#
4CR#
TO AUTODIALER HVAC FAIL/METHANE LEAK
4CR#
TO MAIN CIRCUIT BREAKER SHUNT TRIP (POWER OFF)
4CR#
TO DATA LOGGER

NOTE: UNLESS OTHERWISE INDICATED, ALL DEVICES ARE LOCATED IN ALR PNL.

HVAC & COMBUSTIBLE GAS ALARM PANEL "ALR PNL"


PLC/DATA LOGGER
PCP
CABLE PROVIDED WITH PLC HMI
HMI
3/4"C 2#14 LOSS OF POWER
1-2/C#16 TS CABLE
2#14
120VAC
120VAC
2-2/C#16 TS CABLE
120V
120V
120V
120V
S
S
S
TIT-221
TIT-321
LIT-220
LIT-320
FIT-223
FIT-323
AE/AIT-600
FV-11 FOR LCV-11
FV-12 FOR LCV-12
FV-13 FOR LCV-13
C
C
TANK 102 HEATERS
TANK 103 HEATERS
AUTO DIALER
4#14 (TSH & TSL)
8#14 (TALL-102 & TALL-103 LOSS OF PWR, & COMBUSTIBLE GAS ALARM)
DMM

NOTE: 24 VAC POWER SUPPLY (NOT SHOWN) REQUIRED FOR PLC, HMI & LOOP POWERED INSTRUMENTS.

PLC INTERCONNECTION DIAGRAM

REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: RRR
DRAWN BY: WKT
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: AUGUST 2012

LINE IS 1 INCH AT FULL SIZE (34X22) SCALE ACCORDINGLY

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Renewable Energy Production from DoD Installation Solid Waste by Anaerobic Digestion

CONTROL DIAGRAMS
2 OF 2

PROJECT NO. 50957-73968
FILE NAME: E006
DRAWING NO.
E-6
SHEET NO.
OF 28

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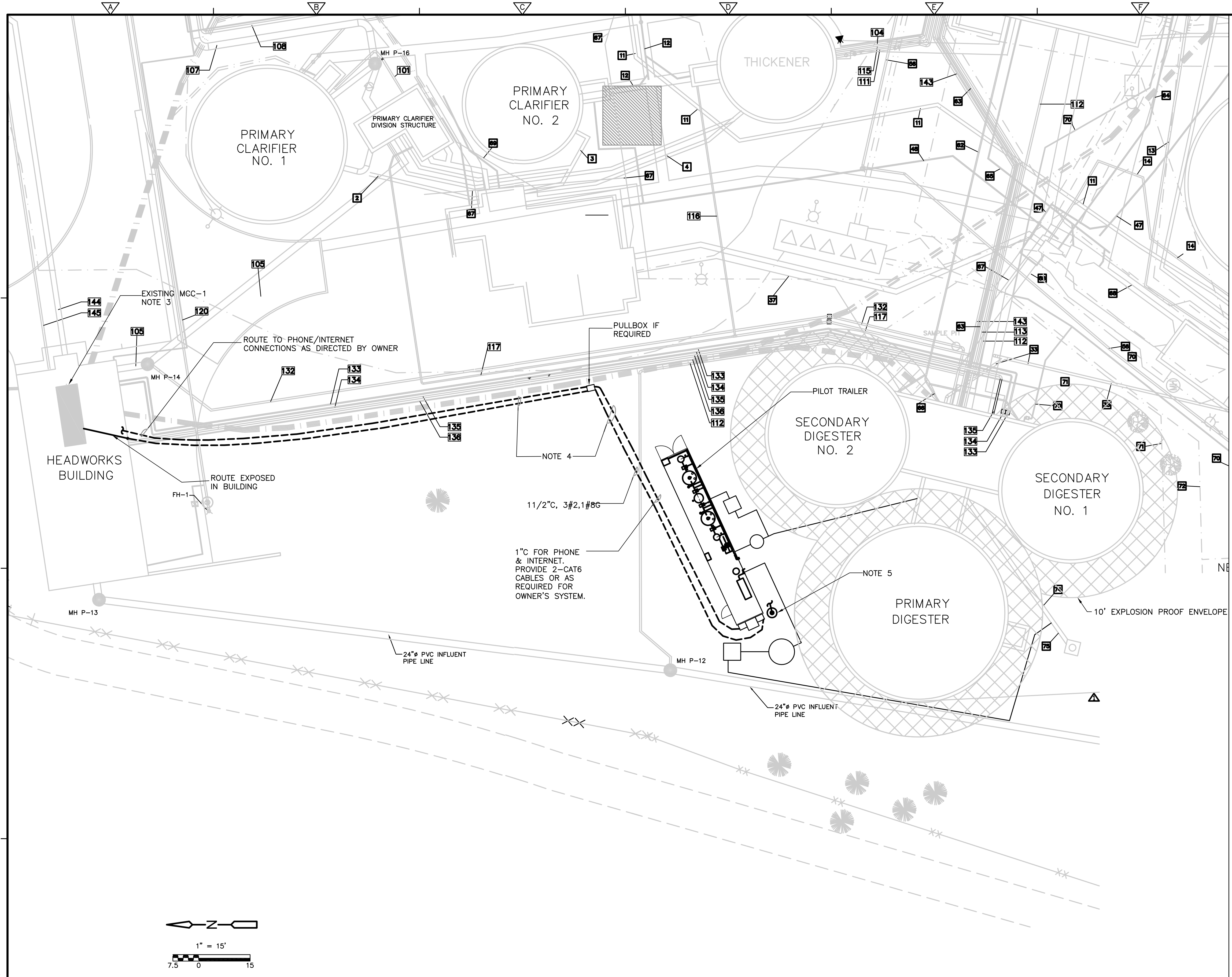
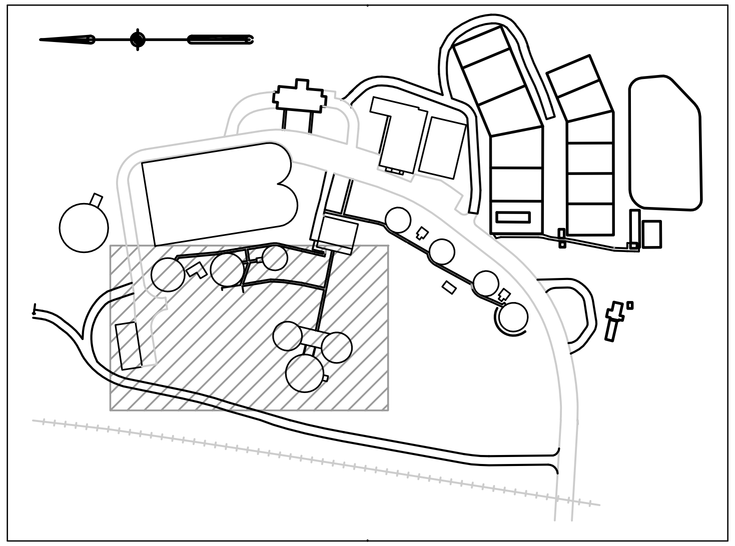

PRIMARY CLARIFIER NO. 1
PRIMARY CLARIFIER DIVISION STRUCTURE
PRIMARY CLARIFIER NO. 2
THICKENER
MH P-16
HEADWORKS BUILDING
EXISTING MCC-1 NOTE 3
ROUTE TO PHONE/INTERNET CONNECTIONS AS DIRECTED BY OWNER
PULLBOX IF REQUIRED
MH P-14
ROUTE EXPOSED IN BUILDING
FH-1
NOTE 4
11/2"C, 3#2,1#8G
1"C FOR PHONE & INTERNET. PROVIDE 2-CAT6 CABLES OR AS REQUIRED FOR OWNER'S SYSTEM.
PILOT TRAILER
SECONDARY DIGESTER NO. 2
SECONDARY DIGESTER NO. 1
PRIMARY DIGESTER
NOTE 5
SAMPLE PIT
10' EXPLOSION PROOF ENVELOPE
MH P-13
MH P-12
24"ø PVC INFLUENT PIPE LINE
24"ø PVC INFLUENT PIPE LINE
NE
1" = 15'
7.5 0 15
N



KEY MAP

NOTES:

1. UNDERGROUND UTILITIES ARE SHOWN BASED ON PLANT RECORD DRAWINGS WHICH REPRESENT THE BEST INFORMATION AVAILABLE. THE TYPE, SIZE, LOCATION, AND NUMBER ARE APPROXIMATE AS SHOWN BY THESE DRAWINGS.
2. PRIOR TO COMMENCEMENT OF ANY EXCAVATION, CONTRACTOR SHALL LOCATE AND MARK THE ACTUAL LOCATION OF UNDERGROUND UTILITIES.
3. PROVIDE 3 PHASE, 100AT BREAKER IN EXISTING "SPACE" AT MCC-1 FOR POWER TO PANEL DPA AT PILOT TRAILER. BREAKER TYPE & BRAND TO BE COMPATIBLE WITH EXISTING MCC.
4. SCHEDULE 40 PVC DB CONDUITS, MINIMUM 24" BELOW GRADE, SAND ENCASED. SPACE 9" APART. EXACT ROUTING TO BE DETERMINED IN FIELD. NO MORE THAN 3-90 DEGREE BENDS ALLOWED. IF ADDITINAL BENDS ARE REQUIRED, PROVIDE PULL BOX.
5. PROVIDE 3/4" X 10' COPPER GROUND ROD. EXOTHERMICALLY WELD TO #2 BARE GROUND WIRE. EXTEND GROUND WIRE TO TRAILER GROUND BUS.

LEGEND:

- 72 EXISTING PIPELINE LABEL
- 117 NEW PIPELINE LABEL
- EXISTING UNDERGROUND ELECTRICAL LINES
- EXISTING PIPELINE TO BE ABANDONED
- EXISTING PIPELINE TO BE REUSED
- NEW PIPELINE
- ▨ LIMITS OF CONCRETE PIPE ENCASEMENT
- ☒ ANCHORS (TYP)

REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: RRR
DRAWN BY:
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: APRIL 2011

LINE IS 1 INCH
AT FULL SIZE
(34X22)
SCALE ACCORDINGLY

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Renewable Energy Production from
DoD Installation Solid Waste by
Anaerobic Digestion

ELECTRICAL SITE PLAN

PROJECT NO. 50957-73968
FILE NAME: E101
DRAWING NO.
E101
SHEET NO.
OF 28

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Appendix H: Supporting Data

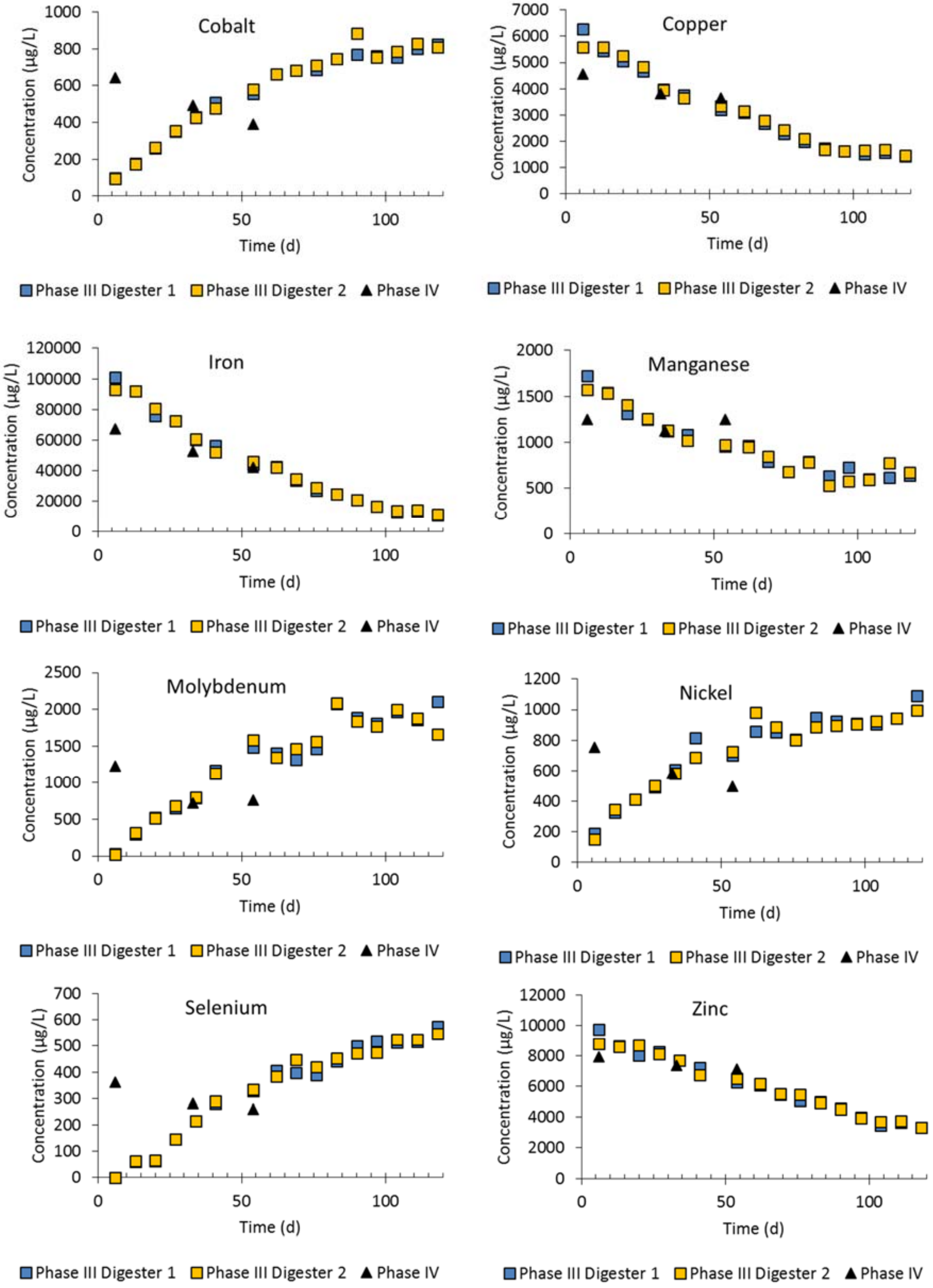


Figure 1. Measured concentrations of metals in the digestate.

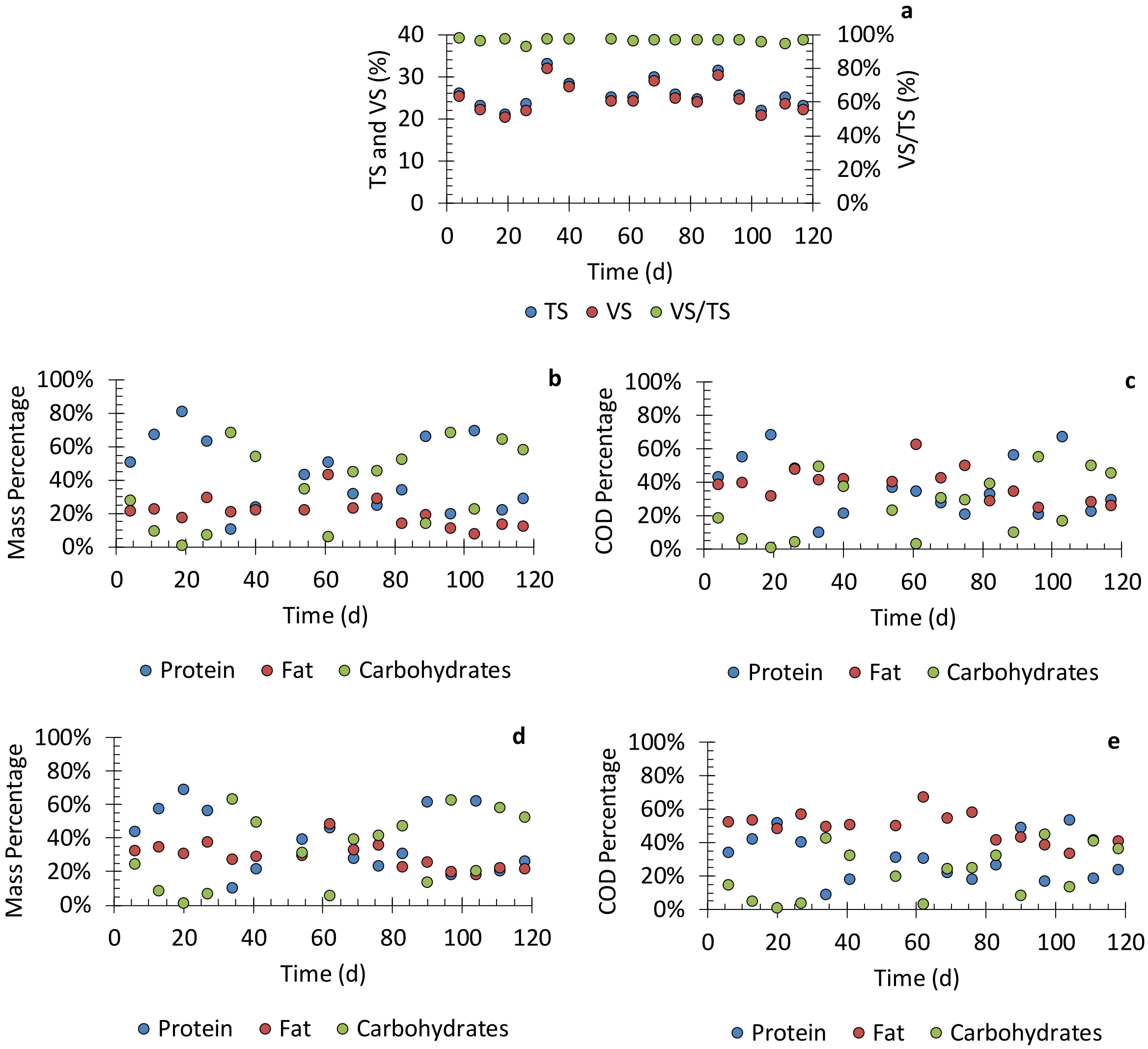


Figure 2. Food waste composition during Phases II and III after removal of foreign debris. Temporal trends are shown for total and volatile solids (a); and fat, protein, and carbohydrates in the organic fraction of food waste alone (b and c) and the food waste/canola oil mixture (d and e) on a mass basis (b and d) and a COD basis (c and e).

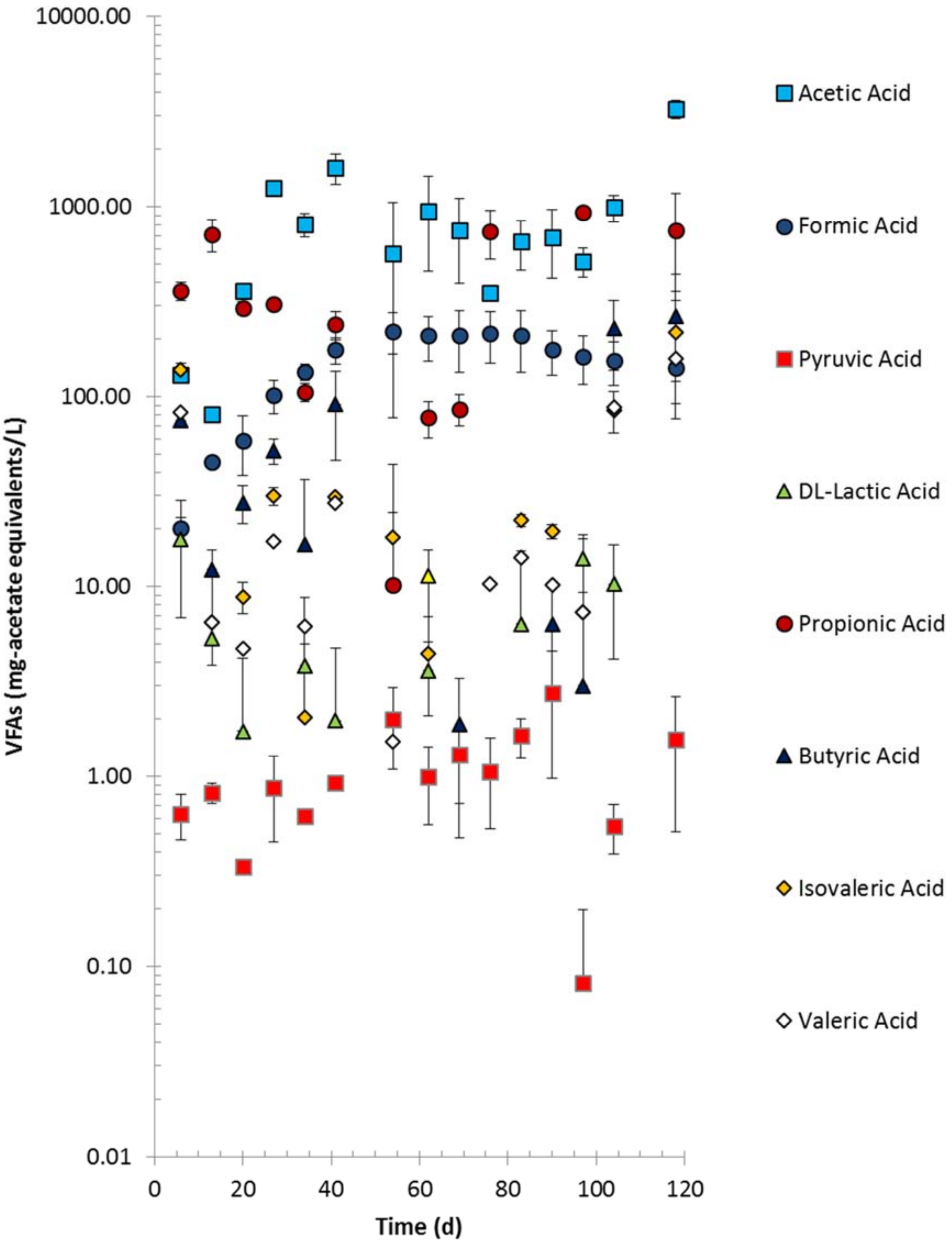


Figure 3. VFA trends during Phases II and III. Propionate data may be suspect because of matrix interferences resulting in inconsistent detections.

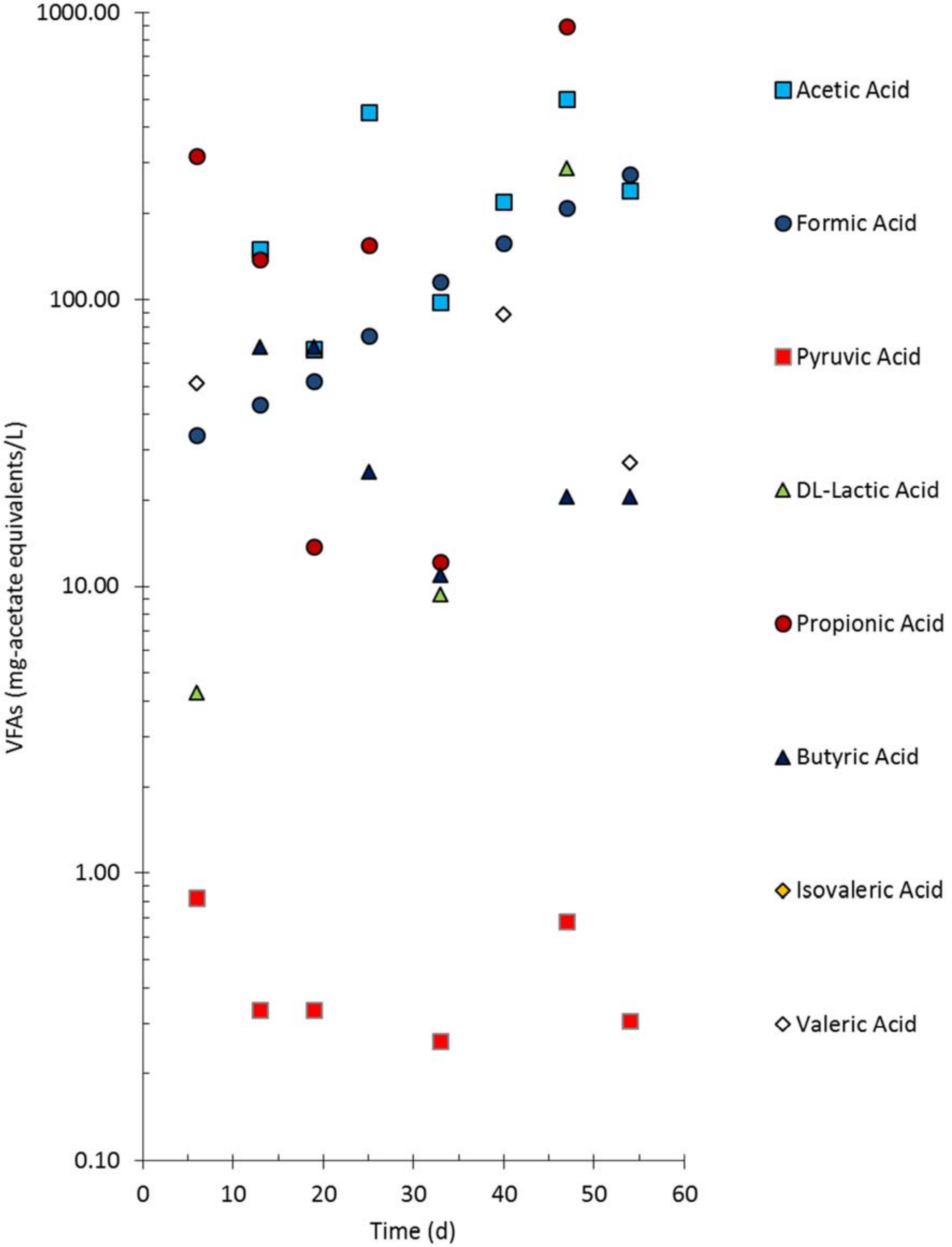


Figure 4. VFA trends during Phase IV. Propionate data may be suspect because of matrix interferences resulting in inconsistent detections.

Appendix I: Digester Feeding Details

Digester Feeding – Procedures, Time Line, and Observations during Phases II and III

Segregation of Food Waste

All of the food waste was segregated by hand. The primary items separated consisted of wrappers, plastic, foil, plastic Saran wrap, Styrofoam, and occasionally glass. I also removed food substances that would not digest or would cause mechanical failures such as bones and various seeds or pits. I removed as much non-biodegradable material as I could, being careful to make sure all larger items were removed. Small shredded wrappers and other small pieces of trash were not always completely removed, but they were not a threat to digester upset or mechanical failure. I also removed any remaining trash found in the feed mixture after the batch was prepared. I was careful to remove only trash from the feed mixture in the mix tank to make sure no food waste would be removed.

Procedure for Preparing the Digester Feed Mixture (Same for both diaphragm and hand pump feed methods):

All of the ingredients for the digester feed were weighed and added to the feed mixture tank. Water was added to the mix tank before all other components. The diaphragm pump was then turned on and the pressure was adjusted to provide enough force to circulate the water without causing any splashing. In the following order, the food waste, oil and nutrients were added to the water. The food waste was carefully added stepwise with handful sized amounts to prevent splashing and to allow for effective mixing without overloading the diaphragm pump with solids. While mixing, any trash or wrappings that floated to the top was carefully removed. The air supply to the diaphragm pump was limited, and mixing would significantly slow over the first 10 – 15 min. of preparing the feed. Depending on the volume of the feed mixture and the characteristics of the food waste, the diaphragm pump’s reduced ability to provide effective circulation there were instances where solids would clump and/or settle. The feed would require a significant amount of mixing by hand with a paddle to break up the clumps and prevent settling. As soon as mixing stopped, the waste would quickly settle regardless of how broken up it was. This was mostly the case for thick or dense food waste, but the preparation of every feed mixture required some extent of manual mixing to assist the diaphragm pump. Oil added to the feed mixture presented an issue since its hydrophobic properties. Oil would quickly rise to the surface of the feed mixture and remain there regardless of how effective the diaphragm pump was mixing and homogenizing the feed. The only way to keep the oil suspended in the feed was to repetitively use the hand paddle to force the oil back into the mixture. Once the feed mixture was prepared and mixed as thoroughly as possible, a sample of the digester feed was collected. With the diaphragm pump continuing to circulate the feed, a 2-L measuring cup was used to scoop up a sample. The measuring cup was used to agitate the mixture by swirling the cup around in the feed and repetitively filling and dumping feed back into the mixture. This was done to avoid settling and oil separation to ensure a representative sample could be collected. When the feed appeared to be as thoroughly mixed as possible from the agitation, the measuring cup was used to scoop up the feed one last time to transfer to a sample container.

Digester Feeding: Diaphragm Pump (12/20/2013 – 1/3/2014).

After the feed mixture was prepared and the sample was collect, the diaphragm pump was shut off to allow time for the air compressor to regenerate. During this time, the digesters were drained to the appropriate volume using a manual ball valve located at the bottom of each digester. Once the digesters were drained, a hose was connected to the outlet of the mix tank and to the inlet of a digester. The feed inlet on both digesters was located near the bottom, so the digesters were always bottom fed. Draining the digesters and setting up the feeding assembly generally took 15 – 20 min. Once set up, the diaphragm pump was turned back on, and the feed mixture was circulated for 5-10 minutes, or until the mixture appeared to be evenly mixed. This step usually required manual mixing with a paddle to assist the diaphragm pump. The diaphragm pump was plumbed to direct the feed mixture to both the mix tank and to the hose for digester feeding in a manner that both paths could be simultaneously used. When the feed was ready, it was directed into the hose toward the digester. To fill the hose with feed, the ball valve on the feed end of the hose was cracked open to the atmosphere to displace air in the hose with the feed mixture. This was to prevent air from entering the digester. Due to the difficulty in removing all air from the hose, it was inevitable for a small volume of air to enter the digester (1 L or so). The valve on the digester inlet and the valve at the end of the hose was opened to allow the feed to flow into the digester. The flow rate was very difficult to control because the diaphragm pump could only be controlled by the amount of air being supplied to it. The valve allowing the feed mixture to circulate in the mix tank had to either be closed or restricted to create enough pressure from the diaphragm pump to feed the digester. Once the digester was fed, the feed hose was disconnected transferred to the second digester. The entire process was then repeated.

Observations and Comments:

- Pressure loss from the diaphragm pump due to lack of compressed air supply resulted in poor ability to effectively mix the digester feed. This caused solids settling and oil separation to occur.
- Hand mixing with a paddle was used to assist the diaphragm pump, but it was not possible to maintain hand mixing while feeding the digester. This led to variability in the consistency of the feed mixture delivered to each digester.
- The only way to effectively control the rate of filling the digesters, various ball valves had to be adjusted, which meant there may have been instances where larger solids were prevented from entering the digester by restricted valves. Valve adjustment while feeding was done carefully to prevent this as much as possible.
- Missed pieces of trash or plastic from food waste separation would sometimes get stuck in the ball valves, which may have hindered some solids from entering the digester.
- Depending on the characteristics of the food waste, it was common for residual food waste to remain in the mix tank after feeding. This was prevented as much as possible with hand mixing, but it is suspected that there were a few occasions when less food waste was fed to the digesters than desired. (Feed mixture entering the digester was diluted due settled solids in the mix tank that were left behind)

- The canola oil would separate and remain at the surface of the digester feed in the mix tank during feed cycles. This was prevented as much as possible by brief opportunities for hand mixing, but it is suspected that the second digester fed received more oil than the first.
- Air was introduced to the digesters during feeding due to residual air in the feed hose prior to feeding the digester. An air pocket would occasionally accumulate in the feed hose while feeding, which was overcome by controlling the feed rate as best as possible so that the pocket would not be forced into the digester.
- Feed would be delivered to the digesters in small "bursts" to prevent filling a greater volume than planned. This required constantly checking the digester volume by moving back and forth between the operation and control room, but the surges from filling the digester caused the pressure transmitter to spike multiple gallons above the actual volume. These spikes took a long time to equilibrate, and the digester volume would occasionally stabilize hours later, indicating up to 2-3 gallons of extra feed was added. Due to the limited volume of feed that was prepared and the observed volume of feed remaining in the mix tank after a feed cycle, the stabilized volume after stabilization could not have been always been completely accurate. This decreased confidence in the actual volume the digesters were fed and presented. It also caused wide fluctuations in the actual digester volume, so the volumes reported from many feed cycles were approximations based on the average value of the fluctuations. Drifting in the volumes over time after each feed created a challenge in determining the most appropriate time to record the actual volumes that were fed, which was typically done between 15 and 30 minutes after the feed cycle was completed.

Digester Feeding: Hand pump (1/6/2014 – 4/25/2014)

All steps involved with using the hand pump remained exactly the same as the diaphragm pump procedure with a few exceptions. Once the feed mixture was prepared, the hand pump assembly was set up. This required a hose between the outlet of the mix tank to the inlet of the hand pump and a hose between the outlet of the hand pump and the inlet of the digester. Once the digester feed was prepared using the method explained above, the diaphragm pump was used to direct the feed to the hand pump while still allowing for decent circulation of the feed in the mix tank. The hand pump would not allow the feed mixture to pass through unless it was manually pumped, so it was easier to control the feeding rate. The air existing in the hose between the hand pump and the digester inlet was displaced in the same manner as previously described, but the process was more effective with the hand pump since it was possible to displace the air by incrementally filling the hose with feed. Once the air was displaced, the all valves in the feed path were opened, and the feed was introduced to the digester in 0.25 gallon increments. Once the digester was fed, the valves were closed, and the mix tank, hoses and pumps were drained and cleaned. Cleaning did not interfere with the digester feeding process.

Observations and Procedural Comments:

- Greater control of feeding the digester allowed for increased confidence in the actual volume delivered to the digester (1 gallon for every 4 pumps).

- It became possible to manually stir the digester feed in the mix tank after every 1-2 gallons of feed delivered to the digester. As a result, both digesters received feed of improved consistency. Though improved, maintaining an evenly mixed feed without settling or oil separation was still difficult.
- Beginning 1/20/2014, the digester feeding process was adjusted so that the order in which the digesters were fed was alternated each feed day to counteract the uneven distribution of solids delivered to each digester.
- By increased hand mixing, settle solids were broken up and mixed often. The actual amount of food waste delivered to the digesters was closer to the planned amount than what was attained when feeding with the diaphragm pump.

Time Line

12/30/2013:

Severe foaming clogged the digester gas lines, the flow meter was plugged and the digesters were over flowing into the foam pots. The gas lines were opened in order to clean the lines and flow meter by flushing with water. The digesters continued to foam out of the gas line where it was disconnected.

12/30/2013 Foaming Event-Digester 1 Foam Pot

The foaming and cleaning process was not fully resolved until 1/3/2014.

1/6/2014:

Feeding the digesters with the hand pump permanently replaced using the diaphragm to feed the digesters. The diaphragm pump was still used for circulating and mixing the feed mixture, and it was used to pump the feed into the influent hose of the hand pump. The consistency of the food waste mixture when being prepared was not affected since the mixture depended solely on the characteristics of the food waste. The primary two differences between feeding methods were:

1) Better control over feeding the digesters with the hand pump increased the accuracy of reported volumes delivered to the digesters.

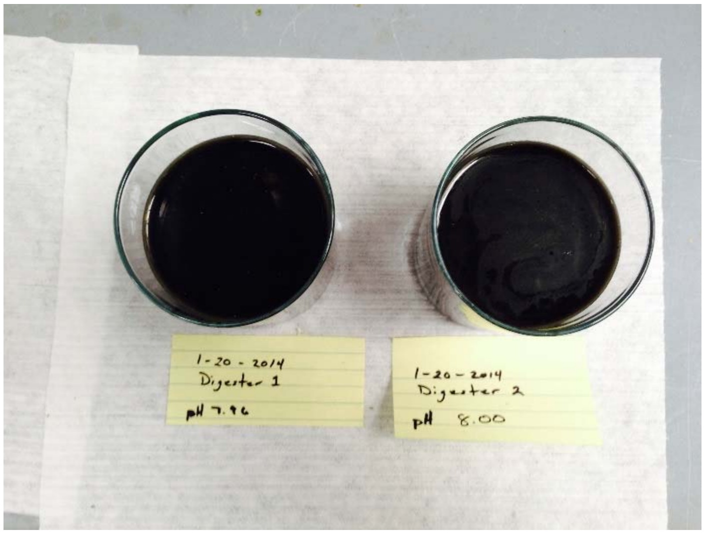
2) Better feeding control allowed the ability to mix the feed by hand in the mix tank more frequently and thoroughly, which improved the consistency of the feed added to each digesters and minimized the amount of food waste remaining in the mix tank after a feed cycle.

1/10/2014:

A thin oily film is present on the surface of the digester sludge when taking samples.

- Digester sludge samples were collected by filling a clean 5 gallon bucket with sludge using the feed inlet at the bottom of each digester. 1-2 gallons of sludge was collected to clear the path length of the feed inlet, the bucket was dumped, and then another 2-3 gallons of sludge was collected. A thin oily film existed at the surface of the sludge in the bucket. This was likely oil that still existed in the digester. The sludge in the bucket was thoroughly mixed by repetitively filling a measuring cup and dumping it back into the bucket in addition to swirling the sludge around with the cup. Once the sludge was adequately mixed, a sample was scooped up with the measuring cup and poured into the sample container. The mixing was carried out between every sample that was collected. When duplicate samples were collected, the process was repeated starting at clearing the digester inlet path length.
- The oil film in the bucket and measuring cup was thin and difficult to see. Samples were taken quickly after agitating the sludge in attempt to collect the sample while the oil remained suspended in the sludge.
- A film can be seen at the surface of the sludge sample on the right side in the picture below. The sample was not from 1/10, but it is easy to see in the picture.
- **The film has been referred to as an 'oil film', but it was only a descriptive observation since the film was not characterized.*

Digester sludge picture taken 1/20/2014. Digester 2 on the right side of the figure offers a good representation of the film that was observed during sample collection.



1/13/2014:

D1 and D2 sludge waste is beginning to become a little thicker. Small solid food pieces are present in the waste sludge for both digesters. Mostly rice and lettuce pieces, approximately 5-10 pieces/gallon. There is not as much oil on the surface of the sludge as 1/10/2014.

- There are not any pictures of sludge samples available between 12/20/2013 and 1/13/2014, but the solids will be observable in many pictures provided in this document.
- It is unknown why the samples from 1/13 appeared to contain less film.

1/14/2014:

Digester 1: Brown solid specs are suspended in the sludge waste. The sludge still appears to be a very dark brownish black, but it may be due to small solid brown specs and thicker consistency. Digester 2: Sludge has the same thickness as digester 1, but there are not any brown specs present. D2 sludge seems slightly lighter in color than D1 sludge.

1/14/2014 Digester 1&2 samples

1/14
D1
1/14
D2

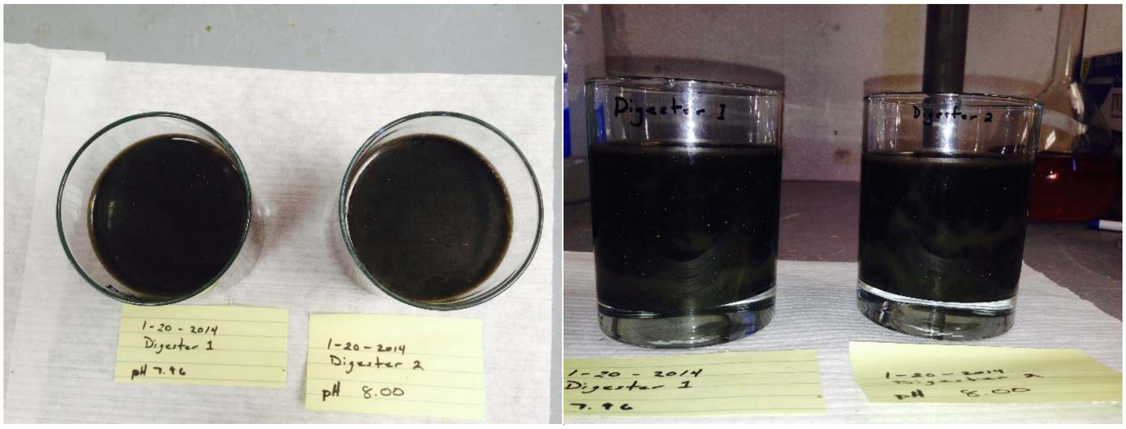
1/17/2014:

No noticeable changes in the consistency and color for the sludge in both digesters since last described on 1/14/2014.

- No picture available, sludge similar pictures above.

1/20/2014:

Digester 1: Brown solid specs are suspended in the sludge waste. The sludge still appears to be a very dark brownish black. It does not seem quite as thick as on 1/17. Digester 2: Now has brown solid specs and looks exactly like D1

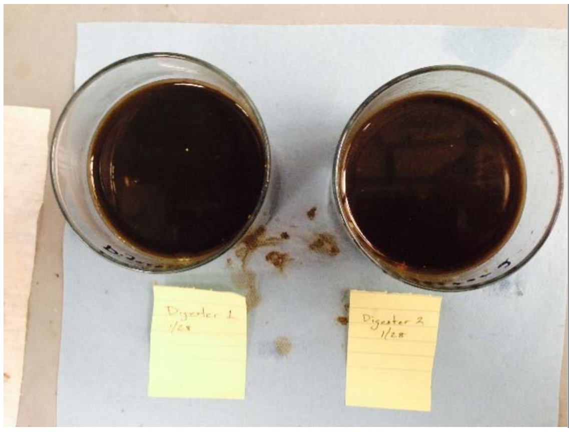

1-20-2014
Digester 1
pH 7.96
1-20-2014
Digester 2
pH 8.00
Digester 1
Digester 2
1-20-2014
Digester 1
7.96
1-20-2014
Digester 2
pH 8.00

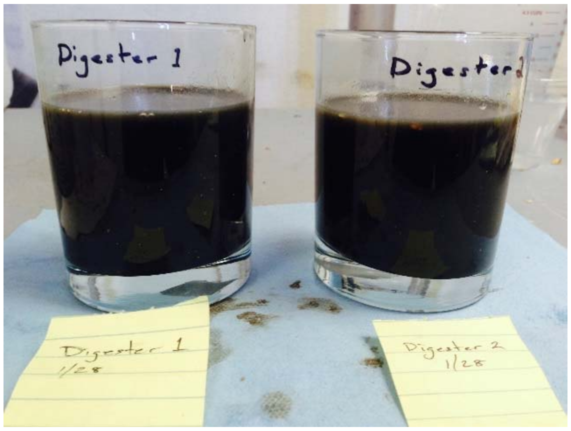
- This was the beginning of alternating the order in which the digesters were fed.

1/28/2014:

D1: Sludge looks a little darker than previous week. Still quite a few brown solid specs, though the sludge looks like it is getting better.

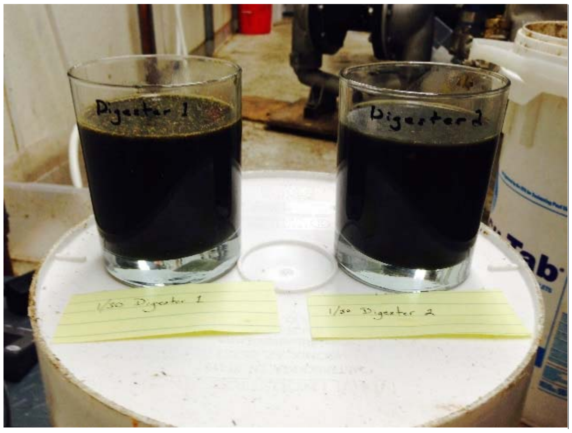
- Lighting conditions when pictures were taken varied, and the actual color of the sludge is not well represented in many of the pictures.

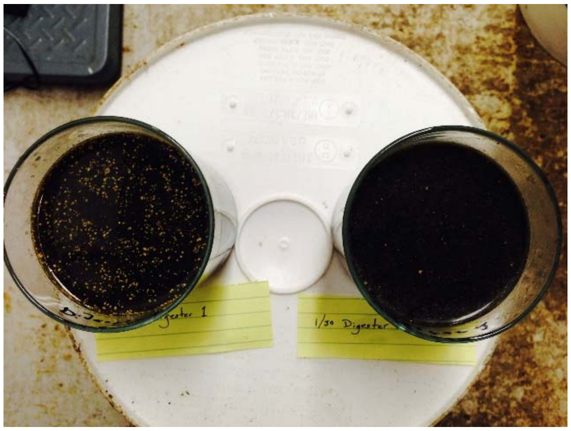

Digester 1
1/28
Digester 2
1/28


Digester 1
Digester2
Digester 1
1/28
Digester 2
1/28

1/30/2014:

D1:Sludge is becoming browner and there are more brown solid specs than any point in the past. The brown specs are about the size of a grain of sand on average. They have a solid texture, but can be smashed easily; similar to the texture of cooked rice. An oily film appears at the surface of the sludge as well. D2: Slude appears more brown, but not quite as much as D1. There isn't nearly as many brown specs as D1 (D2 has 5-10% of the number of brown specs that D1 has). There is more oil on the surface of the D2 sludge than on the D1 sludge.


Digester 1
Digester2
1/30 Digester 1
1/30 Digester 2


1/30 Digester

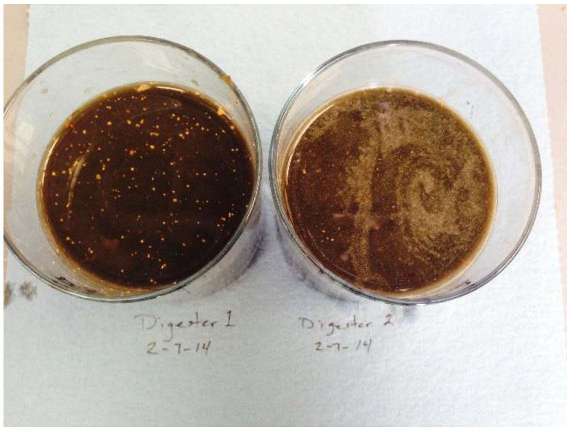
1/31/2014:

D1: Sludge looks better than the previous day. Less Brown solid specs. No noticable change in color or consistency. D2: No noticable changes.

- No picture available.

2/7/2014

1) D1: Brown Specs still present. Number of specs have decreased. No other noticable changes. D2: Tiny specs appeat in sludge. Unlike D1 the specs appear to be tiny slivers of paritcles. Increased oily film on sludge surface.

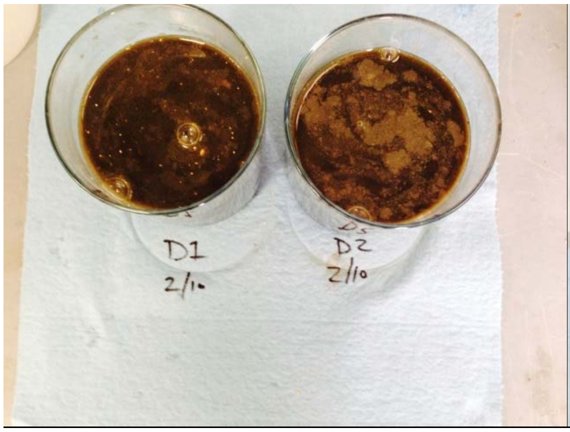


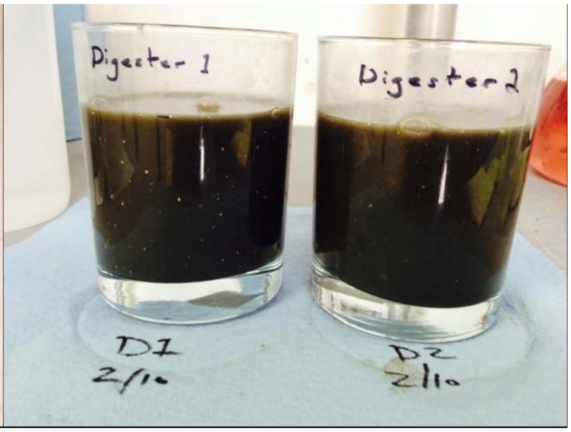
2) Digester Feed Mixture was difficult to keep thoroughly mixed during feeding. Food waste settled in mixture. Digester 2 was fed first and Digester 1 may have received more solids than digester 2 from settling.

- Food Collected from 2/5/2014 used for 2/7/2014 feed: Consisted entirely of eggs, which does not mix well. It forms clumps through entire process that must constantly be broken up and mixed.

2/10/2014:

No change in sludge description for both digesters, except D1 has less solid brown specs than on 2/7

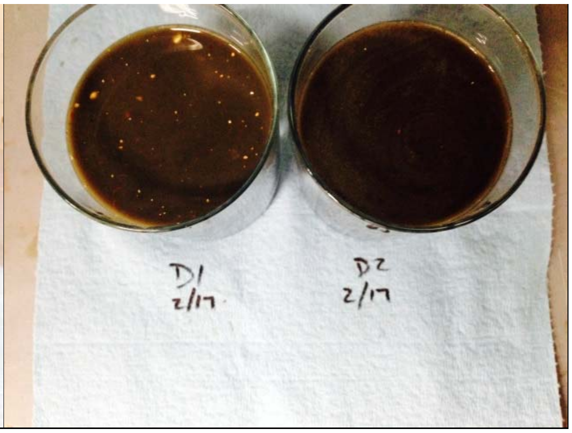

D1
2/10
D2
2/10


Digester 1
Digester 2
D1
2/10
D2
2/10

2/17/2014:

Digester waste sludge for both digesters has not changed in appearance or consistency since last description and seems to be stable, The amount of brown specs and oil film at the surface of the sludge fluctuates; increasing after feeding and decreasing slowly until next the feed.

Digester 1
Digester 2
D1
2/17
D2
2/17


D1
2/17
D2
2/17

3/10/2014:

- D1: Has small solid brown specs, becoming slightly lighter in color- Dark Brown. D2: Becoming slightly lighter in color-dark brown. Very small solid specs 1/4 the size of specs in D1 exist.
- Pictures from 3/10/14 are not recorded, pictures below were taken 3/11/2014.

3/11
D1
3/11
D2
Digester 1
Digester 2
3/11
D1
3/11
D2

4/9/2014:

Used grinder when making digester feed mixture. It did not work great, but food solids were much smaller, and the pump circulated better. There was less food settling as well.

- This was the only time a modification to the feeding process was made. The food waste did not have a large amount of trash, but had a few larger clumps to break up. The grinder was placed in the mix tank to see if it would effectively break up the food waste. The grinder circulated the mixture in the mix tank during feed preparation to supplement the circulation from the diaphragm pump, but the grinder did not have enough force to improve actual mixing speed. This did not significantly impact the feed mixture other than helping break up larger chunks of food more effectively than doing it by hand. The smaller solids did appear to distribute and remain suspended in the feed mixture better than what would have been done by hand. The grinder was removed from the mix tank before feeding the digesters. Removing the grinder was done such that it did not remove any of the feed mixture from the mix tank.
- The consistency of the feed mixture delivered to each digester may have been more consistent, but it was difficult to determine because there were not any unique observations or noticeable differences compared to a normal feed cycle other than the smaller solids.

Appendix J: Standard Operating Procedure for COD Analysis

Standard Operating Procedure for Digester Feed and Digester Sludge COD Analysis.

ESTCP Project ER-200933

Authored by: Pat Evans and Tyler Miller on 5/30/14

Approved by: Shawn Oliviera

Scope and Applicability

This SOP details procedures and safety considerations for analyzing the Chemical Oxygen Demand (COD) of Digester Feed and Digester Sludge samples collected at the pilot-scale anaerobic digestion facility at the US Air Force Academy (ESTCP). The procedure is based on use of the Hach COD test kit. Instructions for the Hach test kit should also be followed. The below procedure covers all steps including sample preparation, reaction, analysis and calculations. The procedure also addresses specific safety hazards that will be encountered upon executing various steps in the process such as safe lab practices, handling hazardous chemicals and being aware of hot surfaces.

Safety/Hazards

Chemical Oxygen Demand vials contain potentially dangerous chemicals including potassium dichromate, sulfuric acid and mercury. The vials must be handled very carefully and held over the bench and close to the bench surface at all times. Potassium dichromate is a strong oxidizer, causing an exothermic reaction upon the addition of any sample containing organic matter. This causes the vial to become extremely hot almost immediately when mixing the sample in the vial. Once a sample is added to a vial, screw the cap back on quickly and tightly, and then gently mix the contents of the vial. Do not touch the vial except for the cap while reacting. The COD solution is composed of 50% sulfuric acid and is damaging to the skin and eyes. Mercury is a very toxic heavy metal and is also damaging to the body and the environment. Always wear gloves, safety glasses and have access to an eyewash station. An acid spill kit can be used in the event a COD vial is spilled or broken and can be disposed in a designated, marked COD waste bucket.

The COD sample preparation in this procedure involves using a blender. Make sure the blender is always on the lowest speed before turning it on to prevent splashing. Splashing can also occur when the samples and DI water are poured into the blender pitchers. Aliquots of each sample will be taken directly from the blender pitcher while the blender blade is spinning. The pipette tip needs to be held closely to the wall of the blender pitcher when drawing the sample and hands should not be placed inside the pitcher. It is important to keep the pitchers clean in between each sample batch and get disinfected at the end of every test. The digester feed and digester sludge samples may contain hydrogen sulfide, dissolved methane, and potentially pathogenic bacteria. Precautions must be taken to avoid dermal and eye contact as well as ingestion of the samples. Personal protective equipment to be used shall include safety glasses, gloves and a 4-gas meter. These items are discussed further in the Health and Safety Plan (HASP). Specific use of these items is discussed in the procedures below.

Equipment

1. VitaMix Blender
2. Blender pitchers (3) w/ lids, Labeled: Sample Blend (SB), Dilution 1 (D1), Dilution 2 (D2)
3. Balance (Make/Model)
4. Hach COD reactor
5. DR 900 Colorimeter COD Vials 50-1500 mg/L Range- 2 per sample
6. 5 ml Eppendorf pipette w/ pipette tips
7. 1000 mg/L COD Standard
8. COD vial cooling rack.
9. Deionized (DI) water
10. Sink w/ potable water
11. Kim Wipes
12. Paper Towels/Rags
13. Alconox/Water Mixture
14. Sponge Scrubber
15. PPE described in HASP
16. Acid spill kit
17. COD waste container

Procedure for COD analysis of Digester Feed Samples

1. Remove sample from the refrigerator and let thaw if necessary
2. Once thawed, carefully pour the sample into the pitcher labeled sample blend. If the sample is still frozen, partially frozen or is poured into the pitcher too quickly, splashing will occur. *Important!*- Secure the lid tightly onto the pitcher before blending to prevent splashing. During this step and the following steps, conduct atmospheric monitoring using the 4-gas meter.
3. Blend the sample vigorously. Make sure the blender is on the variable setting and start on the lowest speed. Slowly increase the speed of the blender until it is at its highest point and then switch the blend setting to high. Blend the sample for approximately 30 seconds on high or until it the sample is thoroughly homogenized. Bring the blending speed back down to low (2-3).
4. While the sample is still mixing, tare the pitcher labeled Dilution 1. Stop the blender, remove the lid, and pour 25 g of the sample into the D1 Pitcher. This should be done quickly to minimize sample separation, but carefully to prevent splashing. Dilute the sample to 250 g using DI water. Record the actual mass of the sample added and the total mass of the diluted mixture as M1 and M2, respectively.
5. Begin blending the D1 Pitcher on a low setting (2-3). During this time, tare the pitcher labeled Dilution 2 on the balance. Stop the blender and quickly pour 20 g of the first dilution into the D2 Pitcher. Dilute to 500 g using DI water. Record the actual mass of the 1st diluted sample added

and the total mass of the diluted mixture M3 and M4, respectively. Begin blending D2 on the lowest setting

6. Prepare 2 COD vials by labeling them with the sample collection date and sample type (i.e. DF for Digester Feed and DS for digester sludge). Remove the caps and place them in the cooling rack.
7. Adjust the 5 mL pipette to draw 2 ml of solution and connect a pipette tip. While blending on the lowest setting, place the pipette tip into the D2 Pitcher along one of the walls of the pitcher. Rinse the pipette 3 times by drawing and dispensing the diluted solution in the blender, being careful not to hit the blade. Do not place your hand in the blender vessel.
8. Once the pipette tip has been rinsed, draw 2 ml of the diluted sample and dispense it into a COD vial. Hold the COD vial at a 45 deg. angle and slowly dispense the sample down the wall of the vial. Try not to touch the pipette tip to the vial. If this occurs, wipe the tip with a kim wipe.
9. Screw the cap tightly back onto the COD vial and gently invert several times to mix the sample into the vial solution. Set in the vial cooling rack until all samples are prepped and ready to be placed into the reactor.
10. Repeat steps 7-9 for the second vial and then dispose the pipette tip.
11. Empty, rinse and thoroughly scrub all three pitchers using the Alconox solution and scrubber. Rinse each pitcher with DI water and wipe dry. Pitchers need to be cleaned and dried after every sample is prepared.
12. Fill one COD vial with 2 ml of the DI water used for diluting the samples. This will serve as a sample blank.
13. Fill two COD vials with 2 ml of 1000 mg/L COD standard in each vial for a sample reference.
14. Turn the reactor on and set for COD. It will take about 15 min. to heat up to temperature (150°C). Once the reactor has reached temperature, open the shield, and place all of the sample vials into the vial slots. Invert each vial 3-4 times before putting in the reactor. Close the reactor shield and press start. The reaction time is two hours. Once 2 hours has passed, the reactor automatically begins cooling. Do not take the vials out of the reactor until the temperature has cooled to at least 120 °C. Take the vials out of the reactor touching only the cap and place them in the vial cooling rack until they reach room temperature.
15. Use the Hach colorimeter to measure the samples. Change the colorimeter program to measure 50-1500 mg/L COD. Place the sample blank vial in the colorimeter and press zero.
16. Read each 1000 mg/L standard. Record the values.
17. Read each sample vial. Vials may be gently wiped clean with a Kim wipe before placing them into the colorimeter if there are any noticeable marks or particles that could interfere with the measurement.
18. Once finished, put COD vials in the designated hazardous waste bucket and clean up area. Discard digester feed samples in the sink and wash out sample containers with soap and water.

Procedure for COD Analysis of Digester Sludge Samples

1. Digester Sludge COD analysis is done using the same method for Digester Feed COD analysis with only one modification: Digester Sludge is only diluted 1 time.

2. Use the Dilution 2 pitcher and weigh 5 g of Digester Sludge. Dilute to 500 g with DI water. Record the actual mass of the digester sludge (M1) and the total mass of the dilution (M2).
3. Blend on the lowest setting, and use the pipette to draw 2 ml of the diluted sample.
4. Dispense 2 ml into the COD vial and invert gently several times before placing it in the vial cooling rack where it will remain until all samples are ready for the reactor.
5. Repeat Steps 3 & 4 for a second COD vial for each Digester Sludge sample.
6. Follow steps 11-20 in the Digester Feed COD analysis procedure.

Calculations

Digester Feed:

Multiply the measured COD value by the dilution factors (M1, M2, M3, M4) to calculate the COD of the original sample (equation 1).

$$\left[Measured\ COD\ \left(\frac{mg}{L}\right)\right] * \frac{M2}{M1} * \frac{M4}{M3} = \left[Digester\ Feed\ COD\ \left(\frac{mg}{L}\right)\right] \qquad (1)$$

Digester Sludge:

Calculating COD for digester sludge samples is shown in equation 2.

$$\left[Measured\ COD\ \left(\frac{mg}{L}\right)\right] * \frac{M2}{M1} = \left[Digester\ Sludge\ COD\ \left(\frac{mg}{L}\right)\right] \qquad (2)$$

Appendix K: Quality Assurance Summary

Quality Assurance Summary

Deviations from the QAPP

As this technology demonstration plan was a research project, the analysis plan and schedule changed was varied based on the preliminary results and information necessary for decision factors. Several deviations were made from the sample schedule and analytical methods outlined in the Technology Demonstration Plan, both increasing and decreasing the frequency of sampling.

Due to the nature of digester samples matrix, metals analysis were performed under United States Environmental Protection Agency (USEPA) methods 6010C (cobalt, copper, iron, manganese, zinc) and USEPA 6020A (molybdenum, nickel, selenium). Results were reported in mg/L due to the liquid matrix.

Evaluation of Data Quality

Data evaluation was performed by an independent quality assurance reviewer for completeness and compliance with the Technology Demonstration Plan. Activities performed by both CDM Smith and subcontracted laboratories (ALS Environmental, Simi Valley, CA; ALS Environmental, Kelso, WA) were compared against the goals and procedures set forth in this document.

Chemical data quality indicators (DQIs) are quantitative and qualitative goals and limits established for laboratory data that provide the means by which data reviewers can assess whether the goals of an investigation have been met. Quality Assurance (QA) indicators for measuring the study data are expressed in terms of precision, accuracy, representativeness, comparability, completeness, and sensitivity (PARCCS). The QA indicators provide a mechanism for ongoing control and evaluation of data quality throughout the project. The treatability QA/QC was assessed by internal QC checks, calibration checks, method blanks, surrogate spikes, adherence to holding times, and laboratory duplicates in accordance with the project plan. Both the pilot and the subcontracted laboratory data are assessed here.

Precision

The precision of a measurement is an expression of mutual agreement among individual measurements taken under prescribed similar conditions. Precision is quantitative and most often expressed in terms of relative percent difference (RPD). Precision of reported results is a function of inherent field-related variability plus laboratory analytical variability. Field duplicates were collected at a frequency of 5% of the total samples. For sample pairs where the concentration of the analyte is greater than 10x the PQL limit, the precision goal is <35%. For sample pairs where one or both of the samples are less than 10x the PQL limit, the precision goal is <50%. Sample pairs where one or both values were less than the PQL did not have RPDs calculated. All field samples met the precision goals set forth in the QAPP.

The contribution of laboratory-related sources to overall variability was measured by calculating the RPD between the matrix spike/matrix spike duplicate results, laboratory duplicate results, and laboratory control sample/control sample duplicate results. The subcontracted laboratory completed replicate analysis in accordance with the method and laboratory SOPs. In general, laboratory analyses met the precision goals, however several samples (Table 1) were outside of the laboratory established control limit (20%) but below the project precision goal of 35%.

Variability was attributed to the heterogeneity of the digester samples, and standard laboratory mixing techniques were not sufficient to homogenize the samples. This was anticipated based on the nature of anaerobic digestion sludge, thus the project precision goals were broader than the typical laboratory standards and thus meet the precision goals of the project.

Table 1. Precision excursions.

Sample Date	Parameter	Sample Name
1/29/2014	Copper	Undiluted Food Waste
2/12/2014	Volatile and Total suspended solids	Digester 1, Digester 2
2/12/2014	Molybdenum	Undiluted Food Waste
2/19/2014	Ash, Copper	Undiluted Food Waste
3/13/2014	Total suspended solids	Digester 2
3/27/2014	Total suspended solids	Digester 1
4/2/2014	Manganese	Undiluted Food Waste

Accuracy

Accuracy is defined as the degree of agreement between a measurement and an accepted reference or true value and is a measure of bias in a system. Accuracy is quantitative and usually expressed as the percent recovery (%R) of a sample result. Accuracy DQIs are calibrations and the recoveries of spiked analytes in LCS, MS, and surrogate compounds. Other indicators of analytical accuracy include the use of the EPA accepted analytical methods, evaluation of blank contamination, acceptable instrument calibrations, and adherence to the required sample preservation and holding times and chain-of custody procedures. The accuracy goals for method defined surrogates, laboratory control samples, and calibration standards are defined by the laboratory's quality assurance plan and standard operating procedure. There were several samples where the concentration of analytes significantly exceeded the matrix spike concentrations preventing accurate spike recoveries or where the digester matrix interfered with spiked recoveries. Table 2 documents summarizes the sample excursions. No excursions were observed in the gas samples or field analyses. Propionic acid results were inconsistent and the HPLC chromatograms indicated peak interference with an unidentified compound. Therefore, propionic acid data are considered suspect. Nevertheless, the contract laboratory (ALS Environmental) applied its SOPs to accept or reject data. The accepted data were used in calculation of ratios of VFA/TALK. All other indicators were acceptable other than the exceptions noted below.

Table 2. Accuracy excursions.

Sample Collection Date	Parameter	Sample Name	Notes
1/30/2014	Iron, molybdenum	Digester 1	MS/MSD Not Applicable: Concentration of sample was significantly higher than the added spike concentration preventing accurate recovery.
1/30/2014	Acetic acid	Digester 1	
2/12/2014	Iron	Digester 1	
2/12/2014	Acetic acid, formic acid	Digester 1	
2/20/2014	Iron, molybdenum	Digester 1	
2/27/2014	Molybdenum, nickel	Digester 1	
2/27/2014	Acetic acid	Digester 2	
3/5/2014	Molybdenum, acetic acid	Digester 1	
4/3/2014	Molybdenum	Digester 1	
2/12/2014	Lactic acid	Digester 1	MS/MSD Not Applicable: Matrix interference in the parent sample prevented accurate recovery of the spiked compound.
2/27/2014	Lactic acid, butyric acid, isovaleric acid, valeric acid	Digester 2	
3/13/2014	Isocaproic acid, butyric acid, propionic acid	Digester 1	
1/30/2014	Nickel	Digester 1	MS/MSD outside range: Matrix spike recovery was outside of the control criteria, suggesting a potential low bias in the sample results.
2/12/2014	Propionic acid, valeric acid	Digester 1	MS/MSD outside range: Matrix spike recovery was outside of the control criteria, suggesting results are potentially biased high.
3/27/2014	Lactic acid, isovaleric acid	Digester 1	

Field and laboratory calibrations were performed in accordance with manufacturers' recommendations and laboratory procedures. Field calibrations were documented in calibration logs. Method blanks were evaluated in the laboratory analyses, no detections exceeded the laboratory quality standards.

Completeness

Completeness is a measure of the amount of usable data that are obtained compared to the amount that was expected to be obtained during project planning. Data that were evaluated and needed no qualification, or were qualified as estimated "J" or "UJ," are considered usable. Completeness is assessed in terms of both sampling and analytical completeness. The completeness requirement, as stated in the QAPP and the demonstration plan, was 90 percent. Analysis were performed at a varied frequency than outlined demonstration plan, with some schedule variations due to the pilot schedule. The results were useable for the intended purpose with the exception of the above temperature liquid shipments and sulfur samples that exceeded the sample hold time (refer to Sensitivity, Representativeness, and Comparability section below for further details). Of the samples analyzed, there was a greater than 98% useable data.

Sensitivity, Representativeness and Comparability

Sensitivity is related to the ability to compare analytical results with project-specific levels of interest, such as regulatory limits. Analytical practical quantitation limits (PQLs) for the various sample analytes were sufficient for the purposes of the demonstration. Laboratory and field analyses methods used for this project were performed in accordance with the demonstration plan, and thus sufficient for the screening and definitive data collected to support the project decisions. ALS Laboratories reported results under the reporting limit but at or above the method detection limit.

Field samples collected and analyzed immediately on site. Acquisition, collection, and handling of samples was performed using appropriate sample preservatives per the analytical methods to ensure representativeness and comparability of results with other analyses that are performed in a similar manner. In addition, multiple lines of evidence were used to ensure that the data was sufficient to meet the decision inputs for this study.

There were a few analyses over the course of the demonstration that exceeded the laboratory hold times. The parameters and impact are summarized below:

- One TS/VS sample (Digester 2, 02/12/2014) that had to be reanalyzed due to a broken crucible. The laboratory hold time was exceeded in the re-analysis. The solids content may not be representative of the digester conditions.
- Ten liquid/solid sample shipments arrived at ALS laboratories below the target temperature range of 4±2°C, ranging from 0.6 to 1.9 °C. This is not expected to impact the data quality for the targeted analysis (VFAs, TS/VS, metals).
- The cooler from the 11/26/13, 9/19/13, and 4/10/14 sampling events were delayed during shipment, and were above the target temperatures upon arrival at the ALS Laboratory (15.2, 14.3, and 8.2 °C, respectively). Increased temperature may not have been sufficient to impede biological activity, thus solids and metals samples may be underestimated. Temperature highly impacts the biological conversion of fatty acids in anaerobic digestion sludge, thus samples from this shipment are not considered representative of the digester concentrations and should be flagged accordingly.
- One cooler from the 10/02/2013 sample event arrived on time at the ALS Laboratory at 14.0°C, above the preservation target. Increased temperature may not have been sufficient to impede biological activity, thus solids and metals samples may be underestimated. Temperature highly impacts the biological conversion of fatty acids in anaerobic digestion sludge. This sample was from Phase 1 which was not used in the data analysis.
- Two shipments of sulfur samples were delayed in shipping and arrived at the ALS laboratory past the recommended hold times. The sulfur content in the Biogas and Sweetened Biogas samples from 04/03/14 and 07/01/14 may be underestimated due to loss from the sample containers.

- The ALS Laboratory exceeded the sample hold time on two sulfur samples, 07/23/14 Biogas and the 10:57 Post-VSA Biogas sample from 07/31/14. The sulfur content may be underestimated in these samples.
- The VSA sample collected on day 47 of Phase IV were not included in the data analysis because of contamination with desorption gas.

Conclusions

The data for the pilot study was reviewed, and all data in the data set, with the exception of the noted hold time exceedances noted above, are considered useable. Overall, the data were determined to be of acceptable quality for meeting the Data Quality Objectives and are representative of the reactor conditions at the time of collection.

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Appendix L: Engineering Calculations for Energy Efficiency

Engergy Demand in 1 MG Digester

$$\text{Mixing} := \frac{\frac{1\cdot \text{Mgal}}{40\cdot \text{min}}\cdot 8.34\cdot \frac{\text{lbf}}{\text{gal}}\cdot .1\cdot \text{ft}}{80\%\cdot 93\%} = 0.633\cdot \text{kW}$$

Use 40 min turnover time, 0.1 ft headloss, no static head, 80% pump efficiency, 93% motor efficiency

$$\text{Recirc}_{\text{pump}} := \frac{500\cdot \text{gpm}\cdot 40\cdot \text{ft}\cdot 8.34\cdot \frac{\text{lbf}}{\text{gal}}}{65\%\cdot 93\%} = 6.235\cdot \text{kW}$$

Use sludge recirc pump at 500 gpm 40ft head (including HEX loss), no static head, 65% pump efficiency, 93% motor efficiency

$$\text{water}_{\text{pump}} := \frac{500\cdot \text{gpm}\cdot 25\cdot \text{ft}\cdot 8.34\cdot \frac{\text{lbf}}{\text{gal}}}{80\%\cdot 93\%} = 3.166\cdot \text{kW}$$

Use water recirc pump at 500 gpm, 25ft head (including HEX loss), no static head, 80% pump efficiency, 93% motor efficiency

$$\text{feed}_{\text{pump}} := \frac{\frac{1\cdot \text{Mgal}}{40\cdot \text{day}}\cdot 40\cdot \text{psi}}{50\%\cdot 93\%} = 0.65\cdot \text{kW}$$

Use feed pump at 40 day SRT, 40 psi discharge pressure, 50% pump efficiency, 93% motor efficiency

withdrawal by gravity - no power

Boiler secondary and hot water loops - not included as part of other plant systems

Energy for CNG

$$Q := 120000\cdot \frac{\text{mg}}{\text{L}}\cdot \frac{1\cdot \text{Mgal}}{40\cdot \text{day}}\cdot 377\cdot \frac{\text{L}}{\text{kg}} = 0.05\,\frac{\text{m}^3}{\text{s}}$$

$$P_{\text{compr}} := \frac{1\cdot \text{atm}\cdot Q\cdot \ln\left(\frac{3600\cdot \text{psi}}{1\cdot \text{atm}}\right)}{55\%\cdot 93\%} = 53.999\cdot \text{kW}$$

Assumes water cooling

$$P_{\text{water.cooling}} := 25\cdot \text{hp}$$

(assumed to include pumping energy and radiator energy)

$$P_{\text{water.scrubber.pump}} := \frac{50\cdot \text{gpm}\cdot 6.5\cdot \text{bar}}{80\%\cdot 93\%} = 2.756\cdot \text{kW}$$

Assumes CO2 removal with water scrubber at 6.5 bar operating pressure

$$\text{CNG}_{\text{energy}} := P_{\text{compr}} + P_{\text{water.cooling}} + P_{\text{water.scrubber.pump}} = 75.397\cdot \text{kW}$$

$$\text{Boiler}_{\text{heating}} := \frac{\frac{1\cdot\text{Mgal}}{40\cdot\text{day}}\cdot 8.34\cdot\frac{\text{lb}}{\text{gal}}\cdot 1\cdot\frac{\text{BTU}}{\text{lb}\cdot\text{R}}\cdot(95-60)\cdot\text{R}}{94\%}\cdot 115\% = 109.02\cdot\text{kW}$$

Assumes 40 day SRT, 60 degree raw FW temp, 95 degree operational temp, 94% boiler efficiency, 15% of heating energy for tank shell losses

$$\text{para}_{\text{elec}} := \text{Mixing} + \text{Recirc}_{\text{pump}} + \text{water}_{\text{pump}} + \text{feed}_{\text{pump}} + \text{CNG}_{\text{energy}} = 86.082\cdot\text{kW}$$

$$\text{para}_{\text{total}} := \text{para}_{\text{elec}} + \text{Boiler}_{\text{heating}} = 195.102\cdot\text{kW}$$

$$\text{Phase3}_{\text{In}} := 120000\cdot\frac{\text{mg}}{\text{L}}\cdot\frac{1\cdot\text{Mgal}}{40\cdot\text{day}}\cdot 1.47\cdot 10^{7}\cdot\frac{\text{J}}{\text{kg}} = 1.932\times 10^{3}\cdot\text{kW}$$

1.47 x 10^7 J/kg is for methane-COD?

$$\text{Phase3}_{\text{conver}} := 73\%\cdot\text{Phase3}_{\text{In}} = 1.41\times 10^{3}\cdot\text{kW}$$

73% is energy conversion not including parasitic demands

$$\text{Phase3}_{\text{adjust.elec}} := \text{Phase3}_{\text{conver}} - \text{para}_{\text{elec}}$$

$$\text{Phase3}_{\text{adjust.total}} := \text{Phase3}_{\text{conver}} - \text{para}_{\text{total}}$$

$$\text{Adj}_{\text{eff.elec}} := \frac{\text{Phase3}_{\text{adjust.elec}}}{\text{Phase3}_{\text{In}}} = 68.545\cdot\%$$

$$\text{Adj}_{\text{eff.total}} := \frac{\text{Phase3}_{\text{adjust.total}}}{\text{Phase3}_{\text{In}}} = 62.902\cdot\%$$

This is the result taking into account parasitic demands. Includes electrical and heating.

Appendix M: ADM1 Modeling of Field Demonstration

ESTCP food digester modeling study summary

Urv Patel, EIT

July 20, 2015

Introduction

The ADM1 model MATHCAD set up by Donnie Stallman from the earlier study on bench scale digesters treating U.S. Air Force Academy (USAFA) food waste was investigated for its ability to predict the measured performance of the pilot scale anaerobic digesters at the USAFA for the period from December 2013 to April 2014. The model investigation work was started in February 2015 by Urv Patel with i issues regarding various approaches to the model inputs and model coefficient assumptions and the initial conditions using the municipal digester seed sludge. Problems were encountered on the choice of the influent feed parameter, as the reported VS and COD data were not in agreement; the COD/VS ratio was too low. The purpose of this summary memo is to document the reason for electing to use the influent COD data for the model application and to provide an analysis of the model simulation using the influent COD data.

Prior to the model simulations using COD preliminary, results indicated difficulty fitting the dramatic decrease in digester VSS concentration after late February 2014. It seemed that the fast and slow fractions used in Stallman's model simulations were not providing reasonable model fits to these observations. Analysis of the remaining solids in the digester model output showed that in order to obtain a fit closer to the observed digester VSS data, it was necessary to have little inert VSS and digestable VSS remaining. The fat plus protein COD faction was also very high for this application (averaged 78%). For this reasons it was decided to use one hydrolysis rate for all the feed as is done in the ADM1 model. A hydrolysis rate of 1.5 d^{-1} was used and the results of this simulation are presented here.

The model fitting success was evaluated by comparing the model predicted versus measured data for the following parameters over the course of the digester Dec 2013 to April 2014 operation: 1) total methane production for each feed interval, 2) digester VSS concentration, and 3) digester ammonia-N and alkalinity concentrations. In addition the model versus the measured methane production rates after feeding profile was compared.

Determining initial conditions for ESTCP food digester simulations

The seed sludge used in the food waste digester was taken from an adjacent municipal wastewater treatment plant sludge digester. Thus, all the influent parameters determined by D. Stallman for municipal digester feed were used. The step by step derivation of the initial condition is as follows:

1. Change all the influent feed characteristics table to the one given below

ADM1 composition and kinetic parameters used to simulate municipal sludge digestion from Straub (2008)

Parameter	Value	Units
$f_{sI,xc}$	0.01	gS_I/gX_c
$f_{xI,xc}$	0.23	gX_I/gX_c
$f_{ch,xc}$	0.20	gX_{ch}/gX_c
$f_{pr,xc}$	0.40	gX_{pr}/gX_c
$f_{li,xc}$	0.16	gX_{li}/gX_c
$f_{rh,xc}$	0.33	gX_{rh}/gX_c
$f_{sh,xc}$	0.43	gX_{sh}/gX_c
$k_{hyd,rh}$	2.2	d^{-1}
$k_{hyd,sh}$	0.25	d^{-1}

2. The flowrate was made continuous (Q) and tank volume was changed to give a 30 day SRT when divided by flowrate
3. The temperature was changed to 36 Celsius
4. All other parameters were same as in D. Stallman
5. The simulation was ran for 200 day period to get a steady state
6. The digester VSS, Ammonia was compared with measured initial values of the food waste digester
7. The influent COD and percent protein was changed until the VSS and the Ammonia were very close to the measured initial conditions

The final initial conditions are tabulated in Appendix-3

SECTION-1

Model application using the influent measured VS concentration data

Assumptions and Inputs

1. The influent VS concentration data was converted to influent COD by using the proximate analyses results for protein (P), lipids (L), and carbs (C) to get their VS fractions and then using factors of COD/VS for these general substrates to get the feed total COD and COD of P, L, and C

2. The hydrolysis rate coefficients and fraction of slowly and rapidly biodegradable solids used were from D. Stallman thesis based on the bench-scale digester calibrations

Coefficient	Fast hydrolysis	Slow hydrolysis
Fraction	0.45	0.55
Hydrolysis rate coefficient, d^{-1}	1.50	0.15

3. Used the same coefficient values as per Stallman fermentation and Methanogenesis equations

4. Stallman's moles N/g protein COD coefficient of 0.009414 was changed to 0.008403 based on literature reference

5. 15% of biomass is assumed as inert

Poor model fit with VS influent data (See Appendix-1 for plots)

1. The methane production predicted by the model was 2 times the measured values.

2. The VSS predicted by the model was very high and never near the measured VSS.

3. The ammonia and alkalinity concentrations predicted by the model were 25-30 % greater than the measured values. We considered the measured ammonia and alkalinity data to be very reliable because they agreed with each other well based on the fact that most of the alkalinity in the digesters had to be derived from deamination of protein to ammonia.

Conclusion and next step

Thus, it was concluded that influent VS data is not reliable and over predicts all the parameters. Now, in SECTION-2 we show the model simulation results using measured COD data.

SECTION-2

Model application using influent measured COD data and coefficient determined by Stallman, et al

Assumptions and Inputs

1. The influent COD concentration data was used as model input

2. Measured proximate analysis was used after some unit conversions (elaborated in Appendix-B)

3. Percentage influent inert was assumed to be 1% in concentration

4. The hydrolysis rate coefficients and fraction of slowly and rapidly biodegradable solids used were from D. Stallman thesis based on the bench-scale digester calibrations

Coefficient	Fast hydrolysis	Slow hydrolysis
Fraction	0.45	0.55
Hydrolysis rate coefficient, d^{-1}	1.50	0.15

5. All other fermentation, methanogenesis etc. were used as per D.Stallman

6. Stallman's moles N/g protein COD coefficient of 0.009414 remained the same

Poor model fit with influent COD data and using coefficient determined by Stallman, et al.

(See Appendix-2 for plots)

1. The methane production predicted by the model has a poor match due to the slowly and rapidly hydrolysable fractions of solids

2. The VSS predicted by the model was very high and never near the measured VSS, because less fraction of the influent was digested resulting in higher undigested solids

3. The ammonia and alkalinity concentrations predicted by the model were close to measured values

Conclusion and next step

From this section, it is clear that using influent COD gives us reasonable fit in case Ammonia and Alkalinity but the predicted VSS was much higher. The primary reason for the higher VSS can be hypothesized to be the high fraction of undigested solids (shown in fig-XX, Appendix-2); this leaves us to the conclusion of using a higher hydrolysis rate of increasing the rapidly hydrolysable fraction of influent COD. After several iteration a particular set of coefficients were determined to have most reasonable fit, these coefficients and the final iteration using them is discussed in detailed.

SECTION-3

Model Simulation using the measured influent COD concentration data and coefficients determined through model iterations

Assumptions and Inputs

1. The influent COD concentration data was used as model input

2. Measured proximate analysis was used after some unit conversions (elaborated in Appendix-B)

3. Percentage influent inert was assumed to be 1% in concentration

4. Hydrolysis rate coefficient for both slowly and rapidly degradable fraction was 1.5 day^{-1}

5. Decay rate was changed from 0.02 (D.Stallman thesis) to 0.04 day^{-1} to lower the VSS in late February, 2014

6. Stallman's moles N/g protein COD coefficient of 0.009414 was changed to 0.008403 based on literature reference

7. Other coefficients were same as the model simulation using VS data (described in SECTION-1)

Model simulation predictions and comparisons with measured data

Figure 8 Predicted VSS in the digester (total, inert, undigested, biomass)

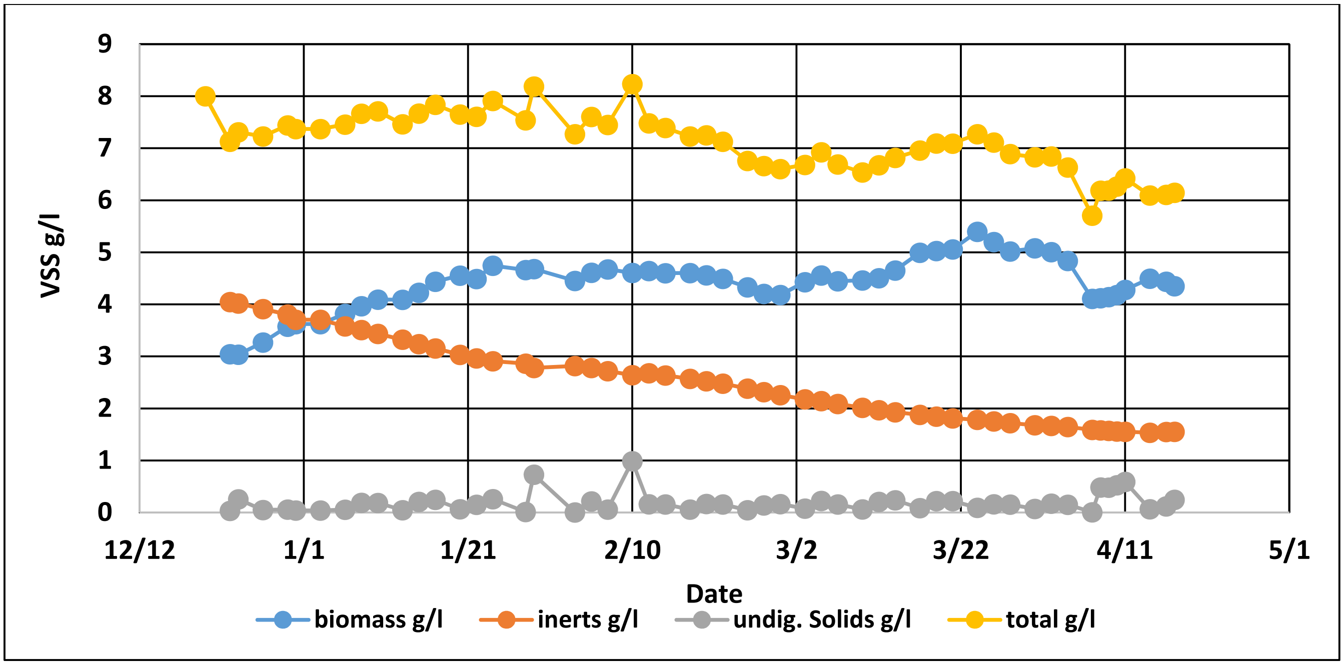
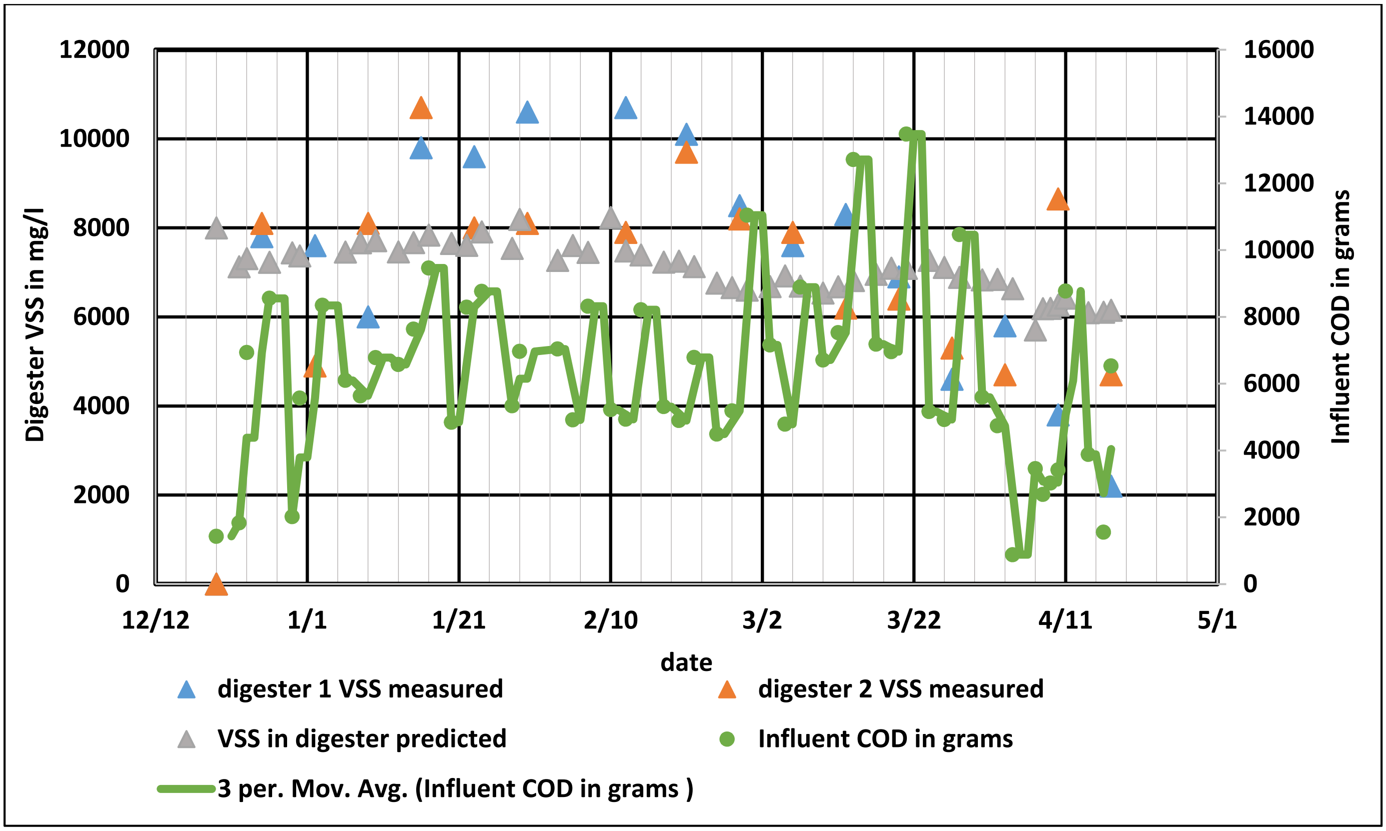


Fig-1 shows that due to the high hydrolysis rate used almost all the solids are digested (grey). The biomass is maintained between 3-5 g/l. The total predicted digester VSS concentration is compared to the measured digester VSS concentration in Fig-2.

Figure 2 VSS in digester predicted and measured; influent COD



*(3 per. Mov. Avg. is 3 Period Moving Average)

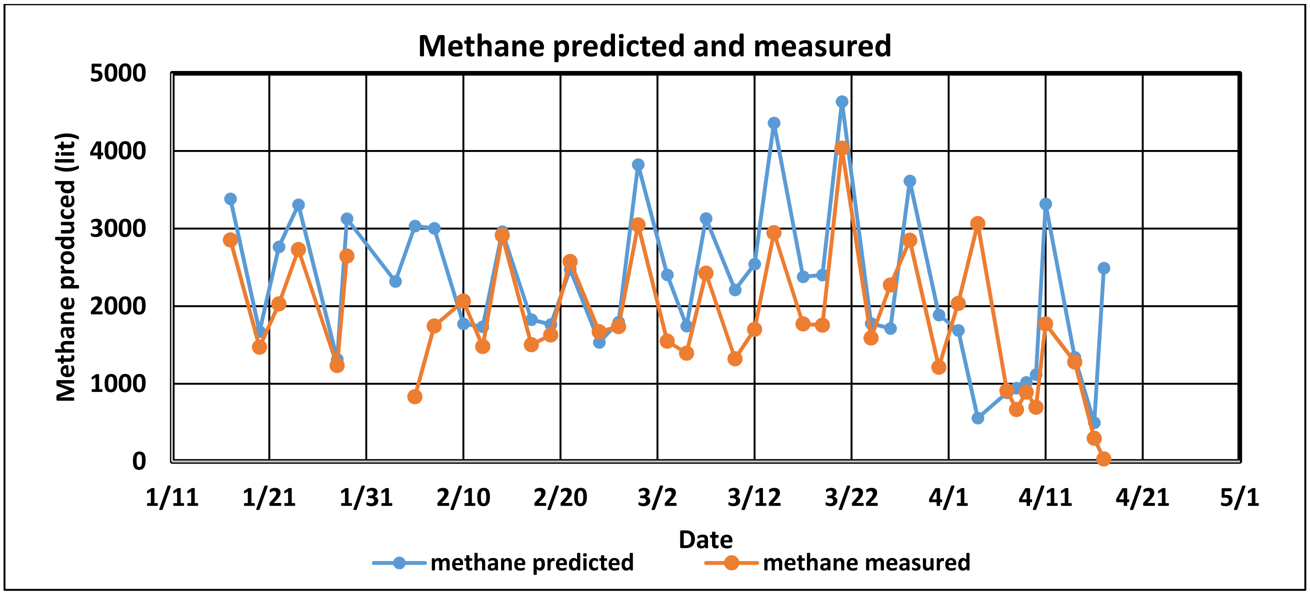
Observations from Fig-2

- The predicted digester VSS concentration (grey) is not able to match the measured digester VSS concentration trend in the digester 1 and 2 (blue and orange).
- The measured VSS in the digester 1 and 2 shows some drastic change in the VSS concentration for example: between 1/9 and 1/16 there is a jump of 2600 mg/l in the digester 2 VSS with no corresponding increase in the influent COD
- There is consistent increasing trend in the VSS from startup till 2/20 despite no corresponding increase in influent COD (grams)
- There is a decrease in the digester VSS concentration after late Feb despite an increase in the average influent COD which self-contradicts

Conclusions from Fig-2

- The mostly likely conclusion is that the measured VSS concentration data is not reliable

Figure 3 Total Methane predicted over feed interval (liter)



From the fig-3 we can observe that the predicted methane is slightly over predicted at several places but has a good correlation to measured data overall.

Figure 4 Correlation between predicted and measured total methane generation per feed interval (liters)

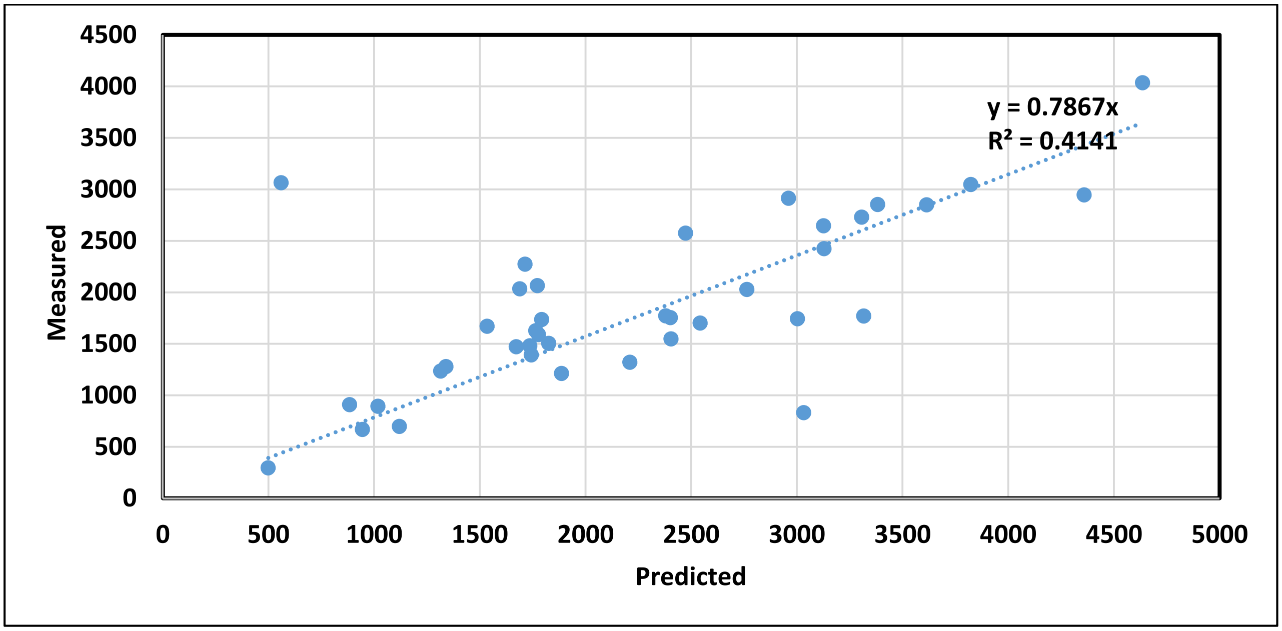


Figure 5 Methane generation rate in liter per hour on January17-19, 2014 (72 hour interval)
* (total methane measured is 2853 liter and total methane predicted is 3383 liter in fig 5)

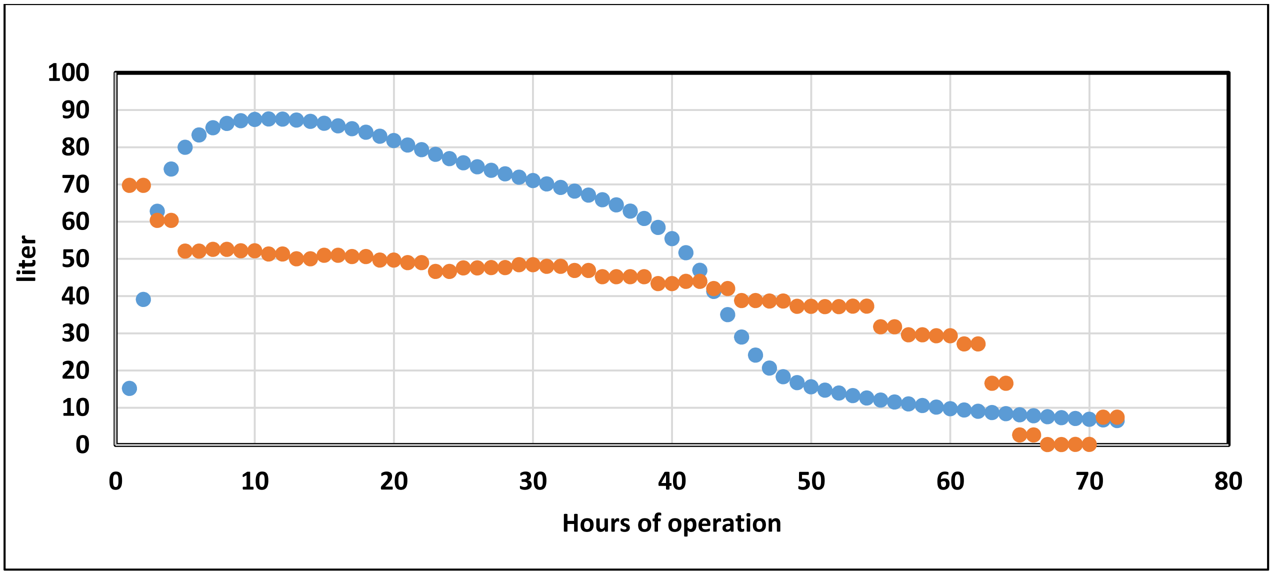


Figure 6 Methane generation rate in liter per hour on January20-21, 2014 (48 hour interval)

* (total methane measured is 1471 liter and total methane predicted is 1600 liter in fig 6)

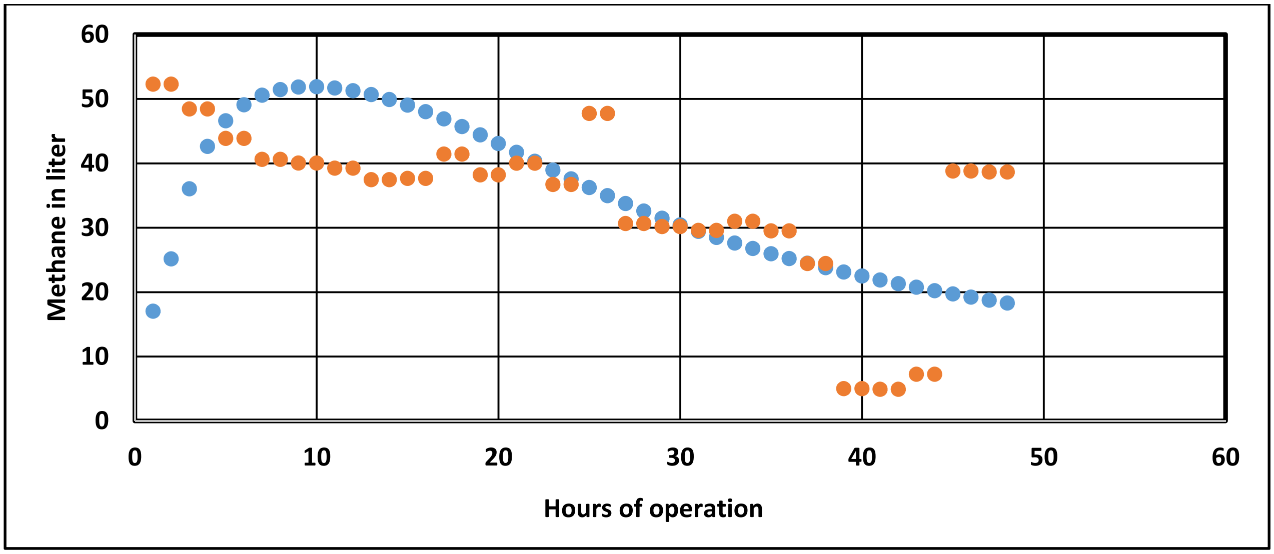


Fig-5 suggest that the hydrolysis rate chosen i.e. 1.5 per day is too high and Fig-6 suggests that the measured and predicted generation closely matches to some degree. This suggests that food waste composition may be changing drastically over the period of operation. Thus we face a limitation of inaccurately predicting the hydrolysis of food waste as the hydrolysis rate and fractions are fixed.

Very good Ammonia and Alkalinity fit was seen when we used the measured influent COD data.

Figure 6 Ammonia in digester predicted and measured

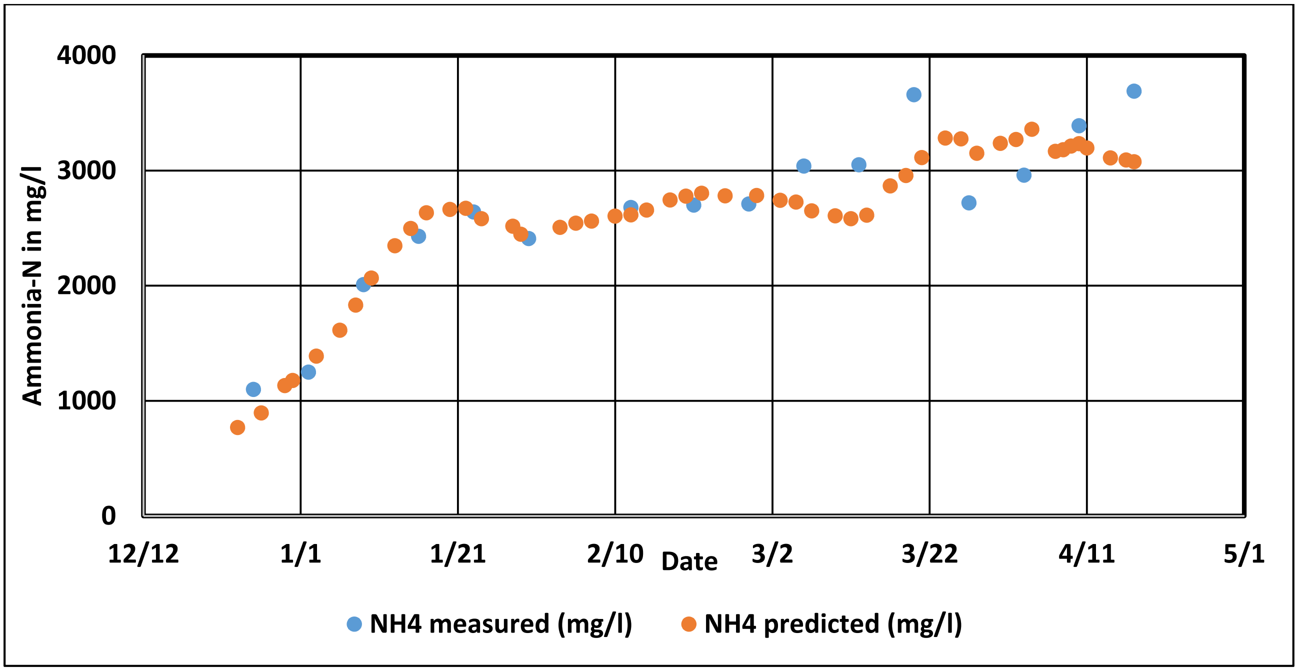
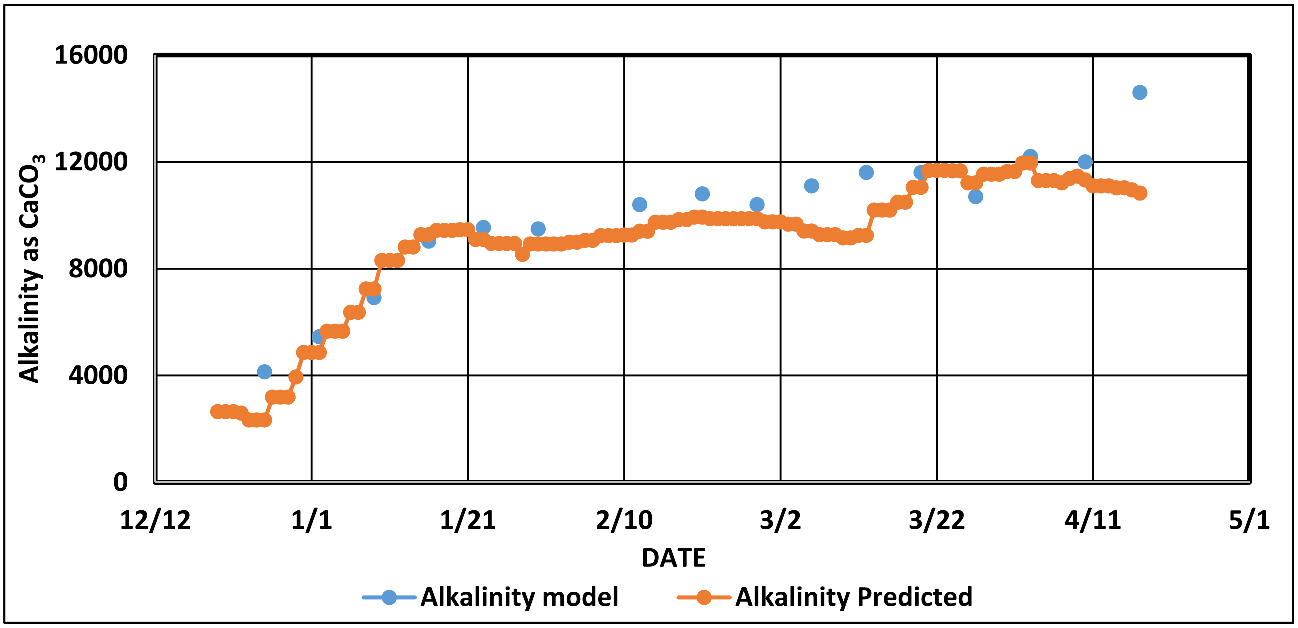


Figure 7 Alkalinity in digester predicted and measured

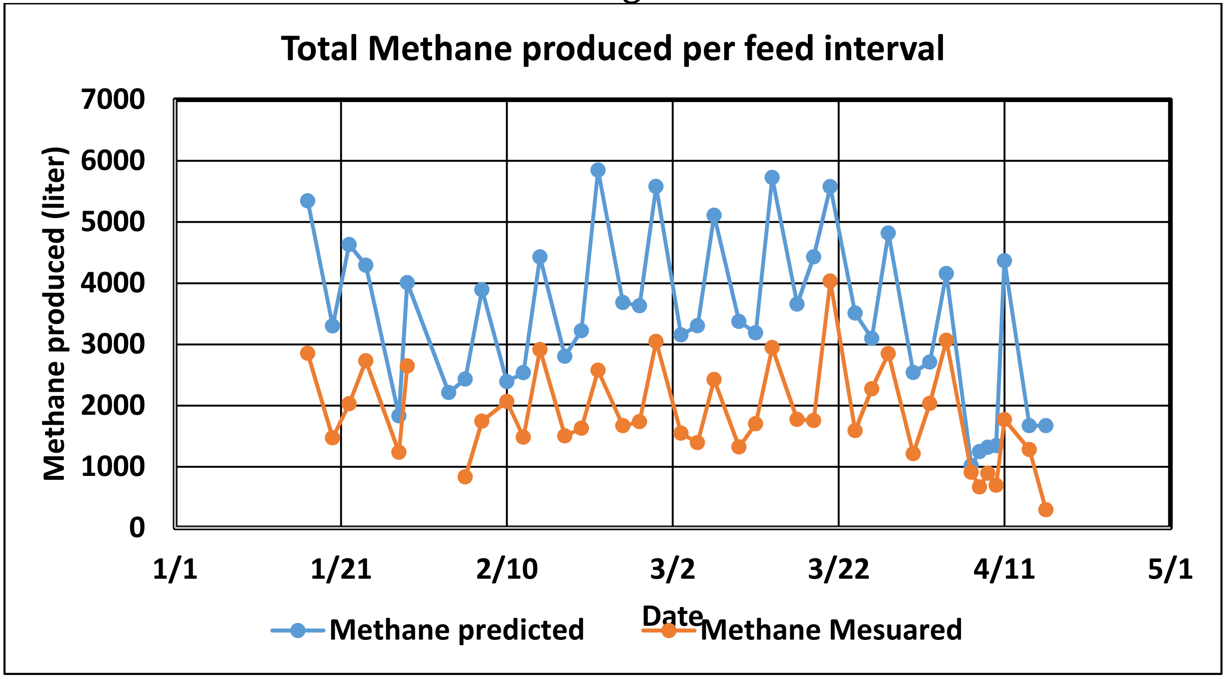


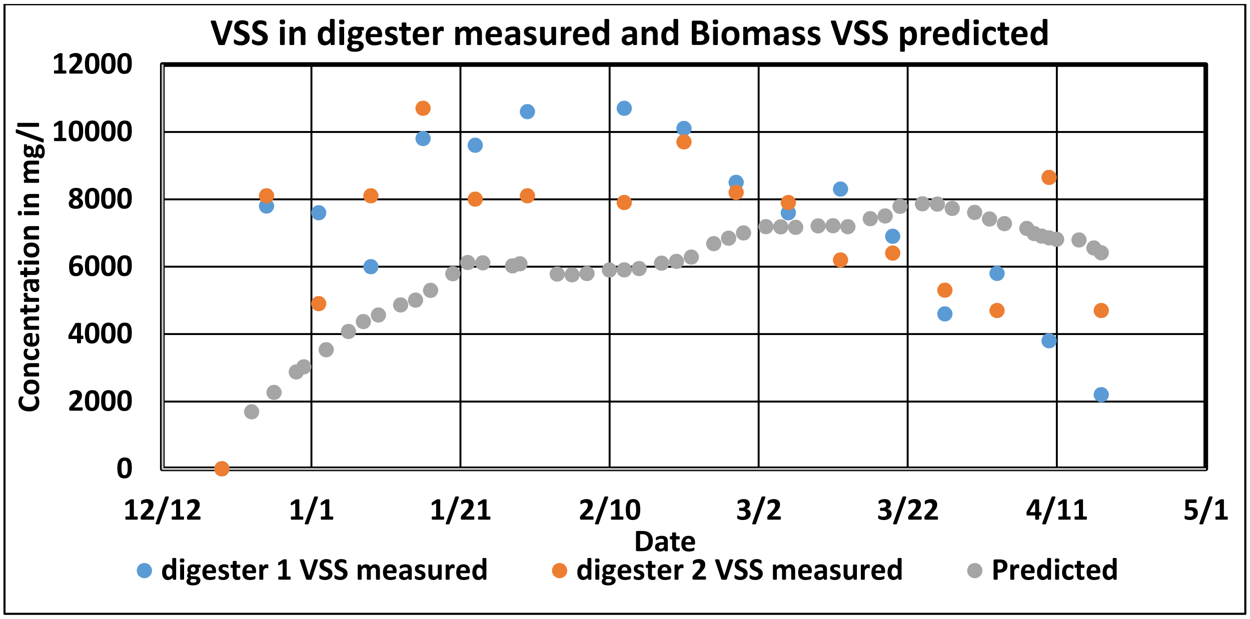
Conclusion

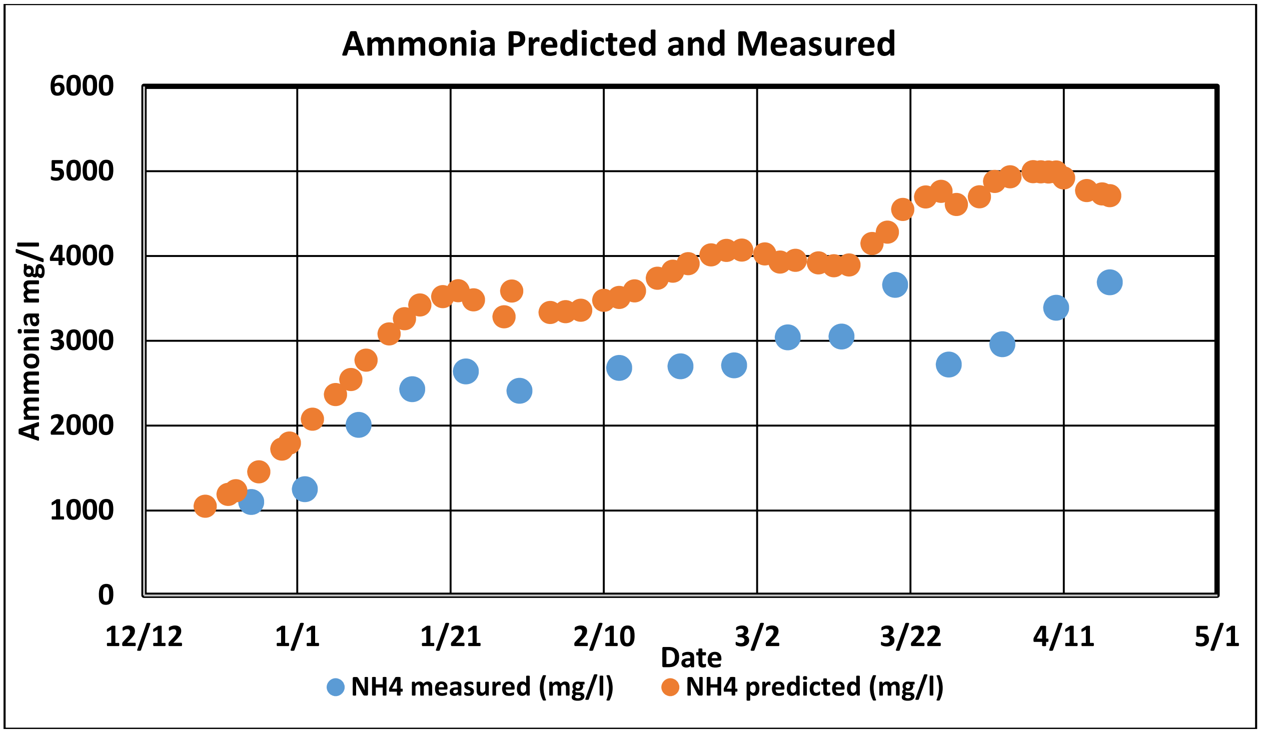
The decrease in the VSS in the later period cannot be replicated in the model because of following reasons:

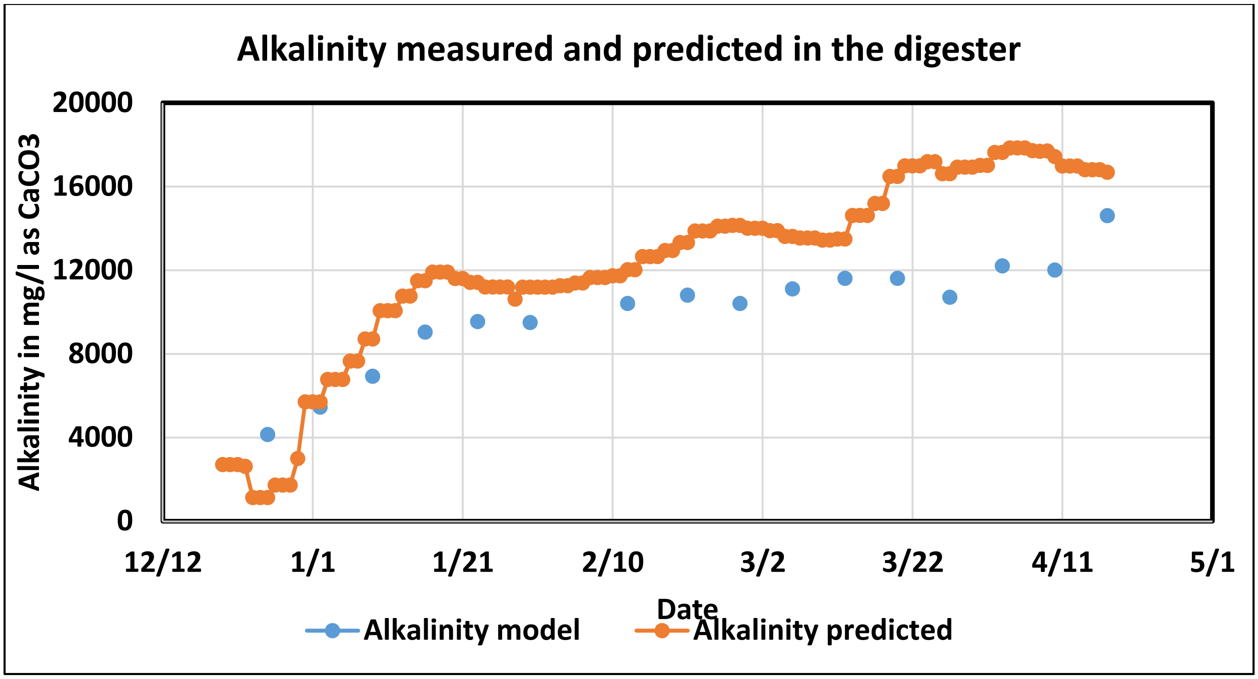
- A higher hydrolysis rate used which leaves almost negligible undigested solids, which eliminates the chance of using a yet higher hydrolysis rate which possibly could suppress the VSS trend in the post Feb-20 region.
- The model prediction of the ammonia and the alkalinity was fairly accurate and methane too had a closer fit with measured data; only the digester VSS prediction was not matching to the measured data. This facts points out that there may be some discrepancy in the measured VSS data.
- The point that the digester VSS data was not accurate is further supported by the fact that despite an increase in the influent COD the measured data shows a decreasing trend in the digester VSS during Mid Feb to April (fig-2).

APPENDIX-1
Model simulation results using measured influent VS data



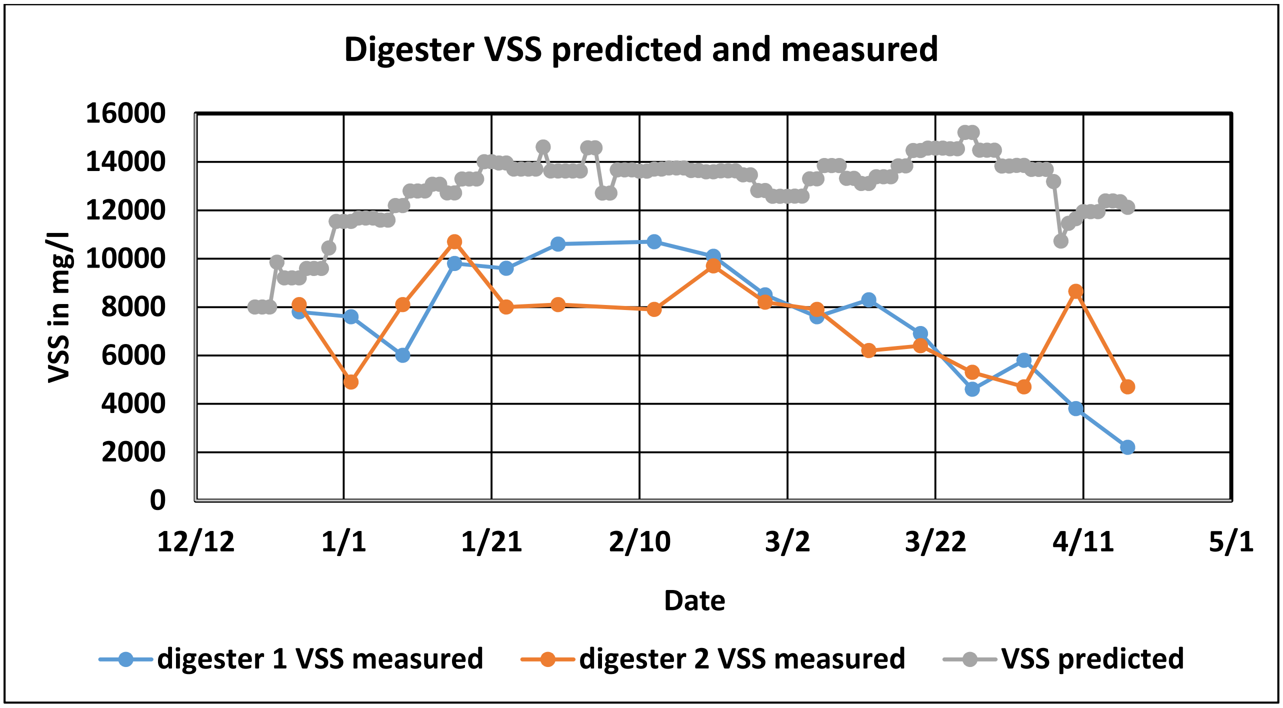


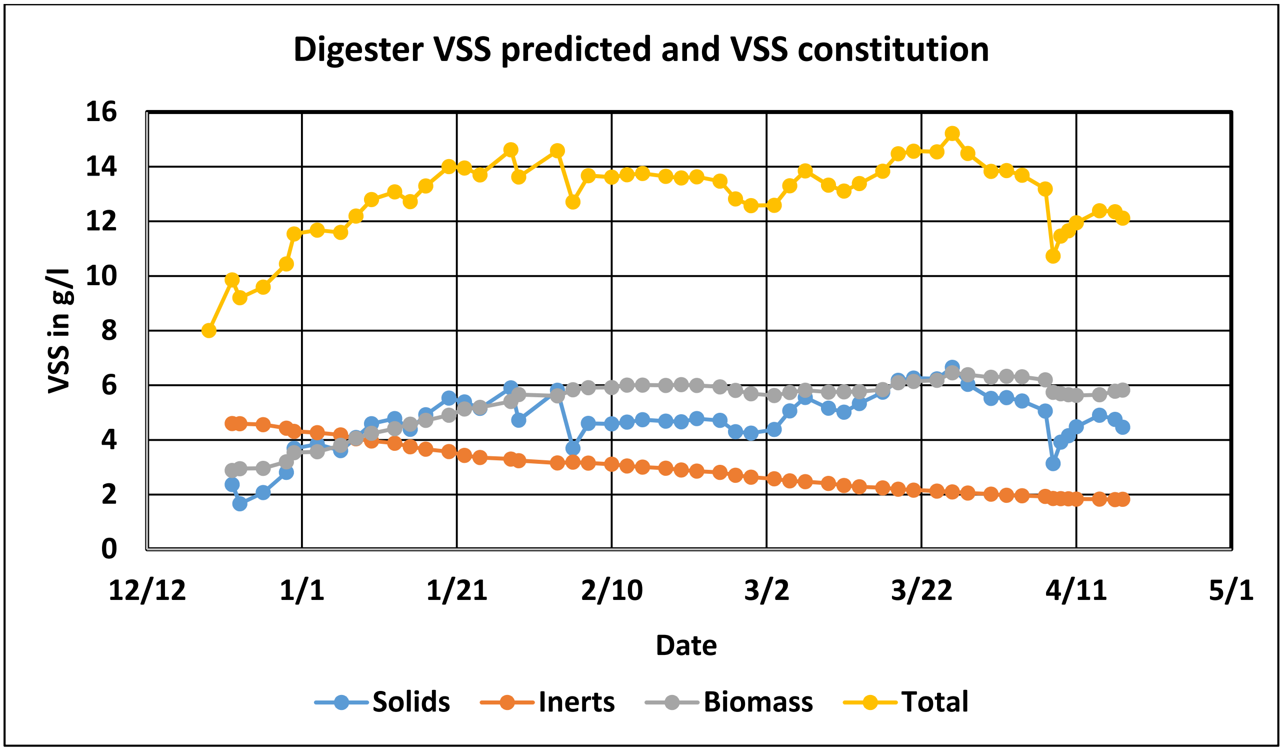

Ammonia Predicted and Measured
Ammonia mg/l
6000
5000
4000
3000
2000
1000
0
12/12
1/1
1/21
2/10
3/2
3/22
4/11
5/1
Date
● NH4 measured (mg/l)
● NH4 predicted (mg/l)

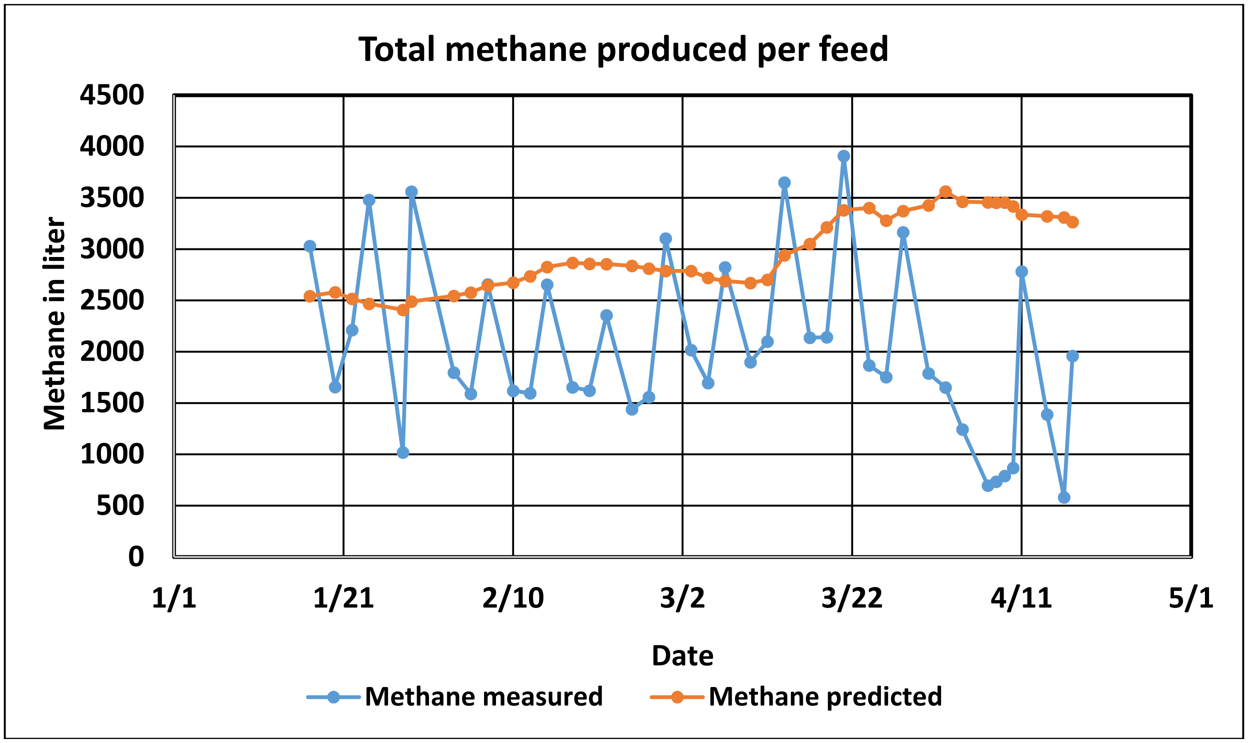

Alkalinity measured and predicted in the digester
Alkalinity in mg/l as CaCO3
20000
16000
12000
8000
4000
0
12/12
1/1
1/21
2/10
3/2
3/22
4/11
5/1
Date
Alkalinity model
Alkalinity predicted

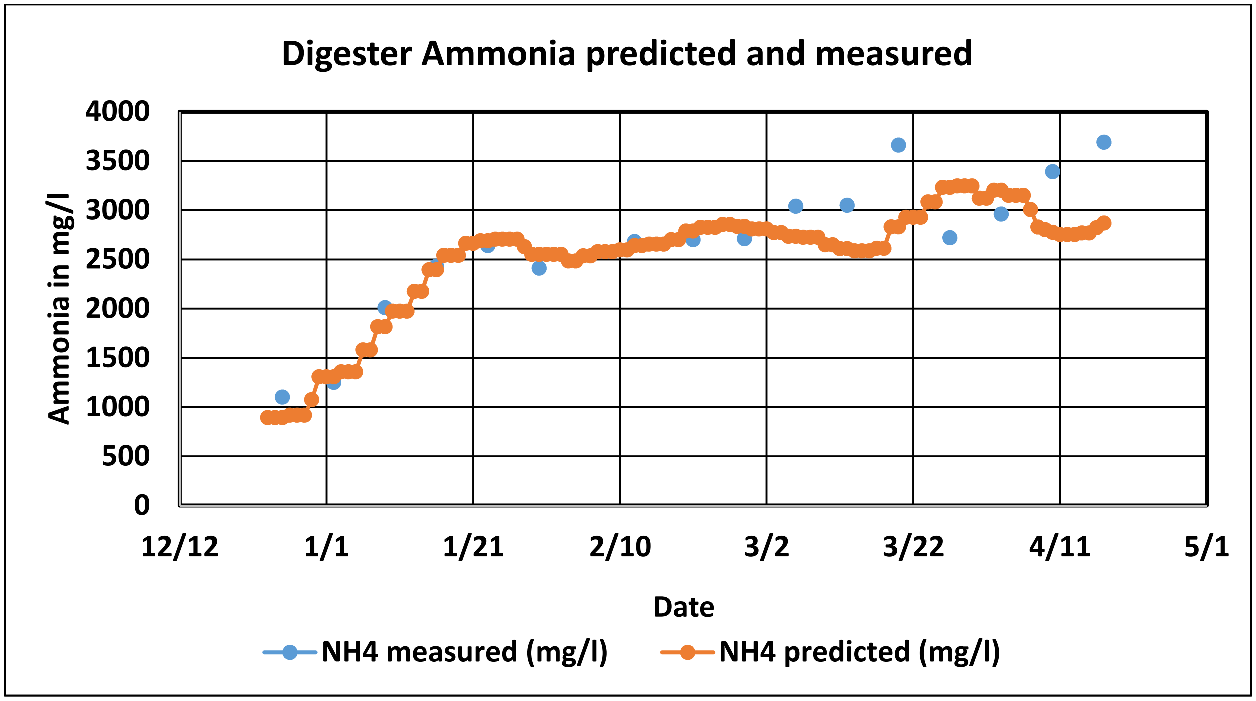
APPENDIX-2

Model simulation results using measured influent COD data and Stallman Coefficient






Total methane produced per feed
Methane in liter
4500
4000
3500
3000
2500
2000
1500
1000
500
0
1/1
1/21
2/10
3/2
3/22
4/11
5/1
Date
Methane measured
Methane predicted


Digester Ammonia predicted and measured
Ammonia in mg/l
4000
3500
3000
2500
2000
1500
1000
500
0
12/12
1/1
1/21
2/10
3/2
3/22
4/11
5/1
Date
NH4 measured (mg/l)
NH4 predicted (mg/l)

Appendix-3
Initial conditions used to simulate the food waste digester

Variable	Value
Rapidly Hydrolysable (Xrh)	0.426678
Slowly Hydrolysable (Xsh)	3.598118
Preexisitng RH (Xrh0)	0
Preexisting SH (Xsh0)	0
Soluble Inerts (Si)	0.90192
Particulate Inerts (Xi)	6.46
Soluble Amino Acids (Saa)	3.69E-03
Amino Acid Utilizers (Xaa)	0.61077
Soluble Fatty Acids (Sfa)	0.0908
Fatty Acid Utilzers (Xfa)	0.580196
Soluble Sugars (Ssu)	8.23E-03
Sugar utilizers (Xsu)	1.109
Propionate (Spro)	0.032058
Propionate Utilzers (Xpro)	0.1533
Valerate (Sva)	8.39E-03
Butyrate (Sbu)	0.013345
But/Val Utilzers (Xc4)	0.285
Acetate (Sac)	0.080966
Acetate Utilzers (Xac)	0.908
Hydrogen Utilzers (Xh2)	0.448
Soluble Hydrogen (Sh2)	1.66E-07
Soluble Methane (Sch4)	0.06441
Methane Gas (Sgas_ch4)	1.496109
CO2 Gas (Sgas_co2)	0.016828
Hydrogen Gas (Sgas_h2)	5.00E-06
Soluble Inorganic Carbon (SIC)	0.068248

Soluble Ammonium (Snh4)	0.058569
Proton (SH)	1.00E-07
Bicarbonate (SHCO3)	0.056894
Soluble CO2 (Sco2)	0.011354
Feed2 RH (Xrh2)	0
Feed2 SH (Xsh2)	0
Composite Material (Xc)	1.07E-04
Composite Material (Xc0)	0
Composite Material (Xc2)	0
Endogenous Decay (Xed)	6.86E-06
pH Inhibition for Acetate Utilizers	1

Appendix N: Sludge Dewatering Test

Dewatering Evaluation of U.S. Air Force Academy Food Waste Digester

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Claire W. Carlson Chair in Environmental Engineering
Bucknell University
Lewisburg, PA

OVERVIEW

A dewaterability test was performed to evaluate the food waste digestate from the U.S. Air Force Academy anaerobic digester. Testing was performed using a standardized protocol developed at Bucknell University such that the only variable is the digestate characteristics. In addition, the cation and PO_4^{3-} concentrations were measured.

TESTING METHODS

Dewaterability. The dewaterability of the samples was analyzed using a standardized laboratory protocol developed at Bucknell University. First, the optimum polymer dose was determined by establishing the polymer dose-response curve using capillary suction time (CST) as the measure of conditioning. The polymer was an SNF 6440 SH, high molecular weight, cation polymer made to a 0.5% concentration on the day of the dewatering experiment. A 500 mL sample of digestate is placed in a 2 L, baffled circular container. The polymer is added to the solids and mixed using a single paddle mixer at 563 rpm (G = 1000/s) for 30 s, followed by 54 rpm (G = 100/s) for 90 s, after which the CST was measured. The dosage with the lowest CST is considered the optimum polymer dose, and this sample will be dewatered.

Dewatering is performed by first gravity draining the solids on belt filter press fabric. The drained solids are then placed in a specially designed belt filter press centrifuge cup. These cups comprise a piece of belt filter press fabric that was suspended approximately half way up the depth of the cup, as shown in Figure 1. The samples are then centrifuged at 3000 x g for 10 minutes, and the cake is scraped off the belt filter press fabric for analysis of total solids (TS) and VS according to Standard Methods (APHA, 2012). The gravitational force can be adjusted to better simulate either belt filter press or centrifuge pressures experienced in full scale equipment. This method provides reproducible results that are similar to full-scale equipment.

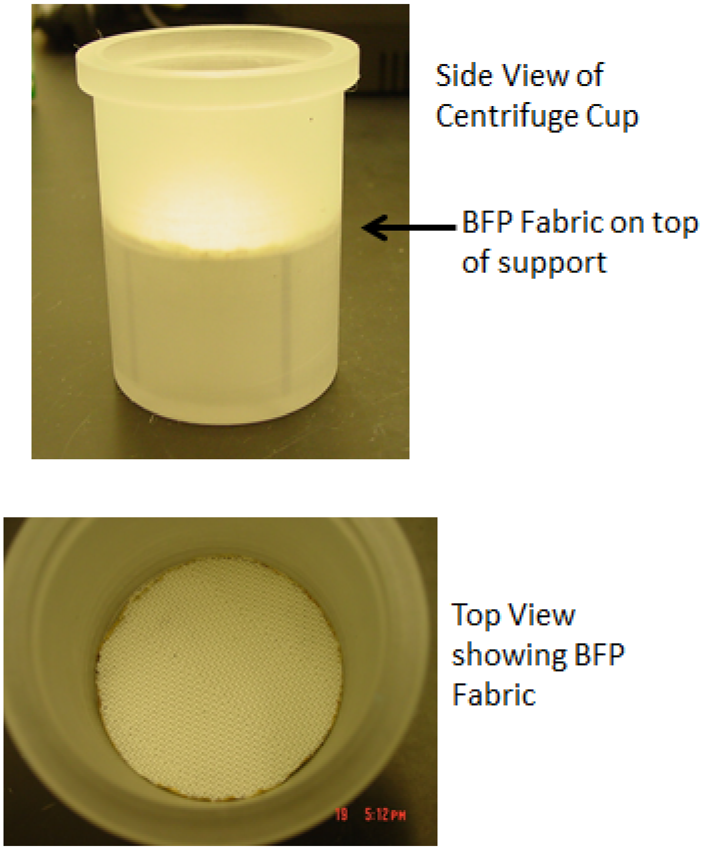
Side View of Centrifuge Cup
BFP Fabric on top of support
Top View showing BFP Fabric
19 5:12PM

Figure 1. Belt filter press centrifuge cups used for dewatering experiments.

Cations and PO$_4^{3-}$ Analysis. The cations, Na+, NH4+, K+, Mg2+, Ca2+ and PO43- were all analyzed using a ion chromatography. A 50 mL aliquot was placed in a centrifuge tube and centrifuge for 10 minutes at 3000 x g. The centrate was then filtered through a 0.45 μm filter. Cations and anions were analyzed using ion chromatography. Specifically, the cations Na+, NH4+, K+, Mg2+, and Ca2+ were analyzed using a cation exchange column and the phosphate concentration was measured using an anion exchange column on a Dionex (Sunnyvale, CA) IC system.

RESULTS

The results of the testing are summarized in Table 1. The M/D ratio of the sample was relatively high, with a value of 53. The high M/D ratio is mainly due to the high ammonium and sodium concentrations with a relatively low concentration of calcium and magnesium. The dewaterability in terms of the cake solids averaged 9.5% in duplicate samples. This is the lowest cake solids measured in comparison to many other samples tested using this same laboratory protocol. Figure 1 shows the results of other testing in comparison to the US AF Academy sample. The reason for the lower cake solids is unknown, but could be due to the relatively high VS/TS fraction of the digestate which is around 0.85. Most of the samples tested had VS fractions between 0.6-0.78.

Table 1. Summary of testing results for digestate sample.

Parameter	**Value**
Digester TS (%)	2.37
Soluble PO_4^{3-} (mg/L)	85
Soluble Na^+ (mg/L)	545
Soluble NH_4^+ (mg/L)	2740
Soluble K^+ (mg/L)	748
Soluble Ca^{2+} (mg/L)	56
Soluble Mg^{2+} (mg/L)	11
M/D Ratio	53
Cake Solids (%)	9.5

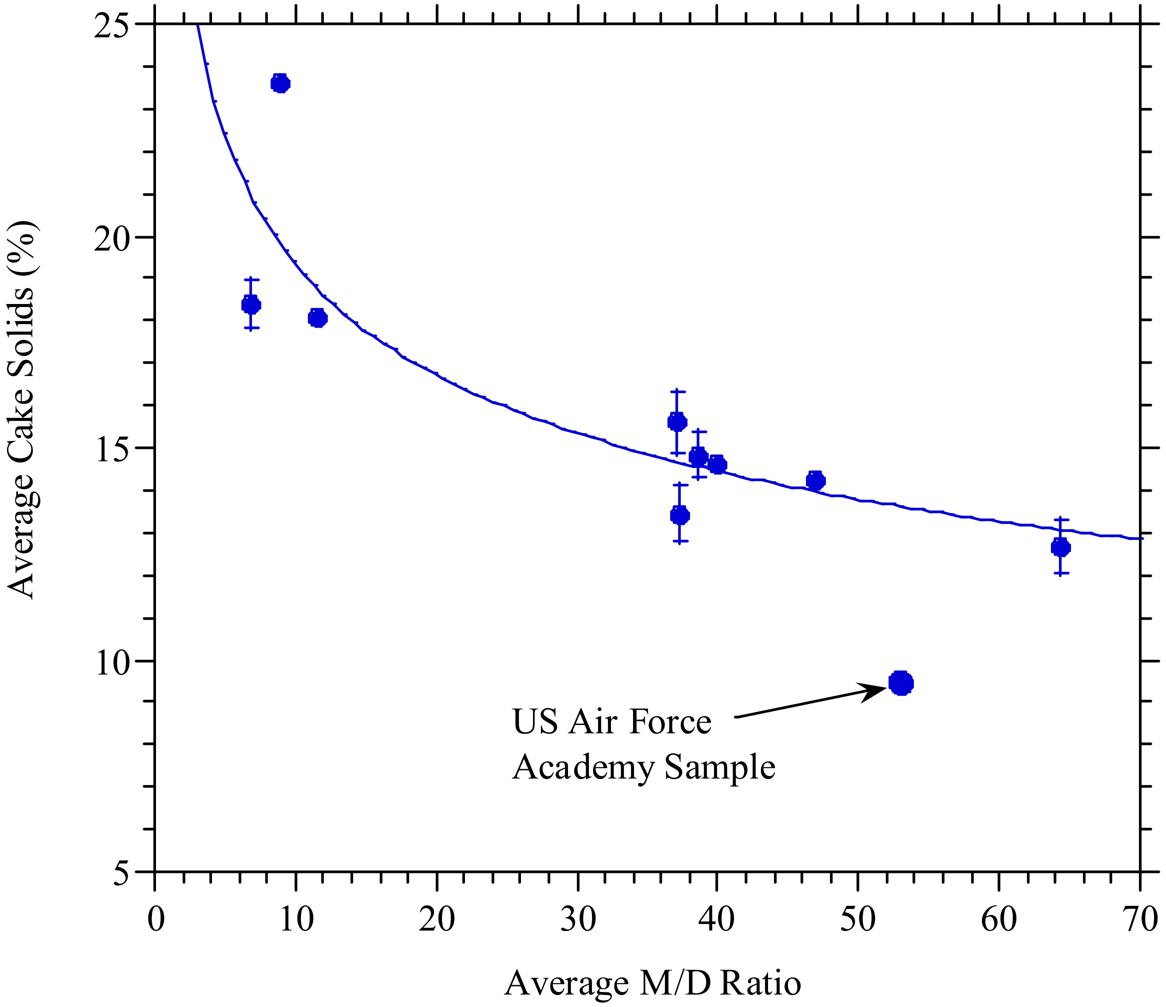

Figure 1. Cake solids as a function of average M/D Ratio. Adapted from Higgins et al. (2014).

SUMMARY

The results from the testing show that the digestate has relatively poor dewaterability likely due to a combination of a high M/D ratio and low inert concentration and possibly other unknown factors.

REFERENCES

Higgins, M.J., S. Beightol, C. Bott, P. Schauer (2014) Does Bio-P Impact Dewatering after Anaerobic Digestion? *Proc. 2014 Water Env. Federation Annual Conference,* Austin, Texas.

Appendix O: Greenhouse Gas Accounting Calculations

$\mathrm{Mgal} := 1000000 \cdot \mathrm{gal}$

Calculate Methane Production in 1 Mgal facility

$CH_4 := 270 \cdot \frac{L}{kg}$ Volume of methane produced per mass COD fed to digester

$COD := 120000 \cdot \frac{mg}{L}$ COD of Feed

$CH_{4.produced} := COD \cdot 1 \cdot \frac{Mgal}{40 \cdot day} \cdot CH_4 = 1.083 \times 10^5 \cdot \frac{ft^3}{day}$ 40 d is SRT in Phase III

Calculate net gasoline gallon equivalents generated

$Boiler := 109 \cdot kW$ From parasitic loads calculation

$CH_{4.LHV} := 914 \cdot \frac{BTU}{ft^3}$

$CH_{4.recovery} := 93.6\%$ From TDA report

$gasoline_{LHV} := 114000 \cdot \frac{BTU}{gal}$

$$gas_{net} := \frac{CH_{4.produced} \cdot CH_{4.LHV} \cdot CH_{4.recovery} - Boiler}{gasoline_{LHV}} = 2.682 \times 10^5 \cdot \frac{gal}{yr}$$

Calculate CO2 offset from bioCNG production

$gas_{ghg} := 8.78 \cdot \frac{kg}{gal}$

$CO2_{offset} := gas_{net} \cdot gas_{ghg} = 2.596 \times 10^3 \cdot \frac{ton}{yr}$

Calculate Energy Input

$elect_{demand} := 86 \cdot kW$ From parasitic loads calc.

$elec_{ghg} := 1.34 \cdot \frac{lb}{kW \cdot hr}$

$CO2_{produced} := elect_{demand} \cdot elec_{ghg} = 505.086 \cdot \frac{ton}{yr}$

Calculate CO2 in biogas

$$CO_{2.biogas} := CH_{4.produced} \cdot \frac{40\%}{60\%} \cdot \frac{44 \cdot gm}{22.4 \cdot L} = 1.617 \times 10^{3} \cdot \frac{ton}{yr}$$

Calculate Net GHG emissions

$$GHG_{net} := CO2_{produced} + CO_{2.biogas} - CO2_{offset}$$

$$GHG_{net} = -473.987 \cdot \frac{ton}{yr}$$

Comparison from WERF Sustainable Food Waste Evaluation

$$Landfill := 0.15 \cdot \frac{lb}{lb} \cdot 92000 \cdot \frac{mg}{L} \cdot \frac{1 \cdot Mgal}{40 \cdot day} = 525.796 \cdot \frac{ton}{yr}$$

Tons CO2/year produced
92000 mg/L is the TS of the feed

$$Compost := 0.05 \frac{lb}{lb} \cdot 92000 \cdot \frac{mg}{L} \cdot \frac{1 \cdot Mgal}{40 \cdot day} = 175.265 \cdot \frac{ton}{yr}$$

$$Food\_waste_{dry} := \frac{Landfill}{0.15} = 3.505 \times 10^{3} \cdot \frac{ton}{yr}$$

$$Food\_waste_{wet} := \frac{Food\_waste_{dry}}{9.2\%} = 104.318 \cdot \frac{ton}{day}$$

$$Food\_waste_{wet} = 9.464 \times 10^{4} \cdot \frac{kg}{day}$$

Appendix P: Economic Analysis Calculations

Estimate Biogas Production from Military Base Food Waste

Base Sizes for Comparison

$$\mathrm{Pop} := \begin{pmatrix} 10000 \\ 20000 \\ 40000 \end{pmatrix} \cdot \mathrm{person}$$

Per capita food waste generation

$$\mathrm{Production}_{wet} := 0.635 \cdot \frac{\mathrm{lb}}{\mathrm{person} \cdot \mathrm{day}}$$

Based on EPA 2012 document listing 4.38 lb/person/day and food waste fraction of 14.5%

$$\mathrm{Production} := \mathrm{Production}_{wet} 24.5\% = 0.156 \cdot \frac{\mathrm{lb}}{\mathrm{person} \cdot \mathrm{day}}$$

dry pounds per day based on ESTCP study

Food Waste Characteristics and Performance from ESTCP Pilot Data

$$TS_{fw} := 245000 \frac{\mathrm{mg}}{\mathrm{L}}$$

$$VS_{fw} := 96\%$$

$$COD_{fw} := 324000 \cdot \frac{\mathrm{mg}}{\mathrm{L}}$$

$$TS_{FOG} := 100\%$$

$$VS_{FOG} := 100\%$$

$$COD_{FOG} := 2.89 \cdot \frac{\mathrm{gm}}{\mathrm{gm}}$$

$$\rho_{fw} := 1.1 \cdot \frac{\mathrm{gm}}{\mathrm{ml}}$$

$$\rho_{FOG} := 0.95 \cdot \frac{\mathrm{gm}}{\mathrm{ml}}$$

Based on pilot results

$$VSR_{all} := 81\%$$

$$VSSR_{all} := 94\%$$

$$CH4_{all} := 7.0 \cdot \frac{\mathrm{ft}^3}{\mathrm{lb}}$$

$$SELR_{all} := 0.44 \cdot \frac{\mathrm{g}}{\mathrm{g} \cdot \mathrm{day}}$$

$$CH4_{LHV} := 914 \cdot \frac{\mathrm{BTU}}{\mathrm{ft}^3}$$

Determine Undiluted Feed Characteristics Assuming 10% FOG by COD

$$COD_{feed} := \frac{1.2 \cdot \mathrm{L} \cdot \rho_{FOG} \cdot COD_{FOG} + 100 \cdot \mathrm{L} \cdot COD_{fw}}{101.2 \cdot \mathrm{L}} = 3.527 \times 10^5 \cdot \frac{\mathrm{mg}}{\mathrm{L}}$$

$$VS_{feed} := \frac{1.2 \cdot L \cdot VS_{FOG} \cdot \frac{1000000 \cdot mg}{L} + 100 \cdot L \cdot VS_{fw} \cdot TS_{fw}}{101.2 \cdot L} = 2.443 \times 10^{5} \cdot \frac{mg}{L}$$

$$Food_{waste} := \frac{Production \cdot Pop}{TS_{fw}} = \begin{pmatrix} 2.88 \times 10^{3} \\ 5.761 \times 10^{3} \\ 1.152 \times 10^{4} \end{pmatrix} \cdot \frac{L}{day}$$

$$Feed_{vol} := Food_{waste} \cdot 1.012 = \begin{pmatrix} 2.915 \times 10^{3} \\ 5.83 \times 10^{3} \\ 1.166 \times 10^{4} \end{pmatrix} \cdot \frac{L}{day}$$

$$COD_{mass.feed} := Feed_{vol} \cdot COD_{feed} = \begin{pmatrix} 1.028 \times 10^{3} \\ 2.056 \times 10^{3} \\ 4.112 \times 10^{3} \end{pmatrix} \cdot \frac{kg}{day}$$

$$VS_{mass.feed} := Feed_{vol} \cdot VS_{feed} = \begin{pmatrix} 712.013 \\ 1.424 \times 10^{3} \\ 2.848 \times 10^{3} \end{pmatrix} \cdot \frac{kg}{day}$$

Determine the VSS Concentration in the CSTR

$$VSS_{CSTR} := VS_{feed} \cdot \left(1 - VSSR_{all}\right) = 1.466 \times 10^{4} \cdot \frac{mg}{L}$$

Assume in feed VS = VSS

Determine CSTR Size based on SELR from pilot data

$$Vol_{CSTR} := \frac{COD_{feed} \cdot Feed_{vol}}{VSS_{CSTR} \cdot SELR_{all}} = \begin{pmatrix} 159.43 \\ 318.86 \\ 637.72 \end{pmatrix} \cdot m^{3}$$

Determine CSTR Heating Demand (assume additional 15% for shell losses from tanks)

$$Heat_{demand} := Feed_{vol} \cdot 8.34 \cdot \frac{lb}{gal} \cdot 1 \cdot \frac{BTU}{lb \cdot R} \cdot (100 - 60) \cdot (R) = \begin{pmatrix} 3.137 \\ 6.274 \\ 12.547 \end{pmatrix} \cdot kW$$

Determine Methane Production from CSTR

$$VS_{destroyed} := Feed_{vol} \cdot VS_{feed} \cdot VSR_{all} = \begin{pmatrix} 6.675 \times 10^{-3} \\ 0.013 \\ 0.027 \end{pmatrix} \frac{kg}{s}$$

$$CH4_{biogas} := VS_{destroyed} \cdot CH4_{all} = \begin{pmatrix} 10.501 \\ 21.002 \\ 42.005 \end{pmatrix} \cdot \frac{m^3}{hr}$$

Equivalent NG production as 1000 cubic feet

$$Energy_{NG} := CH4_{biogas} \cdot \frac{CH4_{LHV}}{NG_{LHV}} \cdot 95\% = \begin{pmatrix} 2.871 \times 10^{3} \\ 5.743 \times 10^{3} \\ 1.149 \times 10^{4} \end{pmatrix} \cdot \frac{1000 \cdot cf}{yr}$$

Determine Energy Value of biogas as Electrical Power Generation

$$Energy_{biogas.power} := Energy_{NG} \cdot CH4_{LHV} \cdot 38\% = \begin{pmatrix} 33.344 \\ 66.687 \\ 133.375 \end{pmatrix} \cdot kW$$

Determine Energy Value of biogas as CHP Heat

$$Energy_{biogas.chp.heat} := CH4_{biogas} \cdot CH4_{LHV} \cdot 42\% = \begin{pmatrix} 41.722 \\ 83.443 \\ 166.887 \end{pmatrix} \cdot kW$$

Greater than heat demand no need for additional heating.

Determine Energy Value as natural gas (assume condensing boiler with on scrbbed gas with overall efficiency of 95%)

$$Energy_{biogas.boiler.heat} := CH4_{biogas} \cdot CH4_{LHV} \cdot 94\% - \frac{Heat_{demand}}{95\%} = \begin{pmatrix} 2.842 \times 10^{3} \\ 5.685 \times 10^{3} \\ 1.137 \times 10^{4} \end{pmatrix} \cdot \frac{GJ}{yr}$$

Determine Energy Value of biogas as vehicle fuel expressed in gallons per year (assume condensing boiler with on scrbbed gas with overall efficiency of 95%)

$$Energy_{biogas.veh} := \frac{CH4_{biogas} \cdot CH4_{LHV} - \frac{Heat_{demand}}{95\%}}{116000 \cdot \frac{BTU}{gal}} = \begin{pmatrix} 2.476 \times 10^{4} \\ 4.952 \times 10^{4} \\ 9.905 \times 10^{4} \end{pmatrix} \cdot \frac{gal}{yr}$$

In GGE

$$USAFA_{production} := Production_{wet} \cdot 4500 person = 1.429 \cdot \frac{ton}{day}$$

Based on national average fuel production rates

$$tenthousand_{production} := Production_{wet} \cdot 10000 person = 3.175 \cdot \frac{ton}{day}$$

$$USAFA\_Energy\_high_{biogas.veh} := 2.476 \cdot 10^4 \frac{gal}{yr} \cdot \frac{USAFA_{production}}{tenthousand_{production}} = 1.114 \times 10^4 \cdot \frac{gal}{yr}$$

$$USAFA_{production.measured} := 5 \frac{ton}{week}$$

$$USAFA\_Energy\_low_{biogas.veh} := 2.476 \cdot 10^4 \frac{gal}{yr} \cdot \frac{USAFA_{production.measured}}{tenthousand_{production}} = 5.57 \times 10^3 \cdot \frac{gal}{yr}$$

Cost Calculations

$\varepsilon_p := 75\%$ $\varepsilon_m := 92\%$ Pump and motor efficiencies

Digester System

Capital Costs - Based on cost curve

Power Requirements - Assumes typical heads and flows for equipement.

$$Primary := \frac{500 \cdot gpm \cdot 10 \cdot ft \cdot 8.34 \cdot \frac{lbf}{gal}}{\varepsilon_p \cdot \varepsilon_m} = 1.366 \cdot kW$$

$$Secondary := \frac{2 \cdot 350 \cdot gpm \cdot 15 \cdot ft \cdot 8.34 \cdot \frac{lbf}{gal}}{\varepsilon_p \cdot \varepsilon_m} = 2.868 \cdot kW$$

$$Solids_{recirc} := \frac{2 \cdot 350 \cdot gpm \cdot 25 \cdot ft \cdot 8.34 \cdot \frac{lbf}{gal}}{\varepsilon_p \cdot \varepsilon_m} = 4.78 \times 10^3 \, W$$

$$Solids_{trans} := \frac{Feed_{vol} \cdot 40 \cdot psi}{\varepsilon_p \cdot \varepsilon_m} = \begin{pmatrix} 0.013 \\ 0.027 \\ 0.054 \end{pmatrix} \cdot kW$$

$$Mixing := \frac{6 \cdot \frac{W}{m^3} \cdot Vol_{CSTR}}{\varepsilon_p \cdot \varepsilon_m} = \begin{pmatrix} 1.386 \\ 2.773 \\ 5.545 \end{pmatrix} \cdot kW$$

$$\text{Total} := \text{Primary} + \text{Secondary} + \text{Solids}_{\text{recirc}} + \text{Solids}_{\text{trans}} + \text{Mixing} = \begin{pmatrix} 10.413 \\ 11.813 \\ 14.613 \end{pmatrix} \cdot \text{kW}$$

Moisture Removal System

Capital Costs- Use quote from C2 Energy originally for Miami-Dade

$$\text{Equip}_{\text{quote}} := 120000$$

$$\text{Size} := \frac{\text{CH4}_{\text{biogas}}}{63\%} = \begin{pmatrix} 16.669 \\ 33.337 \\ 66.674 \end{pmatrix} \cdot \frac{m^3}{hr}$$

$$\text{Size}_{\text{quote}} := 500 \cdot \frac{ft^3}{min}$$

$$\text{Equip} := \text{Equip}_{\text{quote}} \cdot \left(\frac{\text{Size}}{\text{Size}_{\text{quote}}} \right)^{0.6} = \begin{pmatrix} 1.135 \times 10^4 \\ 1.72 \times 10^4 \\ 2.606 \times 10^4 \end{pmatrix}$$

$$\text{Moist}_{\text{cap}} := \text{Equip} \cdot 2 \cdot 125\% = \begin{pmatrix} 2.836 \times 10^4 \\ 4.299 \times 10^4 \\ 6.516 \times 10^4 \end{pmatrix}$$

Power Requirements

$$\text{CH4}_{cp} := 2.2537 \cdot \frac{kJ}{kg \cdot K} \qquad \text{CH4}_{\rho} := 16.043 \cdot \frac{kg}{1000mol} \cdot \frac{1 \cdot mol}{22.4 \cdot L}$$

$$\text{CO2}_{cp} := 0.846 \cdot \frac{kJ}{kg \cdot K} \qquad \text{CO2}_{\rho} := 44.01 \cdot \frac{kg}{1000 \cdot mol} \cdot \frac{1 \cdot mol}{22.4 \cdot L}$$

$$\text{biogas}_{cp} := 63\% \cdot \text{CH4}_{cp} + 37\% \cdot \text{CO2}_{cp} = 1.733 \cdot \frac{kJ}{kg \cdot K}$$

$$\text{biogas}_{\rho} := 63\% \cdot \text{CH4}_{\rho} + 37\% \cdot \text{CO2}_{\rho} = 1.178 \frac{kg}{m^3}$$

$$\text{biogas}_{\text{cool}} := \frac{\text{CH4}_{\text{biogas}}}{63\%} \cdot \text{biogas}_{cp} \cdot \text{biogas}_{\rho} \cdot (100 - 40) \cdot R = \begin{pmatrix} 0.315 \\ 0.63 \\ 1.26 \end{pmatrix} \cdot \text{kW}$$

$$\text{water} := \begin{pmatrix} .284 \\ .524 \\ 1.007 \end{pmatrix} \cdot \frac{\text{gal}}{\text{hr}}$$

$$\text{water}_{\text{cool}} := \text{water} \cdot 8.34 \cdot \frac{\text{lb}}{\text{gal}} \cdot \left[1 \cdot \frac{\text{BTU}}{\text{lb} \cdot \text{R}} \cdot (100 - 40) \cdot \text{R} + 2.26 \cdot \frac{\text{kJ}}{\text{gm}} \right] = \begin{pmatrix} 0.716 \\ 1.321 \\ 2.539 \end{pmatrix} \cdot \text{kW}$$

$$\text{cooling}_{\text{power}} := \frac{\text{biogas}_{\text{cool}} + \text{water}_{\text{cool}}}{2.2}$$

Assumes chiller COP of 2.2

$$\text{cooling}_{\text{power}} = \begin{pmatrix} 0.469 \\ 0.887 \\ 1.727 \end{pmatrix} \cdot \text{kW}$$

Iron Sponge - Based on quote from Clean Methane Option 2, System 3 for Miami-Dade

Capital Costs

$$\text{Equip}_{\text{quote}} := 1015000$$

$$\text{Size} := \frac{\text{CH4}_{\text{biogas}}}{63\%} = \begin{pmatrix} 16.669 \\ 33.337 \\ 66.674 \end{pmatrix} \cdot \frac{\text{m}^3}{\text{hr}}$$

$$\text{Size}_{\text{quote}} := 1700 \cdot \frac{\text{ft}^3}{\text{min}}$$

$$\text{Equip} := \text{Equip}_{\text{quote}} \cdot \left(\frac{\text{Size}}{\text{Size}_{\text{quote}}} \right)^{0.6} = \begin{pmatrix} 4.605 \times 10^4 \\ 6.98 \times 10^4 \\ 1.058 \times 10^5 \end{pmatrix}$$

$$\text{Moist}_{\text{cap}} := \text{Equip} \cdot 2 \cdot 125\% = \begin{pmatrix} 1.151 \times 10^5 \\ 1.745 \times 10^5 \\ 2.645 \times 10^5 \end{pmatrix}$$

Power Costs = 0

Media Costs

$$\text{Media}_{\text{consumption}} := \frac{\text{Size}}{\text{Size}_{\text{quote}}} \cdot 1855 \cdot \frac{\text{lb}}{\text{day}} = \begin{pmatrix} 10.705 \\ 21.411 \\ 42.821 \end{pmatrix} \cdot \frac{\text{lb}}{\text{day}}$$

$$\text{Media}_{\text{cost}} := \text{Media}_{\text{consumption}} \cdot \frac{1.76}{\text{lb}} = \begin{pmatrix} 6.882 \times 10^{3} \\ 1.376 \times 10^{4} \\ 2.753 \times 10^{4} \end{pmatrix} \cdot \frac{1}{\text{yr}}$$

SulfaTrap - Based on TDA report

Capital Costs

$$\text{Equip}_{\text{quote}} := 74000$$

$$\text{Size} := \frac{\text{CH4}_{\text{biogas}}}{63\%} = \begin{pmatrix} 16.669 \\ 33.337 \\ 66.674 \end{pmatrix} \cdot \frac{\text{m}^{3}}{\text{hr}}$$

$$\text{Size}_{\text{quote}} := 2000 \cdot \frac{\text{m}^{3}}{\text{day}}$$

$$\text{Equip} := \text{Equip}_{\text{quote}} \cdot \left(\frac{\text{Size}}{\text{Size}_{\text{quote}}} \right)^{0.6} = \begin{pmatrix} 2.818 \times 10^{4} \\ 4.271 \times 10^{4} \\ 6.473 \times 10^{4} \end{pmatrix}$$

Capital not multiplied by 2 becuase TDA provided installed costs

$$\text{SulfaTrap}_{\text{cap}} := \text{Equip} \cdot 1 \cdot 125\% = \begin{pmatrix} 3.522 \times 10^{4} \\ 5.338 \times 10^{4} \\ 8.091 \times 10^{4} \end{pmatrix}$$

Operating costs based on TDA report. Cost per mass sulfur

$$\text{Operating\_Cost}_{\text{Unit.H2S}} := \frac{41.31}{\text{kg}}$$

$$\text{Conc}_{\text{H2S}} := 2890 \frac{\text{mg}}{\text{m}^{3}}$$

$$\mathrm{Conc}_{S} := \mathrm{Conc}_{H2S}\cdot\frac{32}{34} = 2.72\times 10^{3}\cdot\frac{\mathrm{mg}}{\mathrm{m}^{3}}$$

$$\mathrm{Operating\_Cost}_{Unit.S} := \mathrm{Operating\_Cost}_{Unit.H2S}\cdot\frac{\mathrm{Conc}_{H2S}}{\mathrm{Conc}_{S}} = 43.892\,\frac{1}{\mathrm{kg}}$$

$$\mathrm{Operating\_Cost}_{VOL} := \mathrm{Operating\_Cost}_{Unit.S}\cdot\mathrm{Conc}_{S} = 1.194\times 10^{-4}\,\frac{1}{\mathrm{L}}$$

$$\mathrm{SulfaTrap}_{Annual.Cost} := \mathrm{Size}\cdot\mathrm{Operating\_Cost}_{VOL} = \begin{pmatrix} 1.744\times 10^{4} \\ 3.489\times 10^{4} \\ 6.978\times 10^{4} \end{pmatrix}\cdot\frac{1}{\mathrm{yr}}$$

VSA System - Based on TDA Report

Capital Costs

$$\mathrm{Equip}_{quote} := 295300$$

$$\mathrm{Size} := \frac{\mathrm{CH4}_{biogas}}{63\%} = \begin{pmatrix} 16.669 \\ 33.337 \\ 66.674 \end{pmatrix}\cdot\frac{\mathrm{m}^{3}}{\mathrm{hr}}$$

$$\mathrm{Size}_{quote} := 2000\cdot\frac{\mathrm{m}^{3}}{\mathrm{dav}}$$

$$\mathrm{Equip} := \mathrm{Equip}_{quote}\cdot\left(\frac{\mathrm{Size}}{\mathrm{Size}_{quote}}\right)^{0.6} = \begin{pmatrix} 1.124\times 10^{5} \\ 1.704\times 10^{5} \\ 2.583\times 10^{5} \end{pmatrix}$$

$$\mathrm{Moist}_{cap} := \mathrm{Equip}\cdot 125\% = \begin{pmatrix} 1.405\times 10^{5} \\ 2.13\times 10^{5} \\ 3.229\times 10^{5} \end{pmatrix}$$

Note that TDA provided
installed cost. Not multiply by

Water Scrubber - Based on e-mails from Dirkse-Millieutechniek environmental for San Jose

Capital Costs

$$\mathrm{Equip}_{quote} := 817050$$

$$\text{Size} := \frac{\text{CH4}_{\text{biogas}}}{63\%} = \begin{pmatrix} 16.669 \\ 33.337 \\ 66.674 \end{pmatrix} \cdot \frac{m^3}{hr}$$

$$\text{Size}_{\text{quote}} := 2700 \cdot \frac{m^3}{hr}$$

$$\text{Equip}_{\text{scrub}} := \text{Equip}_{\text{quote}} \cdot \left(\frac{\text{Size}}{\text{Size}_{\text{quote}}} \right)^{0.6} = \begin{pmatrix} 3.86 \times 10^4 \\ 5.85 \times 10^4 \\ 8.868 \times 10^4 \end{pmatrix}$$

$$\text{Equip}_{\text{quote}} := 260000$$

$$\text{Size} := \frac{\text{CH4}_{\text{biogas}}}{63\%} = \begin{pmatrix} 16.669 \\ 33.337 \\ 66.674 \end{pmatrix} \cdot \frac{m^3}{hr}$$

$$\text{Size}_{\text{quote}} := 2700 \cdot \frac{m^3}{hr}$$

$$\text{Equip}_{\text{offgas}} := \text{Equip}_{\text{quote}} \cdot \left(\frac{\text{Size}}{\text{Size}_{\text{quote}}} \right)^{0.6} = \begin{pmatrix} 1.228 \times 10^4 \\ 1.862 \times 10^4 \\ 2.822 \times 10^4 \end{pmatrix}$$

$$\text{Scrub}_{\text{cap}} := \left(\text{Equip}_{\text{scrub}} + \text{Equip}_{\text{offgas}} \right) \cdot 2 \cdot 125\% = \begin{pmatrix} 1.272 \times 10^5 \\ 1.928 \times 10^5 \\ 2.922 \times 10^5 \end{pmatrix}$$

Power Costs

Pressurization of gas included included in pressurization for vehicle fuel

Water Circulation

$$\text{Power} := \frac{\frac{\text{Size}}{2700 \cdot \frac{m^3}{hr}} \cdot 1800 \cdot \frac{m^3}{hr} \cdot 8 \cdot \text{bar}}{\varepsilon_p \cdot \varepsilon_m} = \begin{pmatrix} 3.579 \\ 7.158 \\ 14.315 \end{pmatrix} \cdot kW$$

Tail Gas biofilter - Assume 5 kW

Natural Gas Pipeline Compressors - Based on Glauder from Miami-Dade

Capital Costs

$$\mathrm{Equip}_{\mathrm{quote}} := \frac{975000}{8}$$

$$\mathrm{Size} := \mathrm{CH4}_{\mathrm{biogas}} = \begin{pmatrix} 10.501 \\ 21.002 \\ 42.005 \end{pmatrix} \cdot \frac{m^3}{hr}$$

$$\mathrm{Size}_{\mathrm{quote}} := 268 \cdot \frac{ft^3}{min}$$

$$\mathrm{Equip}_{\mathrm{flow.based}} := \mathrm{Equip}_{\mathrm{quote}} \cdot \left(\frac{\mathrm{Size}}{\mathrm{Size}_{\mathrm{quote}}} \right)^{0.6} = \begin{pmatrix} 1.27 \times 10^4 \\ 1.924 \times 10^4 \\ 2.917 \times 10^4 \end{pmatrix}$$

$$\mathrm{Equip}_{\mathrm{quote}} := \frac{975000}{8}$$

$$\mathrm{Size} := 206kPa$$

$$\mathrm{Size}_{\mathrm{quote}} := 50 \cdot psi$$

$$\mathrm{Equip}_{\mathrm{pressure.based}} := \mathrm{Equip}_{\mathrm{quote}} \cdot \left(\frac{\mathrm{Size}}{\mathrm{Size}_{\mathrm{quote}}} \right)^{0.6} = 8.948 \times 10^4$$

$$\mathrm{Scrub}_{\mathrm{cap}} := \left(\frac{\mathrm{Equip}_{\mathrm{flow.based}} + \mathrm{Equip}_{\mathrm{pressure.based}}}{2} \right) \cdot 2 \cdot 125\% = \begin{pmatrix} 1.277 \times 10^5 \\ 1.359 \times 10^5 \\ 1.483 \times 10^5 \end{pmatrix}$$

Power Requirements

$k := 1.4$ Typical Value for k in adiabadic compressor calculations

$$\mathrm{Comp}_{\mathrm{NG.Power}} := \frac{\frac{k}{k-1} \cdot \mathrm{CH4}_{\mathrm{biogas}} \cdot 1 \cdot atm \cdot \left[\left(\frac{206kPa}{1 \cdot atm} \right)^{\frac{k-1}{k}} - 1 \right]}{\varepsilon_p \cdot \varepsilon_m} = \begin{pmatrix} 0.337 \\ 0.674 \\ 1.348 \end{pmatrix} \cdot kW$$

Microturbine Compressors - Based on Glauder from Miami-Dade

Capital Costs

$$\text{Equip}_{\text{quote}} := \frac{975000}{8}$$

$$\text{Size} := \text{CH4}_{\text{biogas}} = \begin{pmatrix} 10.501 \\ 21.002 \\ 42.005 \end{pmatrix} \cdot \frac{m^3}{hr}$$

$$\text{Size}_{\text{quote}} := 268 \cdot \frac{ft^3}{min}$$

$$\text{Equip}_{\text{flow.based}} := \text{Equip}_{\text{quote}} \cdot \left(\frac{\text{Size}}{\text{Size}_{\text{quote}}}\right)^{0.6} = \begin{pmatrix} 1.27 \times 10^4 \\ 1.924 \times 10^4 \\ 2.917 \times 10^4 \end{pmatrix}$$

$$\text{Equip}_{\text{quote}} := \frac{975000}{8}$$

$$\text{Size} := 620kPa$$

$$\text{Size}_{\text{quote}} := 50 \cdot psi$$

$$\text{Equip}_{\text{pressure.based}} := \text{Equip}_{\text{quote}} \cdot \left(\frac{\text{Size}}{\text{Size}_{\text{quote}}}\right)^{0.6} = 1.733 \times 10^5$$

$$\text{Scrub}_{\text{cap}} := \left(\frac{\text{Equip}_{\text{flow.based}} + \text{Equip}_{\text{pressure.based}}}{2}\right) \cdot 2 \cdot 125\% = \begin{pmatrix} 2.325 \times 10^5 \\ 2.407 \times 10^5 \\ 2.531 \times 10^5 \end{pmatrix}$$

Power Requirements

$k := 1.4$ Typical Value for k in adiabadic compressor calculations

$$\text{Comp}_{\text{MT.Power}} := \frac{\frac{k}{k-1} \cdot \text{CH4}_{\text{biogas}} \cdot 1 \cdot atm \cdot \left[\left(\frac{620kPa}{1 \cdot atm}\right)^{\frac{k-1}{k}} - 1\right]}{\varepsilon_p \cdot \varepsilon_m} = \begin{pmatrix} 1.016 \\ 2.033 \\ 4.065 \end{pmatrix} \cdot kW$$

Vehicle Fuel Compressors

Capital Costs are a component of the vehicle fueling station

Power Requirements - Isothermal Compression

$$\text{Comp}_{\text{input}} := 1 \cdot atm \cdot \text{CH4}_{\text{biogas}} \cdot \ln\left(\frac{24800 \cdot kPa}{1 \cdot atm}\right) = \begin{pmatrix} 1.626 \\ 3.251 \\ 6.503 \end{pmatrix} \cdot kW$$

Assume heat dissipation to maintian isothermal compression equal to power input to the compressor. Assume compressor 55% efficient.

$$\mathrm{Comp}_{\mathrm{VF.power}} := \mathrm{Comp}_{\mathrm{input}} + \frac{\mathrm{Comp}_{\mathrm{input}}}{55\% \cdot \varepsilon_{m}} = \begin{pmatrix} 4.839 \\ 9.677 \\ 19.354 \end{pmatrix} \cdot \mathrm{kW}$$

Appendix Q: Engineering Guidance Document

ESTCP

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Water Environment Research Foundation
Collaboration. Innovation. Results.

ENGINEERING GUIDANCE REPORT

RENEWABLE ENERGY PRODUCTION FROM DoD INSTALLATION SOLID WASTES BY ANAEROBIC DIGESTION

ESTCP Project ER-200933

Scott Vandenburgh and Patrick J. Evans
CDM Smith

June 2016

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14. ABSTRACT

Food waste generation and disposal is a significant source of greenhouse gas emissions and lost opportunity for energy recovery. Anaerobic digestion of food waste and purification of methane-rich biogas was conducted at the US Air Force Academy. Cost and performance of the technology with respect to renewable energy efficiency; biogas purification; digester capacity and stability; waste sludge generation and characteristics; operational reliability, safety, and ease of use; and greenhouse accounting were evaluated. Demonstration results indicated the process was capable of meeting or exceeding most performance objectives. The technology was capable of significant reductions in the solid waste stream while at the same time recovering energy that can be used as vehicle fuel or a variety of other uses. Cost-effectiveness of the technology was comparable or better to landfilling and composting especially for larger installations. The technology was also demonstrated to have favorable greenhouse gas offsets compared to composting and landfilling. An engineering guidance document was prepared that provides installations practical approaches for technology evaluation and implementation.

15. SUBJECT TERMS

Food waste, FOG, solid waste, anaerobic digestion, methane, biogas, biomethane, biogas purification, vehicle fuel, renewable energy, net zero, greenhouse gas, food-to-fuel.

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1.0 INTRODUCTION

This project demonstrated both the technological and the economic viability of anaerobic digestion of Department of Defense (DoD) wastes including pre- and post-consumer food waste, waste cooking oil, and grease trap waste as a viable means of disposal and renewable energy generation. The project demonstrated the ability to digest these wastes in a controlled and predictable manner to maximize the generation of biogas, a methane-rich, high energy product. The project also evaluated the economic viability and potential greenhouse gas offsets with the technology especially when biomethane was used as vehicle fuel. Full details of the ESTCP demonstration can be found in the Final Report (Evans et al. 2016). This document provides engineering guidance for DoD installations considering implementing of the technology.

2.0 BACKGROUND

The DoD is a significant consumer of energy and generator of solid waste. During FY 2009 the DoD consumed 209 trillion BTUs of energy (2.2×10^{17} J), excluding vehicle fuel (DoD 2010). Further, during the same period the DoD generated 5.2 million tons of solid waste. The consumption of energy and the generation of waste place economic, environmental and social burdens on the DoD. In recognition of the burden that these activities place on the Department, the DoD has initiated programs and policies to reduce energy consumption and waste generation.

- The Energy Policy Act of 2005 (EPACT) mandates that federal facilities receive at least 7.5% of their electricity from renewable resources by 2013. If the energy is generated on site from renewable resources the facilities receive double credit toward attainment of this goal.
- The 2008 National Defense Authorization Act (NDAA) implemented a renewable energy goal of 25% for the DoD.
- Executive Order 13423 requires that at least half of the statutorily required renewable energy consumed by the agency in a fiscal year comes from a new renewable source and to the extent feasible, the agency implement renewable energy generation projects on agency property for agency use. Further, the order requires increased diversion of solid waste as appropriate and maintenance of cost effective waste prevention and recycling programs in its facilities (USDOE 2008).
- The DOD Integrated (Non-Hazardous) Solid Waste Management Policy set minimum standards of 40% waste diversion of non-hazardous, non-construction and demolition integrated solid waste (Beehler 2008).

This project demonstrated utilization of anaerobic digestion to treat DoD wastes and produce renewable energy that can offset an installation’s energy demands and reduce its waste disposal rate. This project was measured against 30 performance objectives identified prior to the commencement of the research project. In total, the project met most of these objectives. Most notably, the project met objectives related to the following objectives:

- Energy Conversion
- Methane Production
- Natural Gas Specifications
- Loading Rate
- Solids Destruction
- Safety
- Ease of Use

The first three objectives from the list above were important as they showed that the process could be efficient, produce a valuable fuel that could be purified into a common fuel – compressed natural gas (CNG). Further the loading rate and the solids destruction objectives proved that a target loading rate could be achieved and that the process would significantly reduce the mass of product for ultimate disposal. Safety is always paramount so by showing that the process was safe and further easy to use, it proved that it could be implemented at a DoD installation.

By using the data obtained from the study, full-scale implementation was costed. The costs identified that significant amount of capital would need to be utilized to get the project started. However, the cost savings were significant enough that the project was competitive with common food waste disposal methods. In all the project estimated that a full-scale facility at various installations ranging from 10,000 personnel to 40,000 personnel had the capability to annually produce 25,000 gasoline gallon equivalents of biomethane (at a 10,000 personnel base), 50,000 gasoline gallon equivalents of biomethane (20,000 personnel base), and 99,000 gasoline gallon equivalents of biomethane at a 40,000 personnel base. At current gas prices this equated to an estimated food waste disposal cost as low as $50 per wet ton at the 10,000-personnel base and $22 per wet ton at the 20,000-personnel base. For the larger base of 40,000 personnel, the project projected to provide revenue at $2 per wet ton of food waste generated. In comparison, the cost of landfilling across the United States is $50 per wet ton and composting costs range from $29 to $52 per wet ton.

3.0 DRIVERS

There are many drivers for this project. As the costs obtained from the study indicate, there is an economic driver to implement the project. In addition, there are regulatory drivers as listed below.

- The DoD Strategic Sustainability Performance Plan provides an approach towards meeting these requirements which includes a focus on: 1) reducing energy needs and reliance on fossil fuels; and 2) water resources management.
- American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) 189.1-2009, Leadership in Energy and Environmental Design (LEED) and various Energy Policy Acts all have required more sustainable use of energy.
- The Army has implemented a Net-Zero installations policy seeking to increase and improve sustainability on installations.
- In addition, several other orders and acts promote energy sustainability and minimization of waste generation including:
- EPACT 2005
    - EO 13423
    - 10 United States Code 2577
    - Energy Independence and Security Act 2007
    - FY2008 NDAA
    - Pollution Prevention Act of 1990
    - DoD Instruction 4715.4 “Pollution Prevention”
    - DoD Integrated Solid Waste Management Policy

4.0 IMPLEMENTATION CHALLENGES

This study showed that there are considerable opportunities for food waste digestion at DoD installations. However, there are a number of challenges to get the project going. These challenges fall into the following categories: risk, familiarity with technology and compatibility with installation mission, costing gap analysis, and local conditions and markets.

4.1 RISK

The project requires significant risk of capital. In total the project is estimated to cost between $930,000 to $2.4 million depending on the size of the facility. Although, the program showed that the project was technologically feasible and met nearly all of the performance objectives, the anaerobic digesters showed signs of stress in the Phase III part of the study. Further, Phase IV was not run to full completion and quasi-steady state conditions were not achieved in Phase IV. Additionally, mono-digestion of food waste is not yet common throughout the country. Long term analysis of the impacts to pumping equipment and other components of the digestion were not determined in the study.

Additionally, the economics of the process are related to current market conditions. Some of the market risks are mitigated because gasoline prices are currently low relative to recent past. However, gasoline prices are extremely volatile. The costs are much less sensitive to electrical power costs relative to gasoline prices, but a steep rise in power costs may impact the financial viability of the project. Finally, the vehicle fuel cost contains fuel taxes. This is important as some states, such as Oregon, are moving away from fuel taxes toward taxing vehicles on miles driven. This could reduce the cost savings of the project.

4.2 FAMILIARITY WITH TECHNOLOGY AND COMPATIBILITY WITH FACILITY MISSION

Although anaerobic digestion is ubiquitous at wastewater treatment plants, they do not exist in great numbers at DoD installations. As such, implementation may require new staff or additional training of staff for the technology. Because the skillset will be unlike most other jobs on the installation, it may be necessary to train more than one staff member in the position so that the job is covered during vacations, sick leave, and staff turnover. Additionally, staffing projections for the facility do not warrant a full time position. Therefore, the staff dedicated to this will likely have other jobs.

4.3 COSTING GAP ANALYSIS

The final report on this project identified that the technology was cost competitive with current food waste disposal methods. However, it also identified two cost components that were not included in the technology. One of the end products of the study is a compressed biomethane, similar to compressed natural gas that can fuel a vehicle. The cost components of the study to not cover the cost of vehicle conversion to run on compressed biomethane. The cost of vehicle conversion is not widely published. However, the Honda Civic is currently offered with a gasoline engine or can be purchased to run on CNG. Based on the Manufacturers Suggested Retail Price (available from Honda.com) a Honda Civic with a CNG engine likely costs between $6,000 and

$8,000 more than a gasoline engine. Assuming an average fuel economy of 30 miles per gallon and around 7000 miles driven annually from a typical fleet vehicle, a base may need to retrofit or newly purchase between 110 to 430 (depending on installation size) CNG vehicles to fully utilize the biomethane produced from the digesters. As a result the missing cost for this conversion is likely in the range of $750,000 to $3,000,000 for a vehicle fleet capable of fully utilizing the biomethane.

Another cost not identified was the digestate disposal cost. Due to the significant solids destruction of the food waste in the anaerobic digester, the digestate could likely flow to a local water reclamation facility in the sewer system. As such, there are no expected transportation or hauling costs associated with the digestate. However, the local water reclamation facility may consider this a high strength discharge and elect to charge a service fee for handling it. Service fees from wastewater utilities vary depending on local conditions.

4.4 LOCAL CONDITIONS AND MARKETS

Local conditions and markets should be weighed prior to commencing with a food waste digester project. The costs for landfilling and composting as well as energy and gasoline prices were based on national averages. Local conditions may vary and impact the economic feasibility. In locations where gasoline tends to be higher, such as California, the anaerobic digestion process may be more economically feasible. However, in locations with low gasoline costs, high power costs, and low landfill tipping fees, the project may not be economically competitive.

Local staff acceptance may impact the ability of the project to succeed. In locations where the facility is a long way from typical transportation destinations, the reduced range of a CNG vehicle may not be acceptable. CNG vehicles typically have less than half the range compared to gasoline fueled vehicles. As such, drivers of the vehicles will have less flexibility for long trips. Additionally, the projections identify the production of between 68 gasoline gallon equivalents per day at a 10,000 personnel base to 270 gasoline gallon equivalents per day at the 40,000 personnel base. Installations should consider current fuel demands prior to investment. In the event that there is no demand for the converted biogas then this excess fuel would need to be flared and have no value to offset capital purchases.

5.0 ALTERNATE PROJECT CONSIDERATIONS

Section 4.0 discussed the challenges to implementing the project as a standalone facility at a DoD installation. As a result, it may be appropriate to explore alternate options. More proven than mono-digestion of food waste is co-digestion of food waste with wastewater solids. Co-digestion has become quite common at wastewater treatment plants as these facilities look to maximize their existing assets in their anaerobic digestion and energy systems. The facilities typically, receive a tipping fee for receiving the material and then are able to maximize the output of their engine generation equipment.

Co-digestion would be an option for any DoD installation that generates food waste. It would be a particular advantage for facilities that already have anaerobic digesters, like the United States Air Force Academy and Joint Base Lewis McCord. Although there facilities may not currently have energy production equipment such as biogas scrubbers and vehicle fueling systems, the costs of implementing these features would be reduced compared to a mono-digestion facility that would require the construction of the digestion facilities in addition to the energy recovery facilities. Further, the co-digestion within a DoD installation that already has anaerobic digestion would increase the total energy value in the biogas over a mono-digestion facility that processes only food waste or only municipal wastewater solids. This would effectively make more technologies available for utilization including combined heat and power generation facilities. Finally, the use of co-digestion eliminates the need for a sewer discharge fee that may be required to release digestate into a municipally owned wastewater treatment plant.

Prior to implementing co-digestion at a DoD-owned wastewater treatment plant the facility would need to be checked to determine if the existing digesters have capacity and ensure that the food waste does not impact the wastewater biosolids that would bring them out of compliance with existing regulations.

Since very few DoD installations have anaerobic digestion facilities on site, another option would be to investigate partnering with a local municipality. Many municipalities are already co-digesting on within their facilities and more are studying the process. Although, implementation of co-digestion at a DoD installation may have limited impact in the accounting of greenhouse gasses as the wastewater treatment utility would likely earn the greenhouse gas credits, the DoD installation may be able to reduce costs compared to traditional methods of food waste disposal. DoD installations should explore these partnerships and assess if a requested tipping fee for the food waste disposal is less than the current contracts for landfilling or for composting. Of note, the wastewater utility may require some pre-processing or pre-sorting of the food waste prior to delivery. It would be important to understand what the utility would like with regard to the food waste.

6.0 IMPLEMENTATION DESIGN RECOMMENDATIONS

Implementation of a food waste digestion or co-digestion facility should be well thought out and planned. **Figure 1** shows a potential decision tree for assessing if co-digestion or mono digestion of food waste is appropriate for a DoD installation. Based on the logic diagram, there are four potential outcomes (1) co-digestion at a DoD owned facility, (2) mono-digestion at a DoD owned facility, (3) co-digestion at a partner facility, or (4) continue with current food waste disposal methods.

This decision tree is only a quick tool to determine if food waste digestion may be appropriate. It should be noted that prior to commencing any food waste digestion program, a detailed study be conducted for the specific DoD installation. The decision tree identifies that a partnership with a local agency should be investigated, then negotiations should be conducted. Negotiations should target a tipping fee that is less than the results of the study conclusions. For example, facilities with populations less than 10,000 should consider tipping fees less than approximately $58 per wet ton or less than the facilities current disposal costs. Facilities around 20,000 should consider tipping fees less than $22 per wet ton. Large facilities should only consider partnerships with agencies willing to take the food waste at essentially no cost. It is likely that a site specific study will be needed to confirm these values and assist in negotiations. The site specific study would need to identify costs for the facility assuming a fully independent handling and handling of food waste and recovery of the generated biogas at the base.

Upon confirmation that food waste digestion provides a benefit, the installation should consider a number of factors in the facility design. A list of design criteria for a full-scale system is as shown in **Table 1**.

Table 1 presents the key results from this study that can be used to size equipment and facilities for an independent food waste handling system. It should be noted that **Table 1** does not include the influent characteristics of the food waste. These characteristics should be assessed based on actual food waste data from the plant. The researchers recognize that the food waste generated at the Air Force Academy and used as the basis for this study may be different than at other facilities. Food waste characteristics will affect digester performance but COD and SELR were determined to be a useful parameters for evaluating food waste suitability. In addition, Experience with co-digestion of food waste also suggests a minimum COD of 20,000 mg/L with the optimum > 50,000 mg/L (Hare 2016). The minimum VS/TS value is 65% with the optimum being > 85%. Also refer to Appendix C in the Final Report (Evans et al. 2016) for information relevant to desired waste stream characteristics. Further, the processing applied at the Air Force Academy, specifically the grinder and pulper, may not exist at all facilities. As a result, the facility will need to work with potential vendors of food waste pulping and grinding systems. These vendors are likely to process the food waste differently, which may have impacts on the food waste concentration and other characteristics.

Figure 1. Decision tree for evaluation of anaerobic food waste digestion options.

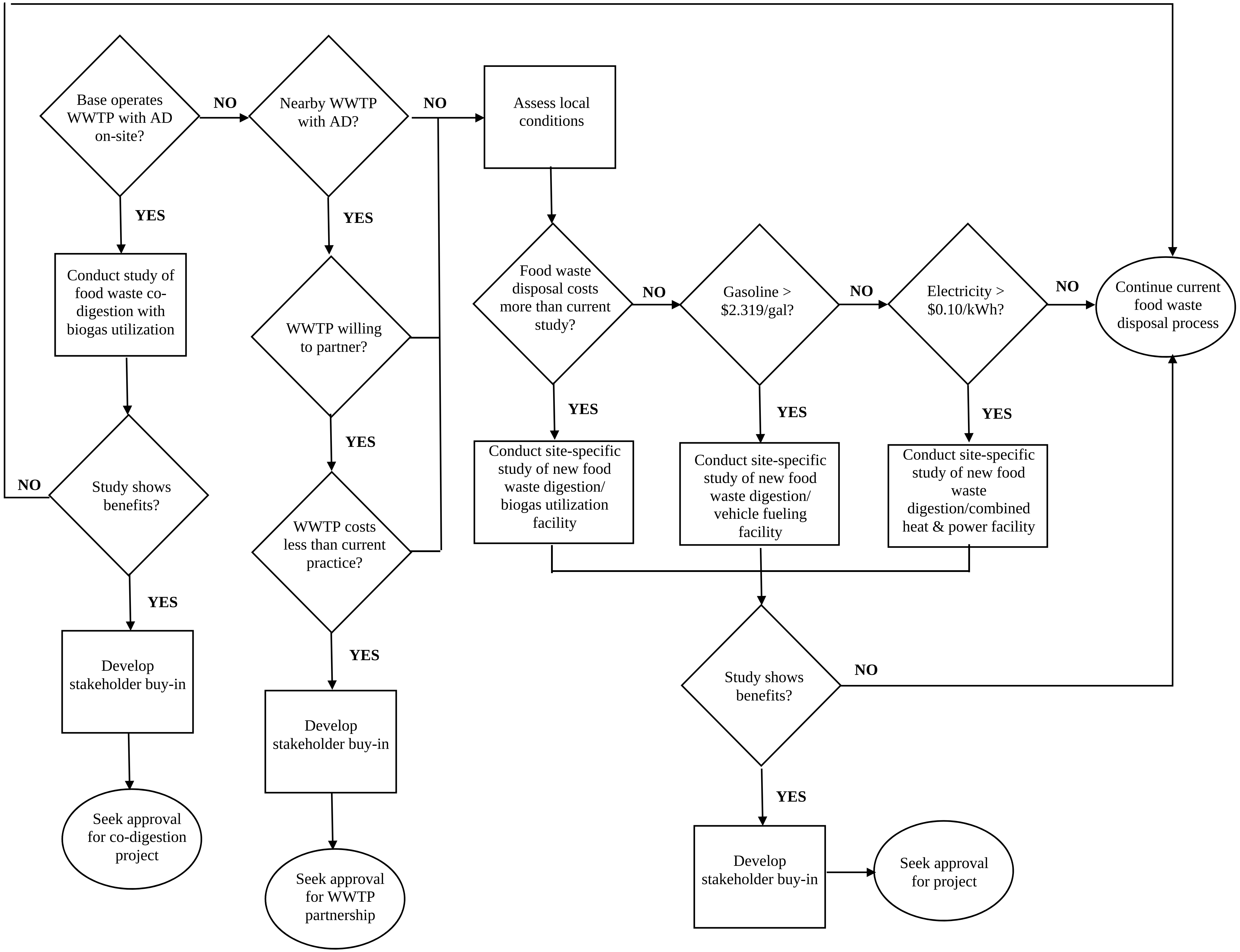
Base operates WWTP with AD on-site?
NO
Nearby WWTP with AD?
NO
Assess local conditions
YES
YES
Conduct study of food waste co-digestion with biogas utilization
WWTP willing to partner?
Food waste disposal costs more than current study?
NO
Gasoline > $2.319/gal?
NO
Electricity > $0.10/kWh?
NO
Continue current food waste disposal process
YES
YES
YES
YES
Conduct site-specific study of new food waste digestion/ biogas utilization facility
Conduct site-specific study of new food waste digestion/ vehicle fueling facility
Conduct site-specific study of new food waste digestion/combined heat & power facility
NO
Study shows benefits?
WWTP costs less than current practice?
YES
YES
Develop stakeholder buy-in
Develop stakeholder buy-in
Study shows benefits?
NO
YES
Develop stakeholder buy-in
Seek approval for co-digestion project
Seek approval for WWTP partnership
Seek approval for project

Table 1. Design criteria.

Parameter	Suggested Design Value	Comments
Methane Production (VS basis)	400 L CH_4/kg VS loaded	Use design value to predict methane production from digester. Use for sizing gas utilization equipment and determining potential revenues and offsets from biogas utilization
Methane Production (COD basis)	250 CH_4/kg COD loaded	Use design value to predict methane production from digester. Use for sizing gas utilization equipment and determining potential revenues and offsets from biogas utilization
Specific COD loading rate (SELR)	0.44 g-COD/g-VSS/day	Use design value for sizing the anaerobic digestion facilities.
pH	7.8	Design value for understanding operational pH in digester
TS Reduction	78%	Use design value for projecting solids to be disposed after process
VSS Reduction	92%	Use in combination with SELR to size anaerobic digestion facilities
Biogas CH_4 Content	60%	Use in combination with methane production to determine size of required digester gas piping and other digester gas conveyance system, flares, etc.
Biogas H_2S Content	2,900 mg/m^3	Use to size hydrogen sulfide removal systems

7.0 LESSONS LEARNED

Overall, the pilot digestion system was determined to be operationally friendly once it was up in running and the troubleshooting period was over. A full-scale facility should have less problems and troubleshooting requirements compared to the pilot. This is in part because a full-scale system would likely use larger pumps, with larger clearances, that are less susceptible to plugging. Further, there are many mechanical grinding equipment that are available and marketed to the wastewater treatment industry. These equipment tend to be sized for full-scale installations and are not easily deployed at the pilot scale.

Safety is the primary concern with a digestion process and the hydrogen sulfide release that occurred in the pilot facility necessitates that a full-scale facility be designed to mitigate potential safety hazards. As with pilot scale facility, it is prudent to construct the digestion facilities in compliance with the National Fire Protection Association (NFPA) publication 820. Although, this publication is for wastewater treatment facilities there is no equivalent publication for a food waste system. NFPA 820 will dictate the electrical classification for equipment, provide design requirements for heating and ventilation systems, and specify the monitoring requirements. NFPA 820 doesn’t specifically address hydrogen sulfide.

This study showed that solids destruction in food waste digestion is high compared to municipal wastewater treatment plant digesters. As a result, the stability of the digestion process was challenging to maintain in the third phase of the study. To compensate for the high solids destruction and loss of alkalinity, CDM Smith conducted Phase Iv of the study. Phase 4 utilized the digestate from the effluent of the digestion process to dilute the food waste to a concentration deemed to be pumpable. This effectively recycled solids and alkalinity back to the digesters and appeared to mitigate the stability issues in Phase III. As a result, future projects should consider using digestate to dilute the food waste solids for pumpability.

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APPENDICES

Appendix A: Points of Contact

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone E-mail	Role in Project
Andrea Leeson, Ph.D.	ESTCP 4800 Mark Center Drive, Suite 17D08 Alexandria, VA 22350-3605	(571) 372-6398 Andrea.Leeson.civ@mail.mil	ESTCP Program Manager
Lauren Fillmore	Water Environment Research Foundation 635 Slaters Lane, Suite G-110 Alexandria, VA 22314	(571) 384-2107 lfillmore@werf.org	WERF Senior Program Director
Patrick Evans, Ph.D.	CDM Smith 14432 SE Eastgate Way, Suite 100 Bellevue, WA 98007	(206) 351-0228 evanspj@cdmsmith.com	Principal Investigator
H. David Stensel, Ph.D.	The University of Washington 303 More Hall, Box 352700 Seattle, WA 98195-2700	(206) 543-9358 stensel@uw.edu	Co-Principal Investigator (ADM1 modeling, anaerobic digestion)
Ambal Jayaraman, Ph.D.	TDA Research, Inc. 12345 W 52nd Avenue Wheat Ridge, CO 80033	(303) 940-5391 ajayaraman@tda.com	Co-Principal Investigator (biogas purification)

Appendix B: Economics Analysis White Paper

CDM

Memorandum

To: *Dr. Andrea Leeson*

From: *Dr. David Parry, Dr. Patrick Evans and Cale McPherson*

Date: *January 31, 2010*

Subject: *Economics White Paper for ER-200933, Renewable Energy Production from DoD Installation Solid Waste by Anaerobic Digestion*

This white paper provides a preliminary expression of the projected economic benefit for the anaerobic digestion of DoD installation solid waste. Projections made within are based on the best available data for construction, operation and maintenance (O&M) costs, as well the expected performance of the proposed technology. The economic analysis has been completed using the National Institute of Standards and Technology (NIST) Building Life-Cycle Cost (BLCC) Program for MILCON Analysis: ECIP Project.[1] This methodology and white paper were requested by the SERDP/ESTCP Program Office in during the Fall, 2010 In-Progress Review.

Base-Case and Proposed Technology Definition

The ECIP Life-Cycle Cost analysis tool requires user inputs that define the capital and O&M costs and savings for the alternative/technology of interest. Costs and savings are based on a comparison with a base-case or do-nothing alternative. For this economic analysis it was assumed that food waste and other digestible organics would be diverted from disposal in a landfill (the base-case) to an organic waste anaerobic digestion system with energy recovery (the proposed technology). To provide a consistent basis of comparison, a population of 50,000 individuals was assumed. Per capita waste generation was estimated at 0.6 pounds of wet waste per day as reported by an EPA study published in 2008.[2] Additional alternative specific assumptions are described below.

Base-Case: Landfilling

Landfilling of organic waste was the assumed base-case as it is the most common disposal method currently employed within the United States. According to the 2008 EPA study, 31.7 million tons of food waste is disposed of each year in the United States. Over 97 percent of the waste is disposed of without recovery, and 87 percent of the waste ends up in a landfill.

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[1] Federal Energy Management Program: Information Resources, 2010

[2] U.S. EPA, 2008

The average cost for disposal at a landfill in the United States is $43.99 per wet ton, with a range between $15 and $120 per wet ton.[3]

Based on these assumptions, the disposal of food waste from 50,000 individuals would cost an average of $241,000 per year with a range of $82,000 to $657,000.

Proposed Technology: Anaerobic Digestion

The initial definition and cost estimate for the anaerobic digestion and energy recovery system is based on a source separated organic stream, a Greenfield site for installation, complete mix digesters, biogas recovery to generate a renewable compressed natural gas (rCNG) vehicle fuel, and national averages for construction, O&M, power and vehicle fuel costs. Major pieces of infrastructure and equipment included:

- Complete Mix Anaerobic Digesters (tanks, piping, mixing equipment, etc.)
- Hot Water Boilers for digester heating
- Processing and Dewatering Equipment
- Biomethane Treatment to bring the biogas to natural gas quality
- rCNG Fueling Infrastructure to compress the biomethane and dispense it as a vehicle fuel equivalent in quality to CNG, but renewable in nature

Additional process specific assumptions are provided in Table 1 with references given in the attached calculations sheet.

Table 1
Process Assumptions for Life-cycle Cost Analysis

Process Characteristic	***Value***	***Units***
Source Food Waste Solids Content	30	%
Source Food Waste Volatile Solids: Total Solids Ratio	0.86	lbs VS/lbs TS
Digester Solids Residence Time (SRT)	20	days
Digester Feed Solids Content (Loading)	10	%
Digester Volatile Solids Loading Rate	0.27	lbs VS ft^{-3} day^{-1}
Volatile Solids Destruction	80	%
Biogas Yield	22	ft^3/lb VS destroyed
Biomethane Treatment Efficiency	95	%
Produced Biosolids Solids Content	25	%

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[3] Waste Business Journal, 2010

Capital and O&M costs for the equipment and infrastructure were based off of recent construction costs and estimates performed by CDM for installations around the United States and Canada including: St. Joseph, MS; Edmonton, AB; Deer Island, MA; Seattle, WA; Des Moines, IA and Dallas, TX. Unit capital costs were compared to industry reports where possible to confirm the accuracy of estimations.[4] [5]

The capital costs for the digestion and energy recovery system are summarized in Table 2. Each line item represents the installed cost inclusive of overhead, insurance, bonding and escalations.

Table 2
Capital Costs for Anaerobic Digestion and Energy Recovery System

Item	***Capital Cost***
Anaerobic Digester	$ 1,290,000
Dewatering & Processing Equipment	$ 281,000
Biogas Boiler	$ 38,300
Biomethane Treatment System	$ 1,240,000
Vehicle Fueling System	$ 1,240,000
Subtotal	$ 4,089,300
Design	$ 818,000
Total	**$ 4,907,300**

Recurring costs of the proposed technology include power, routine and non-routine maintenance on major equipment, labor, and chemicals. Recurring savings include avoided landfill tipping fees, avoided trucking fees, avoided vehicle fuel costs from the generation of the rCNG vehicle fuel, and avoided soil amendment costs from using the digested and dewatered product for land application. A summary of these recurring costs and savings is provided in Table 3.

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[4] AgStar U.S. EPA, Jan. 2010
[5] Greer, 2007

Table 3
Recurring Costs and Savings for Anaerobic Digestion and Energy Recovery System

Item	***Cost (Savings)***
Cost	
Power Costs	$ 85,200
Anaerobic Digestion O&M	$ 64,700
Processing and Dewatering O&M	$ 37,100
Biomethane System O&M	$ 45,000
Vehicle Fueling O&M	$ 52,900
Savings	
Avoided Tipping Fees	$ (151,000)
Avoided Trucking Fees	$ (34,300)
Avoided Vehicle Fuel	$ (645,000)
Avoided Soil Amendment	$ -
Total	**$ (545,400)**

The values provided in Table 2 are based on the following assumptions:

- Power Costs: Based on national average power costs and includes power demand for all equipment.[6]

- Anaerobic Digestion O&M: Includes routine and non-routine maintenance and labor for digestion system and is based on 5 percent of the digester capital construction cost. Cost is exclusive of power costs, which are carried separately.

- Processing and Dewatering: Costs include polymer and labor demand for the processing and dewatering equipment. Cost is exclusive of power costs, which are carried separately.

- Biomethane System O&M: Includes routine and non-routine maintenance for the biomethane treatment system. Cost is based on a similar system installed at the South Treatment Plant in Renton, WA.[7] Cost is exclusive of power costs, which are carried separately.

- Vehicle Fueling O&M: Includes routine and non-routine maintenance for the vehicle fueling infrastructure (gas dryers, compressor, dispensers, control panels). Cost is based on CDM experience and reported O&M from manufacturers

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[6] U.S. Energy Information Administration, 2005
[7] Nelson, 2008

- Avoided Tipping Fees: Based on the national average for tipping fee of $43.99 per wet ton.[8] The savings is realized from diverting the food waste from the landfill to the digestion system.

- Avoided Trucking Fees: Based on an estimated trucking/hauling cost of $10 per wet ton. The savings is realized from diverting the food waste from the landfill to the digestion system.

- Avoided Vehicle Fuel: Based on the national average cost for unleaded gasoline of $2.78 averaged of the previous 12-months.[9]

- Avoided Soil Amendment: No value assumed in the initial analysis as monetizing the value of the biosolids can be difficult and is uncommon. Instead, it is assumed that all biosolids generated are sent to the landfill and are subject to standard tipping and trucking fees.

Life-Cycle Cost Analysis

Based on the above assumptions and estimates an initial baseline ECIP Life-Cycle Cost estimate was performed to determine the simple payback period, and the savings to investment ratio (SIR) for a 10-year and 20-year project life-cycles when the technology is installed under "national average" conditions. National average conditions were defined as the average cost for key economic inputs such as construction, power, tipping fee and fuel costs. However, because national average costs are only applicable to a small subset of the U.S. market and because they only capture a snapshot of current market rates, sensitivity analyses were performed to evaluate the simple payback and SIR based on changing conditions. The following is a summary of all analyses performed:

- Baseline: National average costs for power, vehicle fuel and tipping fees

- Tipping Fee Sensitivity: Tipping fee varied between $20 and $150 per wet ton

- Cost of Electricity Sensitivity: Power costs varied between $0.05 and $0.25/kWh

- Cost of Vehicle Fuel: Vehicle fuel costs varied between $2.00 and $6.50/gallon

- Digester Feed Concentration: Feed concentration to the digester varied between 5 and 30 percent.

- Biosolids Value: Biosolids value varied between $0 and $15.00 per dry ton.

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[8] Waste Business Journal, 2010
[9] U.S. Energy Information Administration, 2011

Copies of the ECIP report summaries are provided in the appendix of this memorandum for reference.

Baseline Analysis

The initial baseline alternative used national average costs for construction, O&M costs including power rates, vehicle fuel costs and tipping fees as well as the process assumptions detailed in Table 1. A summary table for baseline analysis is provided in Table 3.

Table 3
Baseline Life-Cycle Cost Analysis

Simple Payback, yrs	***SIR, 10 yrs***	***SIR, 20 yrs***
9.06	1.04	1.89

According to DoD Instruction Number 4170.11 the above project installed under "national average" conditions would meet the minimum requirements for funding. The minimum DoD requirements are a simple payback of less than 10 years and a savings to investment ratio (SIR) of 1.25.[10] For the 20-year project life-cycle, the SIR is 1.89.

Tipping Fee Sensitivity

In recognition that tipping fees vary considerably across the United States, a sensitivity analysis was conducted to explore how tipping fees ranging from $20 to $150 per wet ton would influence the life-cycle cost metrics. While this range is outside of the current range in the United States, it was selected to encompass the near term range with an expectation that tipping fees will increase in the future. Current tipping fees have been increasing at approximately 6 percent per year as the cost of construction and operation of landfills has increased.[11] This sensitivity is presented graphically in Figure 1.

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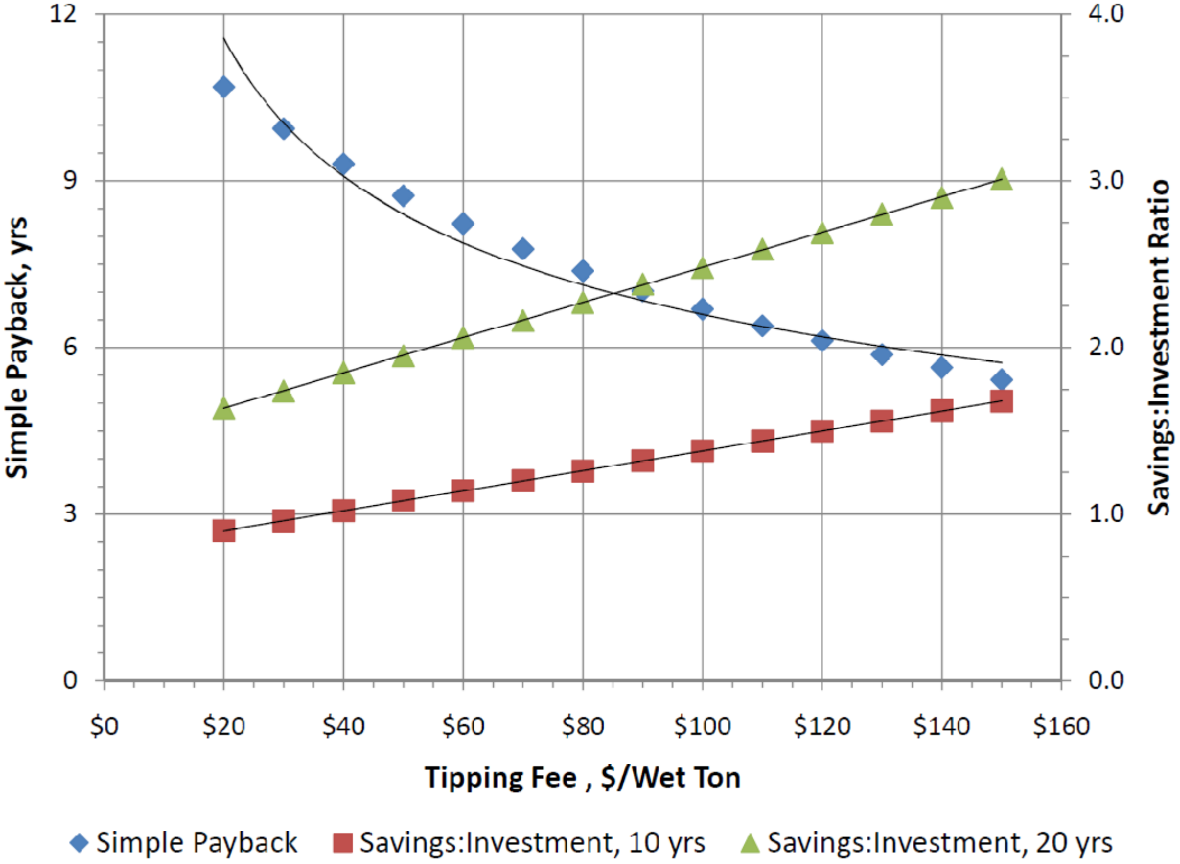
[10] U.S. Department of Defense, 2009

[11] U.S. Landfill Tipping Fees Reach New Record, Despite Economic Downturn, 2010

Figure 1
Tipping Fee Sensitivity Analysis

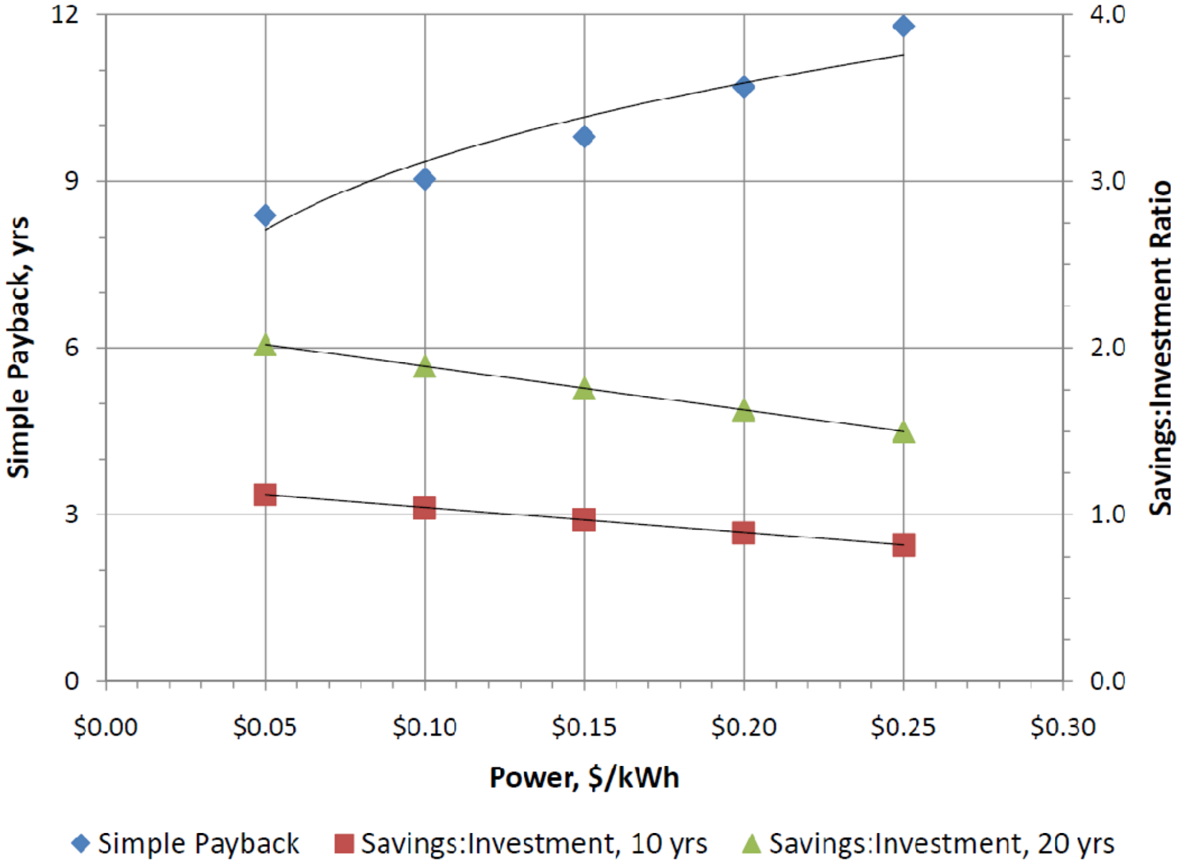


As can be noted in Figure 1, the economic metrics of the proposed technology are greatly influenced by the tipping fee associated with the waste disposal. As tipping fees increase, the simple payback reduces and the SIRs increase sharply. A minimum tipping fee of approximately $40 per wet ton is required to have a simple payback of less than 10 years. The SIR remains above 1.25 for the entire range of tipping fees for the 20-year life-cycle. For the 10-year life-cycle, a minimum tipping fee of $80 per wet ton is required to have an SIR greater than 1.25.

Cost of Electricity Sensitivity

In recognition that power costs vary considerably across the United States, a sensitivity analysis was conducted to explore how power costs ranging from $0.05 to $0.25/kWh would influence life-cycle cost metrics. This sensitivity is presented graphically in Figure 2.

Figure 2
Cost of Electricity Sensitivity Analysis

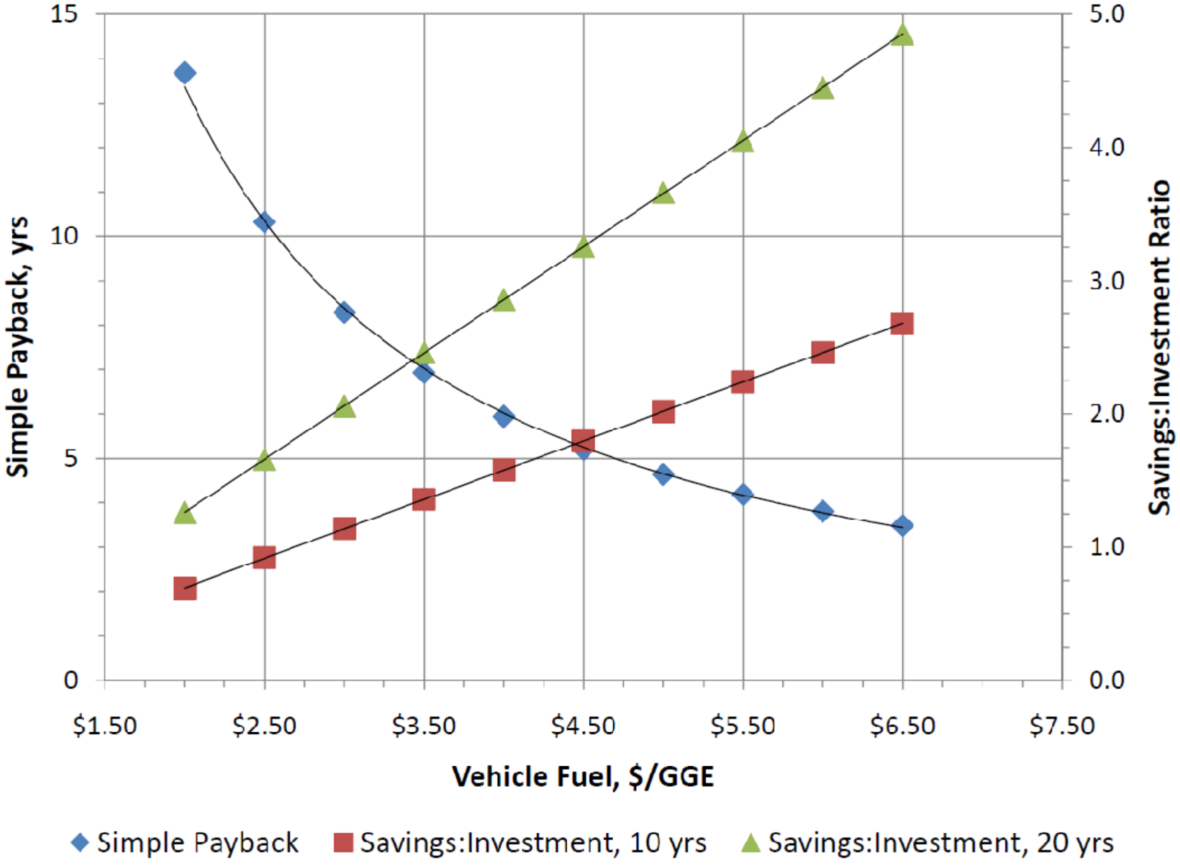


The sensitivity depicted in Figure 2 suggests that the economic metrics of the proposed technology are mildly influenced by the cost of power. As the cost of power increases, the simple payback period increases and the SIRs decrease. The reason for this is that there is a relatively significant power demand associated with the conversion of biogas to vehicle fuel. As power costs increase, the associated O&M costs increase and reduce the overall benefit of this project. In absence of other variables, the cost of power would need to remain below $0.10/kWh for the proposed technology to meet the minimum standards for DoD installations. In excess of this rate, additional variables would need to be considered to determine the viability of the technology.

Cost Vehicle Fuel Sensitivity

In recognition that the cost of vehicle fuel is volatile and that it varies across the United States, a sensitivity analysis was conducted to explore how the cost of fuel ranging from $2.00 to $6.50 per gallon would influence the life-cycle cost metrics. This sensitivity is presented graphically in Figure 3.

Figure 3
Cost of Vehicle Fuel Sensitivity Analysis

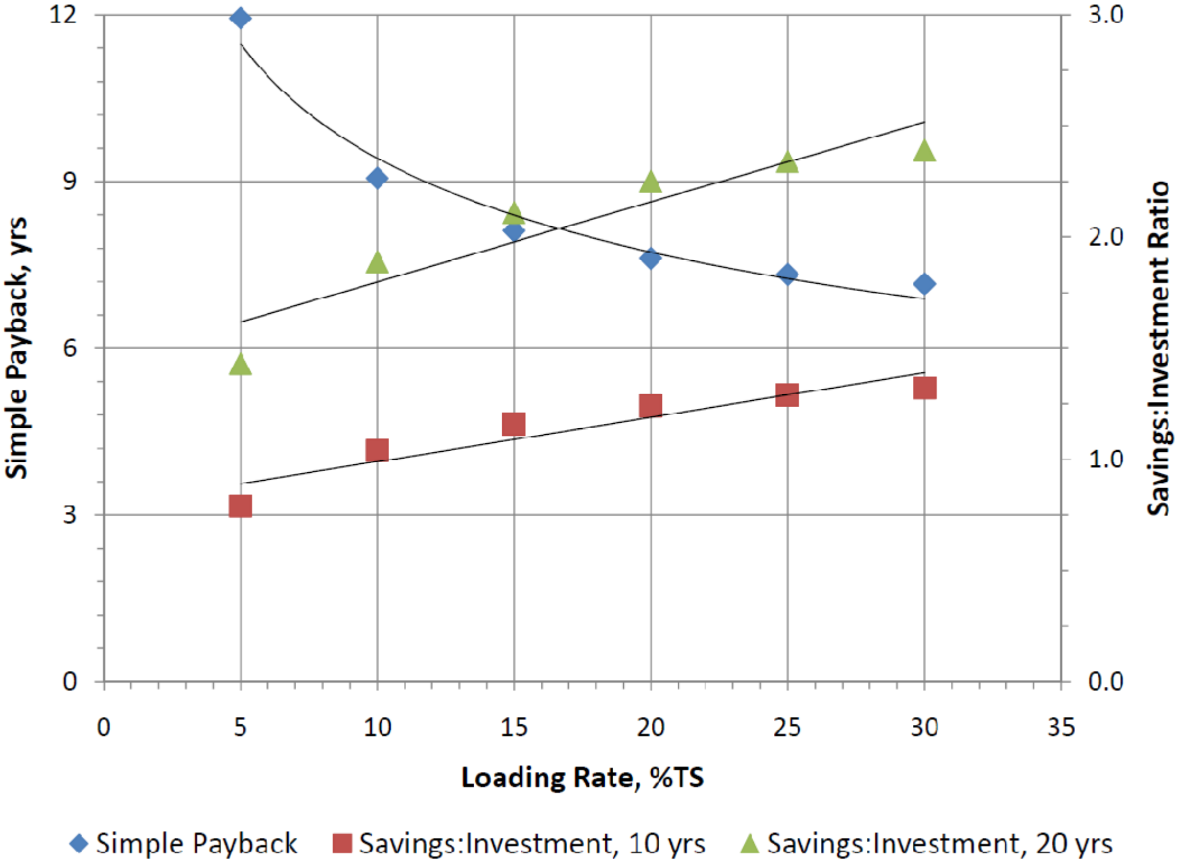


The sensitivity depicted in Figure 3 suggests that the economic metrics of the proposed technology are influenced significantly by the cost of vehicle fuel. As fuel prices increase, the simple payback period decreases and the SIRs increase. The simple payback reduces to less than 10 years and the SIR exceed 1.25 on a 20-year project life-cycle when vehicle fuel costs exceed $2.50 per gallon. This sensitivity suggests that the cost of vehicle fuel has one of the largest impacts on the economic viability of the proposed technology and thus should be considered carefully when evaluating the technology for implementation.

Digester Feed Concentration Sensitivity

The digester feed concentration and solids retention time (SRT) determines the required digester volume, which is directly related to the capital cost of the system. This sensitivity analysis explores how the feed concentration, and by extension the digester volume and capital costs, influence the economic metrics of the life-cycle analysis. For this sensitivity the assumed feed concentration was varied between 5 and 30 percent solids. This sensitivity is presented graphically in Figure 4.

Figure 4
Digester Loading Rate Sensitivity Analysis

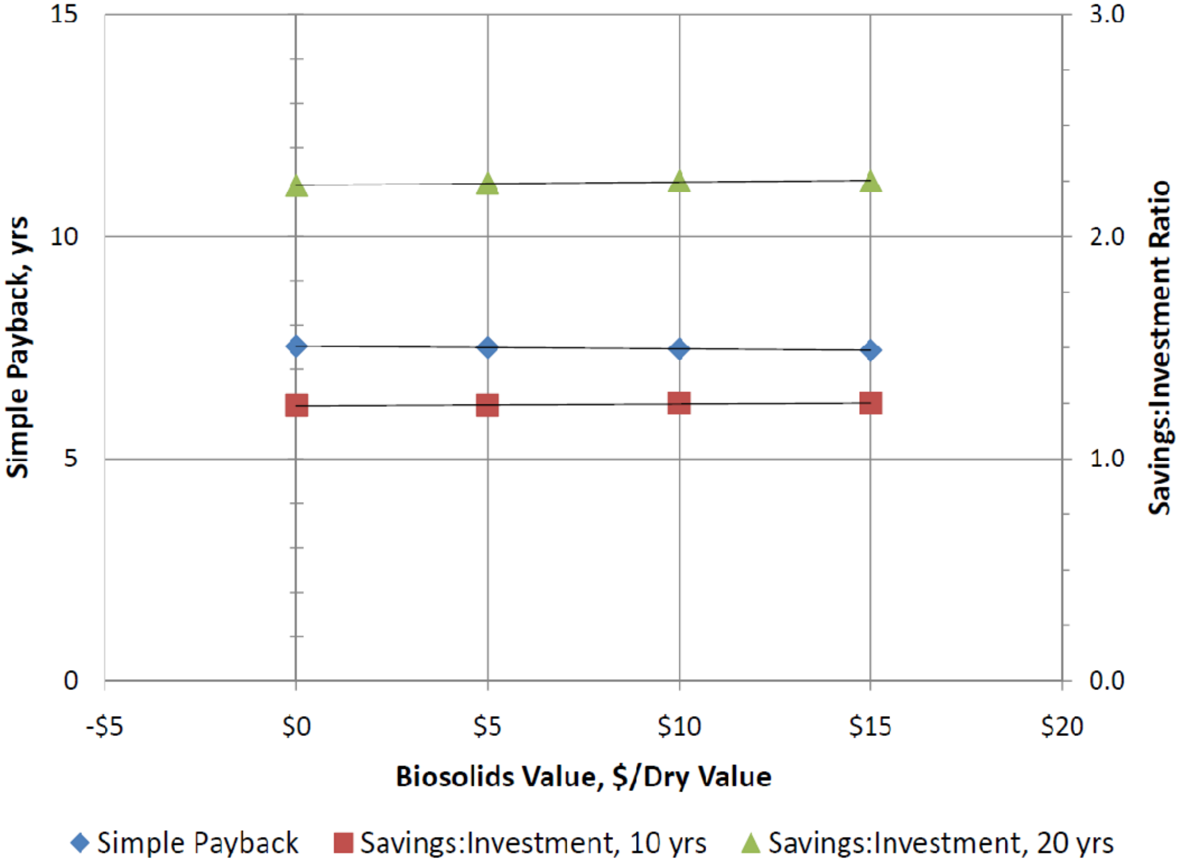


The sensitivity depicted in Figure 4 suggests that the economic metrics of the proposed technology are mildly influenced by the digester feed concentration, but that the influence is diminished as the feed concentration increases above 10 percent solids. At around 10 percent solids, the simple payback period reduces to less than 10 years and the SIRs are in excess of 1.25. Above 10 percent solids the metrics continue to improve, but at a reduced rate. The reason for this is that the digester costs represent a fraction of the overall project costs. Even as these costs are minimized by increasing the feed concentration, the other costs remain constant and keep the economic metrics relatively stable. Overall, it appears that assuming other national average conditions, a digester feed concentration of 10 percent or greater is sufficient to ensure that the project meets the established minimum DoD standards.

Biosolids Value Sensitivity

For the initial analysis it was assumed that any biosolids generated during the digestion process would be disposed of at a landfill and would be subject to the same trucking and tipping fees associated with food waste disposal. This sensitivity analysis explores how the economic metrics are influenced if the biosolids are not disposed of, but are used as a soil amendment. The sensitivity explores biosolids values between $0 and $15 per dry ton. The $0 value would represent a condition where the biosolids are given away (thus avoiding the landfill and trucking fees) and the $15 value would represent a condition in which the price point for the biosolids is set modestly. This sensitivity is presented graphically in Figure 5.

Figure 5
Cost of Vehicle Fuel Sensitivity Analysis



The sensitivity depicted in Figure 5 suggests that the economic metrics of the proposed technology are not influenced significantly by the price point of the biosolids product. However, the ability to give away or sell the biosolids does have a significant impact on the economic metrics. Recall that the initial analysis, which assumed a disposal fee for the biosolids, had a simple payback of 9.06 years and SIRs of 1.04 and 1.89 for the 10 and 20-year life-cycles respectively. By finding a beneficial use for the product, the simple payback was reduced to approximately 7 years, with SIRs of 1.25 and 2.25 for the 10-year and 20-year life-cycles respectively.

Conclusions

Based on this preliminary economic evaluation, it is expected that the proposed technology would meet the established minimum DoD standards for financing under national average conditions for construction, O&M, tipping fee, fuel and power costs. Additionally, as tipping fees and fuel costs increase, the economic viability of technology improves significantly approaching simple payback periods of less than 5 years and SIRs greater than 3.0.

When evaluating minimum conditions for installation, it is suggested that a minimum tipping fee of $40 per wet ton and or minimum fuel cost of $2.50 per gallon be present at the installation to ensure conformance with the minimum DoD standards. Other project variables such as the cost of power, the digester feed concentration, and the value of the biosolids product are also important considerations, but are not as influential.

Completion of the demonstration at the US Air Force Academy is required to validate many of the assumptions listed in Table 1 of this memorandum. However, treatability testing conducted to date has indicated that the assumptions are reasonable for USAFA food waste.

Works Cited

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Appendix

ESTCP ER-0933 Renewable Energy Production from DoD Installation Solid Wastes by Anaerobic Digestion

1.0 Purpose/Objective

This calculation sheet was developed to estimate the capital and operational costs of a greenfield installation system capable of digesting foodwaste and capturing the biogas for use as vehicle fuel. Outputs from this sheet were used in the BLCC Milcon:ECIP Life-Cycle Cost analysis tool to estimate the simple payback and savings to investment ratios for 10-year and 20-year project lifecycles

2.0 Procedure

The calculation sheet systematically estimates capital and operational costs based on standard operational, construction and O&M parameters. Each individual input for the ECIP analysis is calculated separately.

3.0 References/Data Sources

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4.0 Variable Definitions

Variable	***Definition***	***Source***
$\text{Biogas}_{\text{available}}$	Amount of biogas available for conversion to biomethane, expressed in kW	Calculation Based
$\text{Biogas}_{\text{generated}}$	Volumetric flow rate of biogas generated during digestion	Calculation Based
$\text{Biogas}_{\text{heating}}$	Amount of biogas required to provide digester heating, expressed in kW	Calculation Based
$\text{Biogas}_{\text{LHV}}$	Low heating value of biogas	CDM Lab Analysis; East Bay MUD, 2008
$\text{Biogas}_{\text{power}}$	Equivalent power of biogas generated based on flow rate and heat content	Calculation Based
$\text{Biogas}_{\text{yield}}$	Biogas yield per pound of volatile solids destroyed	CDM Lab Analysis; East Bay MUD, 2008
$\text{Biomethane}_{\text{available}}$	Amount of biomethane available for conversion to rCNG, expressed in kW	Calculation Based
$\text{Biomethane}_{\text{Capital}}$	The capital cost for the biomethane treatment system	Calculation Based
$\text{Biomethane}_{\text{Cost}}$	The unit cost for the biomethane treatment	Nelson, 2008
$\text{Biomethane}_{\text{efficiency}}$	Efficiency of biomethane system at converting fuel to biomethane (i.e. methane capture	Nelson, 2008
$\text{Biomethane}_{\text{Labor}}$	The unit cost for labor and materials to operate	Nelson, 2008
$\text{Biomethane}_{\text{Power}}$	The calculated power demand for the biomethane system	Calculation Based

$Biosolids_{DryLoad}$	Mass load of biosolids generated per day, not including water	Calculation Based
$Biosolids_{TS}$	Assumed solids content of dewatered biosolids	Earle, 2005
$Biosolids_{Value}$	Value of the biosolids product as a soil ammendemnt	CDM Experience
$Biosolids_{WetLoad}$	Mass load of biosolids generated per day, including water	Calculation Based
$Boiler_{Capital}$	The capital cost for the boiler	Calculation Based
$Boiler_{Cost}$	The unit cost for a hot water boiler	CDM Experience
$Boiler_{efficiency}$	Efficiency of boiler at converting fuel to thermal energy	Industry Standard
$Boiler_{size}$	Estimated size of boiler required to meet digester heat demand	Calculation Based
$Construction_{Cost}$	The total construction cost for entire system including all overhead, insurance, escalationes, etc.	Calculation Based
Density	Density of food waste and water	Industry Standard
$Design_{Cost}$	The design cost for the entire system	Calculation Based
$Dewatering_{Capital}$	The capital cost for the dewatering system	Calculation Based
$Dewatering_{Cost}$	The unit cost for dewatering equipment	Earle, 2005
$Dewatering_{Power}$	The calculated power demand for the dewatering system	Calculation Based
$Digestate_{TS}$	Calculated concentration of digested solids within the digester	Calculation Based
$Digestate_{WetLoad}$	Mass load of digested solids generated per day, including water	Calculation Based
$Digester_{activevolume}$	Active volume of digester	Calculation Based
$Digester_{Capital}$	The capital cost for the digester	Calculation Based
$Digester_{conevolume}$	Cone volume of digester	Calculation Based
$Digester_{Cost}$	The unit cost for a digester	AgStar US EPA, Jan. 2010; Greer 2007
$Digester_{heat}$	Heat demand of the digester including heatlosses and heating up of influent feed	Calculation Based
$Digester_{loading}$	Energetic loading to digester in terms of mass of VS per unit volume per day	Calculation Based
$Digester_{SRT}$	Solids rentention time in digester	Industry Standard

5.0 Calculations

DEFINITIONS

$\text{people} := 1$

$\text{VS} := 1$

$\text{TS} := 1$

$\text{waste} := 1$

$\text{digester} := 1$

$\text{therm} := 10^{5}\text{BTU}$

$\text{biosolids} := 1$

$\text{dollars} := 1$

$\text{kW}_{\text{fuel}} := 1\text{kW}$

$\text{GGE} := \text{gal}$

$\text{polymer} := 1$

$\text{wet} := 1$

$\text{dry} := 1$

$\text{digestate} := 1$

System Sizing - ASSUMPTIONS

$\text{population} := 50000 \bullet \text{people}$

$$\text{waste}_{\text{pcpd}} := 0.6\frac{\text{lb} \bullet \text{wet} \bullet \text{waste}}{\text{people} \bullet \text{day}}$$

$$\text{Density} := 8.34\frac{\text{lb}}{\text{gal}}$$

$$\text{FW}_{\text{TS}} := .30\frac{\text{lb} \bullet \text{TS}}{\text{lb} \bullet \text{waste}}$$

$$\text{FW}_{\text{VS}} := 0.86\frac{\text{lb} \bullet \text{VS}}{\text{lb} \bullet \text{TS}}$$

$\text{Digester}_{\text{SRT}} := 20\text{day}$

$$\text{Influent}_{\text{TS}} := 0.10\frac{\text{lb} \bullet \text{TS}}{\text{lb} \bullet \text{waste}}$$

System Sizing - CALCULATIONS

First, calculate the total load per day of waste generated

$\text{FW}_{\text{WetLoad}} := \text{population} \bullet \text{waste}_{\text{pcpd}}$

$$\text{FW}_{\text{WetLoad}} = 30000 \bullet \frac{\text{lb} \bullet \text{wet} \bullet \text{waste}}{\text{day}}$$

$\text{FW}_{\text{DryLoad}} := \text{population} \bullet \text{waste}_{\text{pcpd}} \bullet \text{FW}_{\text{TS}}$

$$\text{FW}_{\text{DryLoad}} = 9000 \bullet \frac{\text{lb}}{\text{day}}$$

Second, calculate the load to the digester after the food waste is diluted down

$$\text{Digester}_{\text{WetLoad}} := \frac{\text{FW}_{\text{DryLoad}}}{\text{Influent}_{\text{TS}}}$$

$$\text{Digester}_{\text{WetLoad}} = 90000 \bullet \frac{\text{lb} \bullet \text{wet} \bullet \text{waste}}{\text{day}}$$

Third, confirm the amount of dilution water required to thin out the feed

$$\text{Dilution}_{\text{Flow}} := \frac{\text{Digester}_{\text{WetLoad}} - \text{FW}_{\text{WetLoad}}}{\text{Density}}$$

$$\text{Dilution}_{\text{Flow}} = 7194 \bullet \frac{\text{gal}}{\text{day}}$$

Fourth, calculate the active volume in the digester based on the desired SRT.

$$\text{Digester}_{\text{activevolume}} := \frac{\text{Digester}_{\text{WetLoad}}}{\text{Density}} \bullet \text{Digester}_{\text{SRT}}$$

$$\text{Digester}_{\text{activevolume}} = 215827 \bullet \text{gal}$$

Fifth, calculate the additional volume in the digester for the cone space

$$\text{Digester}_{\text{conevolume}} := \text{Digester}_{\text{activevolume}} \bullet 20\%$$

$$\text{Digester}_{\text{conevolume}} = 43165 \bullet \text{gal}$$

The digester volume is the sum of the active and cone volumes

$$\text{Digester}_{\text{volume}} := \text{Digester}_{\text{activevolume}} + \text{Digester}_{\text{conevolume}}$$

$$\text{Digester}_{\text{volume}} = 258993 \bullet \text{gal}$$

Check the digester loading rate on an energy basis to ensure that it meets expected loading rates

$$\text{Digester}_{\text{loading}} := \frac{\text{FW}_{\text{DryLoad}} \bullet \text{FW}_{\text{VS}}}{\text{Digester}_{\text{activevolume}}}$$

$$\text{Digester}_{\text{loading}} = 0.27 \bullet \frac{\text{lb} \bullet \text{VS}}{\text{ft}^3 \bullet \text{day}}$$

Digester Heating Requirements - ASSUMPTIONS

$SF_{heatloss} := 1.3$

$Temp_{Digester} := 98\Delta°F$

$Temp_{FW} := 55\Delta°F$

$Temp_{Dilution} := 90\Delta°F$

Digester Heating Requirements - Calculations

First, calculate the thermal energy in the feed (food waste + dilution water)

$$Heat_{Feed} := Temp_{FW} \bullet FW_{WetLoad} + Temp_{Dilution} \bullet Dilution_{Flow} \bullet Density$$

$$Heat_{Feed} = 7050000 \bullet \frac{lb \bullet \Delta°F}{day}$$

Second, calculate the thermal energy required in the digester

$$Heat_{Digester} := Temp_{Digester} \bullet FW_{WetLoad} + Temp_{Digester} \bullet Dilution_{Flow} \bullet Density$$

$$Heat_{Digester} = 8820000 \bullet \frac{lb \bullet \Delta°F}{day}$$

The heat demand is the difference between the thermal energies times a specific heat requirement and efficiency.   The heat demand calculated here will be used to estimate the biogas available for utilization

$$Digester_{heat} := \left(Heat_{Digester} - Heat_{Feed}\right) \bullet \frac{1BTU}{lb \bullet \Delta°F} \bullet SF_{heatloss}$$

$$Digester_{heat} = 95875 \bullet \frac{BTU}{hr}$$

$$Digester_{heat} = 28 \bullet kW$$

The boiler is sized assuming no heat recovery from the recycle flow and follows the same principles as above.

$$Boiler_{size} := Digester_{WetLoad} \bullet \left(1 \frac{BTU}{lb \bullet \Delta°F}\right) \bullet \left(Temp_{Digester} - Temp_{FW}\right) \bullet SF_{heatloss}$$

$$Boiler_{size} = 61 \bullet kW$$

Biogas Generation - ASSUMPTIONS

$VS_{Destruction} := 80\%$

$$Biogas_{yield} := 22 \frac{ft^3}{lb \bullet dry \bullet VS}$$

$$Biogas_{LHV} := 580 \frac{BTU}{ft^3}$$

Biogas Generation - CALCULATIONS

First, calculate the amount of volatile solids destroyed in the digester

$$VSD := population \bullet waste_{pcpd} \bullet FW_{TS} \bullet FW_{VS} \bullet VS_{Destruction}$$

$$VSD = 6192 \bullet \frac{lb \bullet dry \bullet VS}{day}$$

Second, calculate biogas produced using a unit production/yield

$$Biogas_{generated} := Biogas_{yield} \bullet VSD$$

$$Biogas_{generated} = 136224 \bullet \frac{ft^3}{day}$$

Third, calculate the raw power of the biogas fuel based on the biogas heating value

$$Biogas_{power} := Biogas_{generated} \bullet Biogas_{LHV}$$

$$Biogas_{power} = 965 \bullet kW_{fuel}$$

Biogas Utilization - ASSUMPTIONS

$Boiler_{efficiency} := 83\%$

$Biomethane_{efficiency} := 95\%$

$$rCNG_{LHV} := 114000 \frac{BTU}{GGE}$$

Biogas Utilization - CALCULATIONS

First, calculate the amount of biogas used for heat.

$$\text{Biogas}_{\text{heating}} := \frac{\text{Digester}_{\text{heat}}}{\text{Boiler}_{\text{efficiency}}}$$

$$\text{Biogas}_{\text{heating}} = 34 \bullet \text{kW}_{\text{fuel}}$$

The biogas available for other uses is the gas produced less that which is used for heating

$$\text{Biogas}_{\text{available}} := \text{Biogas}_{\text{power}} - \text{Biogas}_{\text{heating}}$$

$$\text{Biogas}_{\text{available}} = 931 \bullet \text{kW}_{\text{fuel}}$$

Calculate the volume of biomethane (250 psig) that can be generated from the available biogas based on the system efficiency

$$\text{Biomethane}_{\text{available}} := \text{Biogas}_{\text{available}} \bullet \text{Biomethane}_{\text{efficiency}}$$

$$\text{Biomethane}_{\text{available}} = 884 \bullet \text{kW}_{\text{fuel}}$$

Calculate to volume of rCNG (4,500 psig) that can be generated from the avaialable biomethane

$$\text{rCNG}_{\text{available}} := \text{Biomethane}_{\text{available}}$$

$$\text{rCNG}_{\text{available}} = 884 \bullet \text{kW}_{\text{fuel}}$$

$$\text{rCNG}_{\text{GGE}} := \frac{\text{rCNG}_{\text{available}}}{\text{rCNG}_{\text{LHV}}}$$

$$\text{rCNG}_{\text{GGE}} = 635 \bullet \frac{\text{GGE}}{\text{day}}$$

Biosolids Generated - ASSUMPTIONS

$$\text{Biosolids}_{\text{TS}} := 0.25 \frac{\text{lb} \bullet \text{TS}}{\text{lb} \bullet \text{biosolids}}$$

Biosolids Generated - CALCULATIONS

First, calculate the solids content of the digestate based on the VS destroyed, assuming a conservation of mass within the digester.

$$\mathrm{Digestate}_{TS} := \mathrm{Influent}_{TS} \cdot \left[1 - \left(\mathrm{FW}_{VS}\right)\left(\mathrm{VS}_{Destruction}\right)\right]$$

$$\mathrm{Digestate}_{TS} = 0.031 \cdot \frac{\mathrm{lb} \cdot \mathrm{TS}}{\mathrm{lb} \cdot \mathrm{digestate}}$$

First, calculate the mass load dry solids leaving the digester based on the amount of solids destroyed.

$$\mathrm{Biosolids}_{DryLoad} := \mathrm{FW}_{WetLoad} \cdot \mathrm{FW}_{TS} - \mathrm{VSD}$$

$$\mathrm{Biosolids}_{DryLoad} = 2808 \cdot \frac{\mathrm{lb} \cdot \mathrm{dry} \cdot \mathrm{TS}}{\mathrm{day}}$$

Second, calculate the volumetric load of solids leaving the digester on a wet basis based on the digestate solids concentration and the density of solids

$$\mathrm{Digestate}_{WetLoad} := \frac{\mathrm{Biosolids}_{DryLoad}}{\mathrm{Digestate}_{TS}}$$

$$\mathrm{Digestate}_{WetLoad} = 90000 \cdot \frac{\mathrm{lb} \cdot \mathrm{wet} \cdot \mathrm{digestate}}{\mathrm{day}}$$

Third, calculate the volumetric load of dewatered biosolids based on the assumed solids content of the product.

$$\mathrm{Biosolids}_{WetLoad} := \frac{\mathrm{Biosolids}_{DryLoad}}{\mathrm{Biosolids}_{TS}}$$

$$\mathrm{Biosolids}_{WetLoad} = 11232 \cdot \frac{\mathrm{lb} \cdot \mathrm{wet} \cdot \mathrm{biosolids}}{\mathrm{day}}$$

The difference between the digestate and biosolids wet load is the mass of water expelled each day as pressate. This mass can be converted to a volumetric load of water by the density.

$$\mathrm{Pressate}_{WetLoad} := \mathrm{Digestate}_{WetLoad} - \mathrm{Biosolids}_{WetLoad}$$

$$\mathrm{Pressate}_{WetLoad} = 78768 \cdot \frac{\mathrm{lb}}{\mathrm{day}}$$

$$\mathrm{Pressate}_{Flow} := \frac{\mathrm{Pressate}_{WetLoad}}{\mathrm{Density}}$$

$$\text{Pressate}_{\text{Flow}} = 9445 \bullet \frac{\text{gal}}{\text{day}}$$

The ammount of water sent to the sewer is the difference between the dilution flow and the pressate flow

$$\text{Sewer}_{\text{Flow}} := \text{Pressate}_{\text{Flow}} - \text{Dilution}_{\text{Flow}}$$

$$\text{Sewer}_{\text{Flow}} = 2250 \bullet \frac{\text{gal}}{\text{day}}$$

O & M - ASSUMPTIONS

$$\text{Power}_{\text{mixing}} := 50 \frac{\text{hp}}{10^{6}\text{gal}}$$

$$\text{Power}_{\text{dewatering}} := 14 \frac{\text{kW} \bullet \text{hr}}{\text{ton} \bullet \text{TS}}$$

$$\text{Power}_{\text{biogastreatment}} := 13 \frac{\text{kW} \bullet \text{hr}}{10^{6}\text{BTU}}$$

$$\text{Power}_{\text{rCNG}} := 1.75 \frac{\text{kW} \bullet \text{hr}}{\text{GGE}}$$

$$\text{Polymer}_{\text{dewatering}} := 15 \frac{\text{lb} \bullet \text{polymer}}{\text{ton} \bullet \text{TS}}$$

$$\text{Polymer}_{\text{cost}} := 3 \frac{\text{dollars}}{\text{lb} \bullet \text{polymer}}$$

O & M - CALCULATIONS

Calculate the power demand for the digester

$$\text{Digestion}_{\text{Power}} := \text{Power}_{\text{mixing}} \bullet \text{Digester}_{\text{volume}}$$

$$\text{Digestion}_{\text{Power}} = 10 \bullet \text{kW}$$

Calculate the power demand for the dewatering equipment

$$\text{Dewatering}_{\text{Power}} := \text{Power}_{\text{dewatering}} \bullet \text{Biosolids}_{\text{DryLoad}}$$

$$\text{Dewatering}_{\text{Power}} = 0.82 \bullet \text{kW}$$

Calculate the power demand for the biomethane gas purification system

$\text{Biomethane}_{\text{Power}} := \text{Power}_{\text{biogastreatment}} \bullet \text{Biomethane}_{\text{available}}$

$\text{Biomethane}_{\text{Power}} = 39 \bullet \text{kW}$

Calculate the power demand for the rCNG compression/fueling system

$\text{rCNG}_{\text{Power}} := \text{Power}_{\text{rCNG}} \bullet \text{rCNG}_{\text{GGE}}$

$\text{rCNG}_{\text{Power}} = 46 \bullet \text{kW}$

Calculate the total power demand as the sum of all the power demands

$\text{Total}_{\text{Power}} := \text{Digestion}_{\text{Power}} + \text{Dewatering}_{\text{Power}} + \text{Biomethane}_{\text{Power}} + \text{rCNG}_{\text{Power}}$

$\text{Total}_{\text{Power}} = 96 \bullet \text{kW}$

SENSITIVITY INPUTS

$\text{Digester}_{\text{Cost}} := 5 \frac{\text{dollars}}{\text{gal}}$

$\text{Dewatering}_{\text{Cost}} := 200000 \frac{\text{dollars}}{\left(\frac{\text{dry} \bullet \text{ton}}{\text{day}}\right)}$

$\text{Boiler}_{\text{Cost}} := 220000 \frac{\text{dollars}}{36\text{bhp}}$

$\text{Power}_{\text{Cost}} := 0.1012 \frac{\text{dollars}}{\text{kW} \bullet \text{hr}}$

$\text{Biomethane}_{\text{Cost}} := 1400 \frac{\text{dollars}}{\text{kW}_{\text{fuel}}}$

$\text{Biomethane}_{\text{Labor}} := 0.17 \frac{\text{dollars}}{\text{therm}}$

$\text{rCNG}_{\text{Cost}} := 1400 \frac{\text{dollars}}{\text{kW}_{\text{fuel}}}$

$\text{rCNG}_{\text{Labor}} := 0.20 \frac{\text{dollars}}{\text{therm}}$

$$rCNG_{Value} := 2.78\,\frac{dollars}{GGE} \bullet -1$$

$$TippingFee_{Value} := 43.99\,\frac{dollars}{ton} \bullet -1$$

$$Trucking_{Value} := 10\,\frac{dollars}{ton} \bullet -1$$

$$Biosolids_{Value} := 0\,\frac{dollars}{ton} \bullet -1$$

SUMMARY/LCC INPUTS

Calculate individual component capital cost

$$Digester_{Capital} := Digester_{Cost} \bullet Digester_{volume}$$

$$Digester_{Capital} = 1.29 \times 10^{6} \bullet dollars$$

$$Dewatering_{Capital} := Dewatering_{Cost} \bullet Biosolids_{DryLoad}$$

$$Dewatering_{Capital} = 2.81 \times 10^{5} \bullet dollars$$

$$Boiler_{Capital} := Boiler_{Cost} \bullet Boiler_{size}$$

$$Boiler_{Capital} = 3.83 \times 10^{4} \bullet dollars$$

$$Biomethane_{Capital} := Biomethane_{Cost} \bullet Biomethane_{available}$$

$$Biomethane_{Capital} = 1.24 \times 10^{6} \bullet dollars$$

$$rCNG_{Capital} := rCNG_{Cost} \bullet rCNG_{available}$$

$$rCNG_{Capital} = 1.24 \times 10^{6} \bullet dollars$$

Total construction costs for LCC input

$$Construction_{Cost} := Digester_{Capital} + Dewatering_{Capital} + Boiler_{Capital} + Biomethane_{Capital} \ldots + rCNG_{Capital}$$

$$Construction_{Cost} = 4.09 \times 10^{6} \bullet dollars$$

Design costs for LCC input

$$Design_{Cost} := Construction_{Cost} \bullet 20\%$$

$$Design_{Cost} = 8.18 \times 10^{5} \bullet dollars$$

Calculate total costs for power

$$OM_{Power} := \left(Total_{Power}\right) \bullet Power_{Cost}$$

$$OM_{Power} = 8.52 \times 10^{4} \bullet \frac{dollars}{yr}$$

Calculate total energy use for LCC input

$$Total_{Electricity} := Total_{Power} \bullet 1yr$$

$$Total_{Electricity} = 8.42 \times 10^{5} \bullet kW \bullet hr$$

Calculate the O&M for the individual components

$$OM_{Digestion} := Digester_{Capital} \bullet \frac{5\%}{yr}$$

$$OM_{Digestion} = 6.47 \times 10^{4} \bullet \frac{dollars}{yr}$$

$$OM_{Dewatering} := Polymer_{dewatering} \bullet Biosolids_{DryLoad} \bullet Polymer_{cost} + Dewatering_{Capital} \bullet 5\frac{\%}{yr}$$

$$OM_{Dewatering} = 3.71 \times 10^{4} \bullet \frac{dollars}{yr}$$

$$OM_{Biomethane} := Biomethane_{Labor} \bullet Biomethane_{available}$$

$$OM_{Biomethane} = 4.5 \times 10^{4} \bullet \frac{dollars}{yr}$$

$$OM_{rCNG} := rCNG_{Labor} \bullet Biomethane_{available}$$

$$OM_{rCNG} = 5.29 \times 10^{4} \bullet \frac{dollars}{yr}$$

$$Revenue_{rCNG} := rCNG_{GGE} \bullet rCNG_{Value}$$

$$Revenue_{rCNG} = -6.45 \times 10^{5} \bullet \frac{dollars}{yr}$$

$$rCNG_{available} = 2.65 \times 10^{5} \bullet \frac{therm}{yr}$$

$$\text{Revenue}_{\text{Tipping}} := \left(\text{FW}_{\text{WetLoad}} - \text{Biosolids}_{\text{WetLoad}}\right) \bullet \text{TippingFee}_{\text{Value}}$$

$$\text{Revenue}_{\text{Tipping}} = -1.51 \times 10^{5} \bullet \frac{\text{dollars}}{\text{yr}}$$

$$\text{Revenue}_{\text{Trucking}} := \left(\text{FW}_{\text{WetLoad}} - \text{Biosolids}_{\text{WetLoad}}\right) \bullet \text{Trucking}_{\text{Value}} = -0\,\frac{1}{\text{s}}$$

$$\text{Revenue}_{\text{Trucking}} = -3.43 \times 10^{4} \bullet \frac{\text{dollars}}{\text{yr}}$$

$$\text{Revenue}_{\text{Biosolids}} := \text{Biosolids}_{\text{Value}} \bullet \text{Biosolids}_{\text{DryLoad}}$$

$$\text{Revenue}_{\text{Biosolids}} = 0 \times 10^{0} \bullet \frac{\text{dollars}}{\text{yr}}$$

SIMPLE PAYBACK

$$\text{OM}_{\text{Total}} := \text{OM}_{\text{Power}} + \text{OM}_{\text{Digestion}} + \text{OM}_{\text{Dewatering}} + \text{OM}_{\text{Biomethane}} + \text{OM}_{\text{rCNG}} \cdots$$
$$+ \text{Revenue}_{\text{rCNG}} + \text{Revenue}_{\text{Tipping}} + \text{Revenue}_{\text{Trucking}} + \text{Revenue}_{\text{Biosolids}}$$

$$\text{OM}_{\text{Total}} = -5.45 \times 10^{5} \bullet \frac{\text{dollars}}{\text{yr}}$$

$$\text{Payback}_{\text{simple}} := \frac{\text{Construction}_{\text{Cost}} + \text{Design}_{\text{Cost}}}{\text{OM}_{\text{Total}} \bullet -1}$$

$$\text{Payback}_{\text{simple}} = 9 \bullet \text{yr}$$

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 16:40:39 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Base Case, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$541,690	
5. Simple Payback Period (in years)	9.06	(total investment/first-year savings)
6. Total Discounted Operational Savings	$9,279,521	
7. Savings to Investment Ratio (SIR)	1.89	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	6.33%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 16:51:25 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $20, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$102,100	Annual	15.099	-$1,541,594
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$102,100			-$1,541,594

4. First year savings	$459,290	
5. Simple Payback Period (in years)	10.69	(total investment/first-year savings)
6. Total Discounted Operational Savings	$8,035,375	
7. Savings to Investment Ratio (SIR)	1.64	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.57%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 16:52:26 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $30, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$67,800	Annual	15.099	-$1,023,703
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$67,800			-$1,023,703

4. First year savings	$493,590	
5. Simple Payback Period (in years)	9.94	(total investment/first-year savings)
6. Total Discounted Operational Savings	$8,553,266	
7. Savings to Investment Ratio (SIR)	1.74	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.90%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 16:53:09 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $40, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$33,500	Annual	15.099	-$505,812
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$33,500			-$505,812

4. First year savings	$527,890	
5. Simple Payback Period (in years)	9.30	(total investment/first-year savings)
6. Total Discounted Operational Savings	$9,071,157	
7. Savings to Investment Ratio (SIR)	1.85	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	6.21%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 16:53:50 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $50, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$800	Annual	15.099	$12,079
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$800			$12,079

4. First year savings	$562,190	
5. Simple Payback Period (in years)	8.73	(total investment/first-year savings)
6. Total Discounted Operational Savings	$9,589,048	
7. Savings to Investment Ratio (SIR)	1.95	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	6.51%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 16:55:40 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $60, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$35,100	Annual	15.099	$529,970
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$35,100			$529,970

4. First year savings	$596,490	
5. Simple Payback Period (in years)	8.23	(total investment/first-year savings)
6. Total Discounted Operational Savings	$10,106,939	
7. Savings to Investment Ratio (SIR)	2.06	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	6.79%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 16:56:30 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $70, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$69,400	Annual	15.099	$1,047,861
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$69,400			$1,047,861

4. First year savings	$630,790	
5. Simple Payback Period (in years)	7.78	(total investment/first-year savings)
6. Total Discounted Operational Savings	$10,624,830	
7. Savings to Investment Ratio (SIR)	2.16	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.06%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 16:56:58 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $80, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$103,700	Annual	15.099	$1,565,752
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$103,700			$1,565,752

4. First year savings	$665,090	
5. Simple Payback Period (in years)	7.38	(total investment/first-year savings)
6. Total Discounted Operational Savings	$11,142,721	
7. Savings to Investment Ratio (SIR)	2.27	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.31%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 16:57:29 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $90, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$138,000	Annual	15.099	$2,083,643
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$138,000			$2,083,643

4. First year savings	$699,390	
5. Simple Payback Period (in years)	7.02	(total investment/first-year savings)
6. Total Discounted Operational Savings	$11,660,612	
7. Savings to Investment Ratio (SIR)	2.38	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.56%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 16:57:45 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $100, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$172,300	Annual	15.099	$2,601,534
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$172,300			$2,601,534

4. First year savings	$733,690	
5. Simple Payback Period (in years)	6.69	(total investment/first-year savings)
6. Total Discounted Operational Savings	$12,178,503	
7. Savings to Investment Ratio (SIR)	2.48	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.79%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 16:58:37 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $110, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$206,600	Annual	15.099	$3,119,425
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$206,600			$3,119,425

4. First year savings	$767,990	
5. Simple Payback Period (in years)	6.39	(total investment/first-year savings)
6. Total Discounted Operational Savings	$12,696,394	
7. Savings to Investment Ratio (SIR)	2.59	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	8.01%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 16:58:56 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $120, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$240,900	Annual	15.099	$3,637,316
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$240,900			$3,637,316

4. First year savings	$802,290	
5. Simple Payback Period (in years)	6.12	(total investment/first-year savings)
6. Total Discounted Operational Savings	$13,214,285	
7. Savings to Investment Ratio (SIR)	2.69	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	8.23%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 16:59:39 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $130, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$275,200	Annual	15.099	$4,155,207
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$275,200			$4,155,207

4. First year savings	$836,590	
5. Simple Payback Period (in years)	5.87	(total investment/first-year savings)
6. Total Discounted Operational Savings	$13,732,176	
7. Savings to Investment Ratio (SIR)	2.80	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	8.44%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:00:07 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $140, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$309,500	Annual	15.099	$4,673,098
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$309,500			$4,673,098

4. First year savings	$870,890	
5. Simple Payback Period (in years)	5.64	(total investment/first-year savings)
6. Total Discounted Operational Savings	$14,250,067	
7. Savings to Investment Ratio (SIR)	2.90	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	8.64%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:00:38 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $150, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$343,800	Annual	15.099	$5,190,989
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$343,800			$5,190,989

4. First year savings	$905,190	
5. Simple Payback Period (in years)	5.42	(total investment/first-year savings)
6. Total Discounted Operational Savings	$14,767,958	
7. Savings to Investment Ratio (SIR)	3.01	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	8.83%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:25:46 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Elec, $0.05, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$14.65356	-2,873.0 MBtu	-$42,100	15.130	-$636,979
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$604,500		$10,229,236
Water Subtotal		0.0 Mgal	$0		$0
Total			$604,500		$10,229,236

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$584,800	
5. Simple Payback Period (in years)	8.39	(total investment/first-year savings)
6. Total Discounted Operational Savings	$9,931,788	
7. Savings to Investment Ratio (SIR)	2.02	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	6.70%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:26:21 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Elec, $0.10, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.30711	-2,873.0 MBtu	-$84,200	15.130	-$1,273,958
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$562,400		$9,592,257
Water Subtotal		0.0 Mgal	$0		$0
Total			$562,400		$9,592,257

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$542,700	
5. Simple Payback Period (in years)	9.04	(total investment/first-year savings)
6. Total Discounted Operational Savings	$9,294,809	
7. Savings to Investment Ratio (SIR)	1.89	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	6.34%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:26:56 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Elec, $0.20, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$43.96067	-2,873.0 MBtu	-$126,300	15.130	-$1,910,937
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$520,300		$8,955,278
Water Subtotal		0.0 Mgal	$0		$0
Total			$520,300		$8,955,278

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$500,600	
5. Simple Payback Period (in years)	9.80	(total investment/first-year savings)
6. Total Discounted Operational Savings	$8,657,830	
7. Savings to Investment Ratio (SIR)	1.76	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.97%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:27:42 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Elec, $0.20, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$58.61423	-2,873.0 MBtu	-$168,400	15.130	-$2,547,916
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$478,200		$8,318,299
Water Subtotal		0.0 Mgal	$0		$0
Total			$478,200		$8,318,299

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$458,500	
5. Simple Payback Period (in years)	10.70	(total investment/first-year savings)
6. Total Discounted Operational Savings	$8,020,851	
7. Savings to Investment Ratio (SIR)	1.63	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.56%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:28:11 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Elec, $0.25, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$73.26778	-2,873.0 MBtu	-$210,500	15.130	-$3,184,895
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$436,100		$7,681,320
Water Subtotal		0.0 Mgal	$0		$0
Total			$436,100		$7,681,320

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$416,400	
5. Simple Payback Period (in years)	11.79	(total investment/first-year savings)
6. Total Discounted Operational Savings	$7,383,872	
7. Savings to Investment Ratio (SIR)	1.50	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.13%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:31:40 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $2.00, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$17.49993	26,500.1 MBtu	$463,750	16.805	$7,793,392
Energy Subtotal		23,627.1 MBtu	$378,540		$6,504,146
Water Subtotal		0.0 Mgal	$0		$0
Total			$378,540		$6,504,146

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$358,840	
5. Simple Payback Period (in years)	13.68	(total investment/first-year savings)
6. Total Discounted Operational Savings	$6,206,698	
7. Savings to Investment Ratio (SIR)	1.26	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	4.22%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:32:37 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $2.50, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$21.89992	26,500.1 MBtu	$580,350	16.805	$9,752,873
Energy Subtotal		23,627.1 MBtu	$495,140		$8,463,627
Water Subtotal		0.0 Mgal	$0		$0
Total			$495,140		$8,463,627

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$475,440	
5. Simple Payback Period (in years)	10.32	(total investment/first-year savings)
6. Total Discounted Operational Savings	$8,166,180	
7. Savings to Investment Ratio (SIR)	1.66	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.66%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:33:02 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $3.00, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$26.29990	26,500.1 MBtu	$696,950	16.805	$11,712,354
Energy Subtotal		23,627.1 MBtu	$611,740		$10,423,109
Water Subtotal		0.0 Mgal	$0		$0
Total			$611,740		$10,423,109

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$592,040	
5. Simple Payback Period (in years)	8.29	(total investment/first-year savings)
6. Total Discounted Operational Savings	$10,125,661	
7. Savings to Investment Ratio (SIR)	2.06	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	6.80%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:33:42 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $3.50, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$30.69988	26,500.1 MBtu	$813,550	16.805	$13,671,836
Energy Subtotal		23,627.1 MBtu	$728,340		$12,382,590
Water Subtotal		0.0 Mgal	$0		$0
Total			$728,340		$12,382,590

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$708,640	
5. Simple Payback Period (in years)	6.93	(total investment/first-year savings)
6. Total Discounted Operational Savings	$12,085,142	
7. Savings to Investment Ratio (SIR)	2.46	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.75%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:34:05 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $4.00, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$35.09987	26,500.1 MBtu	$930,150	16.805	$15,631,317
Energy Subtotal		23,627.1 MBtu	$844,940		$14,342,071
Water Subtotal		0.0 Mgal	$0		$0
Total			$844,940		$14,342,071

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$825,240	
5. Simple Payback Period (in years)	5.95	(total investment/first-year savings)
6. Total Discounted Operational Savings	$14,044,624	
7. Savings to Investment Ratio (SIR)	2.86	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	8.56%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:34:32 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $4.50, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$39.49985	26,500.1 MBtu	$1,046,750	16.805	$17,590,798
Energy Subtotal		23,627.1 MBtu	$961,540		$16,301,553
Water Subtotal		0.0 Mgal	$0		$0
Total			$961,540		$16,301,553

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$941,840	
5. Simple Payback Period (in years)	5.21	(total investment/first-year savings)
6. Total Discounted Operational Savings	$16,004,105	
7. Savings to Investment Ratio (SIR)	3.26	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	9.27%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:35:00 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $5.00, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$43.89983	26,500.1 MBtu	$1,163,350	16.805	$19,550,280
Energy Subtotal		23,627.1 MBtu	$1,078,140		$18,261,034
Water Subtotal		0.0 Mgal	$0		$0
Total			$1,078,140		$18,261,034

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$1,058,440	
5. Simple Payback Period (in years)	4.64	(total investment/first-year savings)
6. Total Discounted Operational Savings	$17,963,586	
7. Savings to Investment Ratio (SIR)	3.66	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	9.90%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:35:28 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $5.50, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$48.19982	26,500.1 MBtu	$1,277,300	16.805	$21,465,227
Energy Subtotal		23,627.1 MBtu	$1,192,090		$20,175,982
Water Subtotal		0.0 Mgal	$0		$0
Total			$1,192,090		$20,175,982

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$1,172,390	
5. Simple Payback Period (in years)	4.19	(total investment/first-year savings)
6. Total Discounted Operational Savings	$19,878,534	
7. Savings to Investment Ratio (SIR)	4.05	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	10.46%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:35:52 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $6.00, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$52.59980	26,500.1 MBtu	$1,393,900	16.805	$23,424,708
Energy Subtotal		23,627.1 MBtu	$1,308,690		$22,135,463
Water Subtotal		0.0 Mgal	$0		$0
Total			$1,308,690		$22,135,463

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$1,288,990	
5. Simple Payback Period (in years)	3.81	(total investment/first-year savings)
6. Total Discounted Operational Savings	$21,838,015	
7. Savings to Investment Ratio (SIR)	4.45	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	10.98%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:36:15 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $6.50, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$56.99979	26,500.1 MBtu	$1,510,500	16.805	$25,384,190
Energy Subtotal		23,627.1 MBtu	$1,425,290		$24,094,944
Water Subtotal		0.0 Mgal	$0		$0
Total			$1,425,290		$24,094,944

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$1,405,590	
5. Simple Payback Period (in years)	3.49	(total investment/first-year savings)
6. Total Discounted Operational Savings	$23,797,497	
7. Savings to Investment Ratio (SIR)	4.85	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	11.46%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:46:09 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Loading 5%, 20yr.xml		

1. Investment

Construction Cost	$5,390,000
SIOH	$0
Design Cost	$1,078,000
Total Cost	$6,468,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$6,468,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$541,690	
5. Simple Payback Period (in years)	11.94	(total investment/first-year savings)
6. Total Discounted Operational Savings	$9,279,521	
7. Savings to Investment Ratio (SIR)	1.43	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	4.88%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:46:48 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Loading 10%, 20yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$541,690	
5. Simple Payback Period (in years)	9.06	(total investment/first-year savings)
6. Total Discounted Operational Savings	$9,279,521	
7. Savings to Investment Ratio (SIR)	1.89	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	6.33%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:47:47 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Loading 15%, 20yr.xml		

1. Investment

Construction Cost	$3,660,000
SIOH	$0
Design Cost	$732,000
Total Cost	$4,392,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,392,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$541,690	
5. Simple Payback Period (in years)	8.11	(total investment/first-year savings)
6. Total Discounted Operational Savings	$9,279,521	
7. Savings to Investment Ratio (SIR)	2.11	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	6.93%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:48:28 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Loading 20%, 20yr.xml		

1. Investment

Construction Cost	$3,440,000
SIOH	$0
Design Cost	$688,000
Total Cost	$4,128,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,128,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$541,690	
5. Simple Payback Period (in years)	7.62	(total investment/first-year savings)
6. Total Discounted Operational Savings	$9,279,521	
7. Savings to Investment Ratio (SIR)	2.25	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.26%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:49:24 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Loading 25%, 20yr.xml		

1. Investment

Construction Cost	$3,310,000
SIOH	$0
Design Cost	$662,000
Total Cost	$3,972,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$3,972,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$541,690	
5. Simple Payback Period (in years)	7.33	(total investment/first-year savings)
6. Total Discounted Operational Savings	$9,279,521	
7. Savings to Investment Ratio (SIR)	2.34	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.46%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:49:53 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Loading 30%, 20yr.xml		

1. Investment

Construction Cost	$3,230,000
SIOH	$0
Design Cost	$646,000
Total Cost	$3,876,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$3,876,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	15.099	-$297,448
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$297,448

4. First year savings	$541,690	
5. Simple Payback Period (in years)	7.16	(total investment/first-year savings)
6. Total Discounted Operational Savings	$9,279,521	
7. Savings to Investment Ratio (SIR)	2.39	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.60%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:58:16 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Biosolids, $0, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$90,800	Annual	15.099	$1,370,977
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$90,800			$1,370,977

4. First year savings	$652,190	
5. Simple Payback Period (in years)	7.53	(total investment/first-year savings)
6. Total Discounted Operational Savings	$10,947,946	
7. Savings to Investment Ratio (SIR)	2.23	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.22%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:58:52 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Biosolids, $5, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$93,360	Annual	15.099	$1,409,630
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$93,360			$1,409,630

4. First year savings	$654,750	
5. Simple Payback Period (in years)	7.50	(total investment/first-year savings)
6. Total Discounted Operational Savings	$10,986,599	
7. Savings to Investment Ratio (SIR)	2.24	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.24%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:59:19 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Biosolids, $10, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$95,920	Annual	15.099	$1,448,283
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$95,920			$1,448,283

4. First year savings	$657,310	
5. Simple Payback Period (in years)	7.47	(total investment/first-year savings)
6. Total Discounted Operational Savings	$11,025,252	
7. Savings to Investment Ratio (SIR)	2.25	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.25%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:59:54 PST 2011
BOD:	January 1, 2011	Economic Life:	20 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Biosolids, $15, 20 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	15.130	-$1,289,246
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	16.805	$10,866,215
Energy Subtotal		23,627.1 MBtu	$561,390		$9,576,969
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$9,576,969

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$98,480	Annual	15.099	$1,486,936
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$98,480			$1,486,936

4. First year savings	$659,870	
5. Simple Payback Period (in years)	7.44	(total investment/first-year savings)
6. Total Discounted Operational Savings	$11,063,905	
7. Savings to Investment Ratio (SIR)	2.25	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.27%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 16:35:06 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Base Case, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$541,690	
5. Simple Payback Period (in years)	9.06	(total investment/first-year savings)
6. Total Discounted Operational Savings	$5,110,744	
7. Savings to Investment Ratio (SIR)	1.04	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	3.42%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:10:15 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $20, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$102,100	Annual	8.657	-$883,897
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$102,100			-$883,897

4. First year savings	$459,290	
5. Simple Payback Period (in years)	10.69	(total investment/first-year savings)
6. Total Discounted Operational Savings	$4,397,394	
7. Savings to Investment Ratio (SIR)	0.90	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	1.87%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:09:47 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $30, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$67,800	Annual	8.657	-$586,956
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$67,800			-$586,956

4. First year savings	$493,590	
5. Simple Payback Period (in years)	9.94	(total investment/first-year savings)
6. Total Discounted Operational Savings	$4,694,334	
7. Savings to Investment Ratio (SIR)	0.96	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	2.54%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:09:18 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $40, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$33,500	Annual	8.657	-$290,015
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$33,500			-$290,015

4. First year savings	$527,890	
5. Simple Payback Period (in years)	9.30	(total investment/first-year savings)
6. Total Discounted Operational Savings	$4,991,275	
7. Savings to Investment Ratio (SIR)	1.02	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	3.17%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:08:48 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $50, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$800	Annual	8.657	$6,926
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$800			$6,926

4. First year savings	$562,190	
5. Simple Payback Period (in years)	8.73	(total investment/first-year savings)
6. Total Discounted Operational Savings	$5,288,216	
7. Savings to Investment Ratio (SIR)	1.08	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	3.77%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:08:23 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $60, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$35,100	Annual	8.657	$303,867
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$35,100			$303,867

4. First year savings	$596,490	
5. Simple Payback Period (in years)	8.23	(total investment/first-year savings)
6. Total Discounted Operational Savings	$5,585,157	
7. Savings to Investment Ratio (SIR)	1.14	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	4.34%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:07:57 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $70, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$69,400	Annual	8.657	$600,808
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$69,400			$600,808

4. First year savings	$630,790	
5. Simple Payback Period (in years)	7.78	(total investment/first-year savings)
6. Total Discounted Operational Savings	$5,882,098	
7. Savings to Investment Ratio (SIR)	1.20	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	4.88%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:07:19 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $80, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$103,700	Annual	8.657	$897,749
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$103,700			$897,749

4. First year savings	$665,090	
5. Simple Payback Period (in years)	7.38	(total investment/first-year savings)
6. Total Discounted Operational Savings	$6,179,039	
7. Savings to Investment Ratio (SIR)	1.26	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.40%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:06:48 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $90, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$138,000	Annual	8.657	$1,194,690
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$138,000			$1,194,690

4. First year savings	$699,390	
5. Simple Payback Period (in years)	7.02	(total investment/first-year savings)
6. Total Discounted Operational Savings	$6,475,980	
7. Savings to Investment Ratio (SIR)	1.32	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.90%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:06:15 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $100, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$172,300	Annual	8.657	$1,491,631
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$172,300			$1,491,631

4. First year savings	$733,690	
5. Simple Payback Period (in years)	6.69	(total investment/first-year savings)
6. Total Discounted Operational Savings	$6,772,921	
7. Savings to Investment Ratio (SIR)	1.38	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	6.37%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:05:39 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $110, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$206,600	Annual	8.657	$1,788,572
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$206,600			$1,788,572

4. First year savings	$767,990	
5. Simple Payback Period (in years)	6.39	(total investment/first-year savings)
6. Total Discounted Operational Savings	$7,069,862	
7. Savings to Investment Ratio (SIR)	1.44	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	6.83%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:04:22 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $120, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$240,900	Annual	8.657	$2,085,513
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$240,900			$2,085,513

4. First year savings	$802,290	
5. Simple Payback Period (in years)	6.12	(total investment/first-year savings)
6. Total Discounted Operational Savings	$7,366,803	
7. Savings to Investment Ratio (SIR)	1.50	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.27%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:03:50 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $130, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$275,200	Annual	8.657	$2,382,454
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$275,200			$2,382,454

4. First year savings	$836,590	
5. Simple Payback Period (in years)	5.87	(total investment/first-year savings)
6. Total Discounted Operational Savings	$7,663,744	
7. Savings to Investment Ratio (SIR)	1.56	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.69%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:03:14 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $140, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$309,500	Annual	8.657	$2,679,394
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$309,500			$2,679,394

4. First year savings	$870,890	
5. Simple Payback Period (in years)	5.64	(total investment/first-year savings)
6. Total Discounted Operational Savings	$7,960,685	
7. Savings to Investment Ratio (SIR)	1.62	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	8.10%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:02:33 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Tipping Fee, $150, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$343,800	Annual	8.657	$2,976,335
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$343,800			$2,976,335

4. First year savings	$905,190	
5. Simple Payback Period (in years)	5.42	(total investment/first-year savings)
6. Total Discounted Operational Savings	$8,257,626	
7. Savings to Investment Ratio (SIR)	1.68	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	8.50%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:17:50 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Elec, $0.05, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$14.65356	-2,873.0 MBtu	-$42,100	8.696	-$366,115
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$604,500		$5,656,193
Water Subtotal		0.0 Mgal	$0		$0
Total			$604,500		$5,656,193

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$584,800	
5. Simple Payback Period (in years)	8.39	(total investment/first-year savings)
6. Total Discounted Operational Savings	$5,485,647	
7. Savings to Investment Ratio (SIR)	1.12	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	4.15%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:18:16 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Elec, $0.10, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.30711	-2,873.0 MBtu	-$84,200	8.696	-$732,231
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$562,400		$5,290,077
Water Subtotal		0.0 Mgal	$0		$0
Total			$562,400		$5,290,077

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$542,700	
5. Simple Payback Period (in years)	9.04	(total investment/first-year savings)
6. Total Discounted Operational Savings	$5,119,531	
7. Savings to Investment Ratio (SIR)	1.04	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	3.44%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:21:23 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Elec, $0.15, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$43.96067	-2,873.0 MBtu	-$126,300	8.696	-$1,098,346
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$520,300		$4,923,962
Water Subtotal		0.0 Mgal	$0		$0
Total			$520,300		$4,923,962

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$500,600	
5. Simple Payback Period (in years)	9.80	(total investment/first-year savings)
6. Total Discounted Operational Savings	$4,753,416	
7. Savings to Investment Ratio (SIR)	0.97	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	2.67%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:20:42 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Elec, $0.20, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$58.61423	-2,873.0 MBtu	-$168,400	8.696	-$1,464,461
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$478,200		$4,557,847
Water Subtotal		0.0 Mgal	$0		$0
Total			$478,200		$4,557,847

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$458,500	
5. Simple Payback Period (in years)	10.70	(total investment/first-year savings)
6. Total Discounted Operational Savings	$4,387,301	
7. Savings to Investment Ratio (SIR)	0.89	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	1.85%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:20:14 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Elec, $0.25, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$73.26778	-2,873.0 MBtu	-$210,500	8.696	-$1,830,577
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$436,100		$4,191,731
Water Subtotal		0.0 Mgal	$0		$0
Total			$436,100		$4,191,731

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$416,400	
5. Simple Payback Period (in years)	11.79	(total investment/first-year savings)
6. Total Discounted Operational Savings	$4,021,185	
7. Savings to Investment Ratio (SIR)	0.82	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	0.97%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:43:07 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $2.00, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$17.49993	26,500.1 MBtu	$463,750	9.314	$4,319,278
Energy Subtotal		23,627.1 MBtu	$378,540		$3,578,261
Water Subtotal		0.0 Mgal	$0		$0
Total			$378,540		$3,578,261

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$358,840	
5. Simple Payback Period (in years)	13.68	(total investment/first-year savings)
6. Total Discounted Operational Savings	$3,407,715	
7. Savings to Investment Ratio (SIR)	0.69	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	-0.69%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:42:51 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $2.50, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$21.89992	26,500.1 MBtu	$580,350	9.314	$5,405,268
Energy Subtotal		23,627.1 MBtu	$495,140		$4,664,251
Water Subtotal		0.0 Mgal	$0		$0
Total			$495,140		$4,664,251

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$475,440	
5. Simple Payback Period (in years)	10.32	(total investment/first-year savings)
6. Total Discounted Operational Savings	$4,493,705	
7. Savings to Investment Ratio (SIR)	0.92	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	2.10%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:42:34 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $3.00, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$26.29990	26,500.1 MBtu	$696,950	9.314	$6,491,258
Energy Subtotal		23,627.1 MBtu	$611,740		$5,750,241
Water Subtotal		0.0 Mgal	$0		$0
Total			$611,740		$5,750,241

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$592,040	
5. Simple Payback Period (in years)	8.29	(total investment/first-year savings)
6. Total Discounted Operational Savings	$5,579,695	
7. Savings to Investment Ratio (SIR)	1.14	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	4.33%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:42:20 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $3.50, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$30.69988	26,500.1 MBtu	$813,550	9.314	$7,577,248
Energy Subtotal		23,627.1 MBtu	$728,340		$6,836,231
Water Subtotal		0.0 Mgal	$0		$0
Total			$728,340		$6,836,231

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$708,640	
5. Simple Payback Period (in years)	6.93	(total investment/first-year savings)
6. Total Discounted Operational Savings	$6,665,685	
7. Savings to Investment Ratio (SIR)	1.36	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	6.20%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:41:45 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $4.00, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$35.09987	26,500.1 MBtu	$930,150	9.314	$8,663,238
Energy Subtotal		23,627.1 MBtu	$844,940		$7,922,221
Water Subtotal		0.0 Mgal	$0		$0
Total			$844,940		$7,922,221

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$825,240	
5. Simple Payback Period (in years)	5.95	(total investment/first-year savings)
6. Total Discounted Operational Savings	$7,751,675	
7. Savings to Investment Ratio (SIR)	1.58	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	7.82%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:42:05 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $4.50, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$39.49985	26,500.1 MBtu	$1,046,750	9.314	$9,749,228
Energy Subtotal		23,627.1 MBtu	$961,540		$9,008,211
Water Subtotal		0.0 Mgal	$0		$0
Total			$961,540		$9,008,211

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$941,840	
5. Simple Payback Period (in years)	5.21	(total investment/first-year savings)
6. Total Discounted Operational Savings	$8,837,665	
7. Savings to Investment Ratio (SIR)	1.80	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	9.24%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date	January 1, 2011	Preparation Date:	Sat Jan 29 17:41:16 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $5.00, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$43.89983	26,500.1 MBtu	$1,163,350	9.314	$10,835,218
Energy Subtotal		23,627.1 MBtu	$1,078,140		$10,094,201
Water Subtotal		0.0 Mgal	$0		$0
Total			$1,078,140		$10,094,201

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$1,058,440	
5. Simple Payback Period (in years)	4.64	(total investment/first-year savings)
6. Total Discounted Operational Savings	$9,923,655	
7. Savings to Investment Ratio (SIR)	2.02	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	10.51%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:41:00 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $5.50, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$48.19982	26,500.1 MBtu	$1,277,300	9.314	$11,896,527
Energy Subtotal		23,627.1 MBtu	$1,192,090		$11,155,509
Water Subtotal		0.0 Mgal	$0		$0
Total			$1,192,090		$11,155,509

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$1,172,390	
5. Simple Payback Period (in years)	4.19	(total investment/first-year savings)
6. Total Discounted Operational Savings	$10,984,963	
7. Savings to Investment Ratio (SIR)	2.24	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	11.64%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:40:38 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $6.00, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$52.59980	26,500.1 MBtu	$1,393,900	9.314	$12,982,517
Energy Subtotal		23,627.1 MBtu	$1,308,690		$12,241,499
Water Subtotal		0.0 Mgal	$0		$0
Total			$1,308,690		$12,241,499

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$1,288,990	
5. Simple Payback Period (in years)	3.81	(total investment/first-year savings)
6. Total Discounted Operational Savings	$12,070,953	
7. Savings to Investment Ratio (SIR)	2.46	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	12.70%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:40:23 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Fuel, $6.50, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$56.99979	26,500.1 MBtu	$1,510,500	9.314	$14,068,507
Energy Subtotal		23,627.1 MBtu	$1,425,290		$13,327,489
Water Subtotal		0.0 Mgal	$0		$0
Total			$1,425,290		$13,327,489

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$1,405,590	
5. Simple Payback Period (in years)	3.49	(total investment/first-year savings)
6. Total Discounted Operational Savings	$13,156,943	
7. Savings to Investment Ratio (SIR)	2.68	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	13.68%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Mon Jan 31 08:53:36 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Version 1\Loading\Loading 5, 10 yr.xml		

1. Investment

Construction Cost	$5,390,000
SIOH	$0
Design Cost	$1,078,000
Total Cost	$6,468,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$6,468,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$541,690	
5. Simple Payback Period (in years)	11.94	(total investment/first-year savings)
6. Total Discounted Operational Savings	$5,110,744	
7. Savings to Investment Ratio (SIR)	0.79	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	0.60%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:54:56 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Loading 10, 10yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$541,690	
5. Simple Payback Period (in years)	9.06	(total investment/first-year savings)
6. Total Discounted Operational Savings	$5,110,744	
7. Savings to Investment Ratio (SIR)	1.04	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	3.42%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:55:24 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Loading 15, 10yr.xml		

1. Investment

Construction Cost	$3,660,000
SIOH	$0
Design Cost	$732,000
Total Cost	$4,392,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,392,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$541,690	
5. Simple Payback Period (in years)	8.11	(total investment/first-year savings)
6. Total Discounted Operational Savings	$5,110,744	
7. Savings to Investment Ratio (SIR)	1.16	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	4.57%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:55:51 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Loading 20, 10yr.xml		

1. Investment

Construction Cost	$3,440,000
SIOH	$0
Design Cost	$688,000
Total Cost	$4,128,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,128,000

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$541,690	
5. Simple Payback Period (in years)	7.62	(total investment/first-year savings)
6. Total Discounted Operational Savings	$5,110,744	
7. Savings to Investment Ratio (SIR)	1.24	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.22%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:56:23 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Loading 25, 10yr.xml		

1. Investment

Construction Cost	$3,310,000
SIOH	$0
Design Cost	$662,000
Total Cost	$3,972,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$3,972,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$541,690	
5. Simple Payback Period (in years)	7.33	(total investment/first-year savings)
6. Total Discounted Operational Savings	$5,110,744	
7. Savings to Investment Ratio (SIR)	1.29	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.63%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 17:51:27 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Loading 30%, 10yr.xml		

1. Investment

Construction Cost	$3,230,000
SIOH	$0
Design Cost	$646,000
Total Cost	$3,876,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$3,876,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	-$19,700	Annual	8.657	-$170,546
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	-$19,700			-$170,546

4. First year savings	$541,690	
5. Simple Payback Period (in years)	7.16	(total investment/first-year savings)
6. Total Discounted Operational Savings	$5,110,744	
7. Savings to Investment Ratio (SIR)	1.32	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.89%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 18:00:32 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Biosolids, $0, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$90,800	Annual	8.657	$786,071
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$90,800			$786,071

4. First year savings	$652,190	
5. Simple Payback Period (in years)	7.53	(total investment/first-year savings)
6. Total Discounted Operational Savings	$6,067,362	
7. Savings to Investment Ratio (SIR)	1.24	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.21%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 18:01:04 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Biosolids, $5, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$93,360	Annual	8.657	$808,234
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$93,360			$808,234

4. First year savings	$654,750	
5. Simple Payback Period (in years)	7.50	(total investment/first-year savings)
6. Total Discounted Operational Savings	$6,089,524	
7. Savings to Investment Ratio (SIR)	1.24	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.25%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 18:01:40 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Biosolids, $10, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$95,920	Annual	8.657	$830,396
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$95,920			$830,396

4. First year savings	$657,310	
5. Simple Payback Period (in years)	7.47	(total investment/first-year savings)
6. Total Discounted Operational Savings	$6,111,687	
7. Savings to Investment Ratio (SIR)	1.25	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.28%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

NIST BLCC 5.3-10: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A
The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2010.

Location:	Colorado	Discount Rate:	3%
Project Title:	ESTCP ER 0933	Analyst:	Cale McPherson - CDM
Base Date:	January 1, 2011	Preparation Date:	Sat Jan 29 18:02:13 PST 2011
BOD:	January 1, 2011	Economic Life:	10 years 0 months
File Name:	C:\Program Files\BLCC5\projects\Biosolids, $15, 10 yr.xml		

1. Investment

Construction Cost	$4,090,000
SIOH	$0
Design Cost	$818,000
Total Cost	$4,908,000
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$4,908,000

2. Energy and Water Savings (+) or Cost (-)
Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$29.65880	-2,873.0 MBtu	-$85,210	8.696	-$741,017
Natural Gas	$24.39991	26,500.1 MBtu	$646,600	9.314	$6,022,308
Energy Subtotal		23,627.1 MBtu	$561,390		$5,281,291
Water Subtotal		0.0 Mgal	$0		$0
Total			$561,390		$5,281,291

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Annually Recurring	$98,480	Annual	8.657	$852,558
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$98,480			$852,558

4. First year savings	$659,870	
5. Simple Payback Period (in years)	7.44	(total investment/first-year savings)
6. Total Discounted Operational Savings	$6,133,849	
7. Savings to Investment Ratio (SIR)	1.25	(total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	5.32%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

Appendix C: DoD Food Waste Generation White Paper

Memorandum

To: *Dr. Andrea Leeson*

From: *Dr. Patrick Evans*

Date: *December 7, 2015*

Subject: *DoD Waste Stream Characterization White Paper for ER-200933, Renewable Energy Production from DoD Installation Solid Waste by Anaerobic Digestion, Revision 3*

A DoD waste characterization analysis was conducted to identify and quantify waste streams generated by the Navy, Marine Corps, Air Force, and Army that are suitable for anaerobic digestion. The analysis consisted of two parts. In part one, data and information from the DoD branches were collected and reviewed to identify total waste generation rates and component-specific generation rates. In part two, the waste component categories were evaluated for their suitability for anaerobic digestion. This white paper was compiled to summarize the results of the DoD waste characterization analysis.

DoD Waste Stream Characterization

The most readily available and reliable data on DoD waste streams is in terms of mass generation rates, e.g., tons/yr. Mass generation rates are typically documented as part of a military base's standard operating procedures for use in billing and conservation measures. Mass generation rates were available from all four combat branches of the DoD.

More specific characterization data identifying separate DoD waste streams by component, e.g., plastics, paper, metals, food waste, etc., is rare and considerably less reliable than the mass generation data. Component specific data is uncommon because DoD wastes are typically comingled and disposed of in heterogeneous mixtures. Component identification in a comingled waste stream is a difficult, messy, and time consuming process that requires hand sorting and/or visual inspection. Due to the substantial manual input required for waste identification, studies characterizing the individual components are expensive and are conducted on an infrequent basis.[1] Further, because there is no uniform directive or requirement within the DoD for the tracking and documentation of individual waste components, it is done inconsistently. None of the branches track total waste generation by component. The Navy and the Marine Corps track recycled materials by component, but because these branches do not estimate capture rates of recyclable materials, the data is insufficient for estimating total component specific generation rates.

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[1] (Tchobanoglous, Theisen, & Vigil, 1993)

A summary of the collected data from the four branches is provided below.

Navy Solid Waste Characterization
The NAVFAC provided Navy installation waste characterization data for the FY 2005 through FY 2009.[2] The data included total waste generation rates, and component specific recycling rates. The total waste generation data for the Navy is provided in Table 1. Per capita generation rates were estimated based on population estimates provided by the DoD Statistical Information Analysis Division (DoD SIAD).[3]

Table 1
Navy Total Waste, 2005 to 2009 (in tons and pounds per capita per day)

	Total Waste Generation					
Year	**2005**	**2006**	**2007**	**2008**	**2009**	**Average**
Population, in thousands	**421**	**396**	**262**	**254**	**252**	**317**
Total MSW - tons	751,646	691,747	611,463	608,811	587,334	650,200
Total MSW – pcpd	9.8	9.6	12.8	13.1	12.8	11.6

The reported waste generation at Navy installations shows relative consistency, ranging from 9.6 to 13.1 pounds per person per day with an average of 11.6.

Recycled material data for the Navy is summarized in Table 2.

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[2] (Hamilton, 2010)
[3] (Department of Defense, 2010)

Table 2
Navy Recycled Materials, 2005 to 2009 (tons, %, and pounds per capita per day)

	Recycled Materials, Tons					
Year	**2005**	**2006**	**2007**	**2008**	**2009**	**Average**
Population, in thousands	**421**	**396**	**262**	**254**	**252**	**317**
Paper and Paperboard	35,068	30,924	28,636	28,257	31,605	30,898
Yard Trimmings	11,263	2,781	4,116	7,232	2,102	5,499
Food Scraps	1,579	2,131	6,976	766	1,806	2,652
Metals	56,611	61,280	57,692	46,932	61,504	56,804
Glass	1,597	1,020	868	736	846	1,013
Wood	24,558	10,754	12,089	20,110	12,478	15,998
Rubber and Leather	-	-	-	-	-	-
Textiles	-	-	-	-	-	-
Misc. Inorganic Wastes	-	-	-	-	-	-
Plastics	1,677	1,413	1,942	1,673	3,244	1,990
Other	25,256	17,169	18,518	34,308	17,579	22,566
Recycled Materials - tons	157,609	127,471	130,837	140,014	131,163	137,419
	Recycled Materials, %					
Year	**2005**	**2006**	**2007**	**2008**	**2009**	**Average**
Paper and Paperboard	22.3%	24.3%	21.9%	20.2%	24.1%	22.5%
Yard Trimmings	7.1%	2.2%	3.1%	5.2%	1.6%	4.0%
Food Scraps	1.0%	1.7%	5.3%	0.5%	1.4%	1.9%
Metals	35.9%	48.1%	44.1%	33.5%	46.9%	41.3%
Glass	1.0%	0.8%	0.7%	0.5%	0.6%	0.7%
Wood	15.6%	8.4%	9.2%	14.4%	9.5%	11.6%
Rubber and Leather	-	-	-	-	-	-
Textiles	-	-	-	-	-	-
Misc. Inorganic Wastes	-	-	-	-	-	-
Plastics	1.1%	1.1%	1.5%	1.2%	2.5%	1.4%
Other	16.0%	13.5%	14.2%	24.5%	13.4%	16.4%
Recycled Materials - %	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
	Recycled Materials, pcpd					
Year	**2005**	**2006**	**2007**	**2008**	**2009**	**Average**
Paper and Paperboard	0.46	0.43	0.60	0.61	0.69	0.56
Yard Trimmings	0.15	0.04	0.09	0.16	0.05	0.09
Food Scraps	0.02	0.03	0.15	0.02	0.04	0.05
Metals	0.74	0.85	1.21	1.01	1.34	1.03
Glass	0.02	0.01	0.02	0.02	0.02	0.02
Wood	0.32	0.15	0.25	0.43	0.27	0.29
Rubber and Leather	-	-	-	-	-	-
Textiles	-	-	-	-	-	-
Misc. Inorganic Wastes	-	-	-	-	-	-
Plastics	0.02	0.02	0.04	0.04	0.07	0.04
Other	0.33	0.24	0.39	0.74	0.38	0.42
Recycled Materials - pcpd	2.1	1.8	2.7	3.0	2.9	2.5

Marine Corps Solid Waste Characterization

The NAVFAC also provided Marine Corps installation waste characterization data for the FY 2006 through FY 2009.[4] Like the data provided for the Navy, this data included total waste generation rates, and component specific recycling rates. The total waste generation data for the Marine Corps is provided in Table 3. Per capita generation rates were estimated based on population estimates provided by the DoD SIAD.[5]

Table 3
Marine Corps Total Waste, 2006 to 2009 (in tons and pounds per capita per day)

	Total Waste Generation				
Year	**2006**	**2007**	**2008**	**2009**	**Average**
Population, in thousands	**218**	**163**	**188**	**199**	**192**
Total MSW - tons	234,969	246,931	235,659	221,101	234,665
Total MSW – pcpd	5.9	8.3	6.9	6.1	6.7

The reported waste generation at Marine Corps installations shows relative consistency, ranging from 5.9 to 8.3 pounds per person per day with an average of 6.7. This generation rate is lower than the rate estimated for the Navy.

Recycled material data for the Marine Corps is summarized in Table 4.

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[4] (Hamilton, 2010)

[5] (Department of Defense, 2010)

Table 4
Marine Corps Recycled Materials, 2005 to 2009 (tons, %, and pounds per capita per day)

	Recycled Materials, Tons				
Year	**2006**	**2007**	**2008**	**2009**	**Average**
Population, in thousands	**218**	**163**	**188**	**199**	**192**
Paper and Paperboard	10,900	9,825	13,422	15,036	12,296
Yard Trimmings	2,293	1,289	1,867	2,124	1,893
Food Scraps	4,518	6,610	5,783	1,800	4,678
Metals	18,930	37,686	23,580	19,394	24,898
Glass	639	558	248	331	444
Wood	14,796	14,520	14,741	22,037	16,524
Rubber and Leather	-	-	-	-	-
Textiles	-	-	-	-	-
Misc. Inorganic Wastes	-	-	-	-	-
Plastics	490	771	422	648	583
Other	2,236	10,294	14,683	7,630	8,711
Recycled Materials - tons	54,804	81,552	74,746	69,001	70,026
	Recycled Materials, %				
Year	**2006**	**2007**	**2008**	**2009**	**Average**
Paper and Paperboard	19.9%	12.0%	18.0%	21.8%	17.6%
Yard Trimmings	4.2%	1.6%	2.5%	3.1%	2.7%
Food Scraps	8.2%	8.1%	7.7%	2.6%	6.7%
Metals	34.5%	46.2%	31.5%	28.1%	35.6%
Glass	1.2%	0.7%	0.3%	0.5%	0.6%
Wood	27.0%	17.8%	19.7%	31.9%	23.6%
Rubber and Leather	-	-	-	-	-
Textiles	-	-	-	-	-
Misc. Inorganic Wastes	-	-	-	-	-
Plastics	0.9%	0.9%	0.6%	0.9%	0.8%
Other	4.1%	12.6%	19.6%	11.1%	12.4%
Recycled Materials - %	100.0%	100.0%	100.0%	100.0%	100.0%
	Recycled Materials, pcpd				
Year	**2006**	**2007**	**2008**	**2009**	**Average**
Paper and Paperboard	0.27	0.33	0.39	0.41	0.35
Yard Trimmings	0.06	0.04	0.05	0.06	0.05
Food Scraps	0.114	0.222	0.169	0.050	0.138
Metals	0.48	1.27	0.69	0.53	0.74
Glass	0.016	0.019	0.007	0.009	0.013
Wood	0.37	0.49	0.43	0.61	0.47
Rubber and Leather	-	-	-	-	-
Textiles	-	-	-	-	-
Misc. Inorganic Wastes	-	-	-	-	-
Plastics	0.01	0.03	0.01	0.02	0.02
Other	0.06	0.35	0.43	0.21	0.26
Recycled Materials - pcpd	1.4	2.7	2.2	1.9	2.1

Air Force Solid Waste Characterization

The Air Force Center for Engineering and the Environment (AFCEE) provided total waste generation data for FY 2002 through FY 2008 (with the exception of FY 2004, which was not available) for Air Force installations.[6] The waste statistics for the Air Force are summarized in Table 5. Per capita generation rates were estimated based on population estimates provided by the DoD SIAD.[7]

Table 5
Air Force Waste Stream Data, 2002 to 2008

	Waste Generation						
Year	**2002**	**2003**	**2005**	**2006**	**2007**	**2008**	**Average**
Population, in thousands	**457**	**464**	**467**	**448**	**446**	**440**	**454**
Total MSW - tons	1,902,944	1,011,119	764,781	2,321,002	840,233	528,852	1,228,155
Total MSW – pcpd	22.8	11.9	9.0	28.4	10.3	6.6	14.8

The reported waste generation at Air Force installations varied substantially throughout the years, ranging from 6.6 to 28.4 pounds per person per day with an average of 14.8. A fourfold difference between low to high is substantial and unusual. No explanation was given from the Air Force to explain the difference in generation rates. It was expected that per capita generation rates would be decreasing as conservation measures were implemented. If the 2006 data is ignored, the per capita generation is steadily reducing since 2002.

Army Solid Waste Characterization

Army solid waste data was obtained from the Solid Waste Annual Report Website[8,9] via the Army's online Installation Management Application Resource Center. Data was collected from four different reports:

- Installation Spreadsheet Totals (FY03 – FY08)
- Headquarters (AEC) Army Report 1 – (Overall)
- Headquarters (AEC) Army Report 2 – (MSW Diversion)
- Measures of Merit (MoM) Elements

The waste statistics for the Army are summarized in Table 6. Per capita generation rates were estimated base on population estimates provided by the DoD SIAD.[10]

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[6] (Carper, 2010)
[7] (Department of Defense, 2010)
[8] (U.S. Army, 2010)
[9] (Eng, 2010)
[10] (Department of Defense, 2010)

Table 6
Army Waste Stream Data, 2003 to 2008

	Waste Generation						
Year	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**Average**
Population, in thousands	**611**	**616**	**635**	**656**	**674**	**715**	**651**
Total MSW - tons	1,759,624	3,544,886	2,209,752	2,328,227	2,859,805	2,237,291	2,489,931
Total MSW - pcpd	15.8	31.5	19.1	19.5	23.2	17.2	21.0

The Army had the highest per capita generation rates of any of the four branches. Generation rates ranged from 15.8 to 31.5 pounds per person per day, with an average of 21.0. No general trend is observed in the generation numbers.

DoD Waste Data Comparison
A summary table of the average waste generation rates across the DoD was compiled for relative comparison between the different branches and for subsequent comparison with reported waste generation rates from detailed studies.

The summary waste generation data across the DoD is provided in Table 7.

Table 7
DoD Waste Stream Data

	Total Waste Generation				
Branch	**Navy**	**Marine Corps**	**Air Force**	**Army**	**DoD Total**
Population, in thousands	**317**	**192**	**454**	**651**	**1,614**
Total MSW - tons	650,200	300,163	1,228,155	2,489,931	4,668,449
Total MSW - pcpd	11.6	8.7	14.8	21.0	15.8

The summary generation numbers indicate a few things about waste generation across the DoD.

- The Army is the single largest generator of solid waste based on its larger population and its higher per capita generation rate.
- The Marine Corps is the smallest generator based on its smaller population and lower per capita generation rate.
- Per capita generation rates range between 8.7 and 21.0 pounds per person per day, with an average of 15.8.
- Average waste generation across the DoD is approximately 4.7 million tons per year

The discrepancy between the per capita generation numbers could be attributable to a number of factors including the possibility that one branch simply generates more waste per capita than the other due to different conservation measures or different activities under command. One would expect the Navy and the Marine Corps, which operate in the naval arena, to have more stringent waste generation policies and practices to minimize wasted space on a vessel afloat. Variation can also be introduced based on reporting methodology in which the different branches or individual bases consider specific wastes differently. For instance, green waste at one base may not be included in waste generation statistics because it is immediately diverted into mulch at the point of generation, while another base may track the green waste because it is generated and then transported before diversion to mulch or other disposal. Likewise, sewage sludge and ash may not be included in the waste generation statistics depending on an individual base's treatment and disposal practices. No information was available from the DoD to determine if different reporting practices were employed at different bases or in different branches.

DoD Waste Data Validation

To further understand and validate the per capita generation rates and to estimate component generation rates, the total waste generation numbers were compared with detailed studies from the Army Corps of Engineers and the U.S. EPA.

Table 8 is populated with waste characterization data from the U.S. EPA report: *Municipal Solid Waste in the United States: 2007 Facts and Figures*[11] and from the Army Corps of Engineers report: *Solid Waste Generation Rates at Army Base Camps.*[12] The EPA report is the most up to date and detailed analysis of the solid waste in the United States. The Army Corps report is the only known waste characterization study conducted at a DoD installation. The characterization was conducted in 2003 and 2006 at two Army base camps to determine the relative generation rates of waste components on a per capita basis.

Table 8
Army Base Camp and U.S. Waste Stream Characterization Data

	2003 (Camp A)		**2006 (Camp B)**		**2007 (US)**	
Component	**pcpd**	**%**	**pcpd**	**%**	**pcpd**	**%**
Paper and Paperboard	1.4	9%	4.1	23%	1.5	33%
Food	1.0	7%	1.5	8%	0.6	12%
Vegetation	0.1	1%	0.2	1%	0.6	13%
Metals	0.1	0%	0.7	4%	0.4	8%
Glass	0.1	1%	0.1	1%	0.2	5%
Wood	11.4	72%	2.9	16%	0.3	6%
Rubber and Leather	0.0	0%	0.0	0%	0.1	3%
Textiles	0.1	0%	0.3	1%	0.2	5%
Plastics	1.2	8%	2.0	11%	0.5	12%
Sewage Sludge[1]	0.2	1%	1.9	10%	-	0%
Ashes[1]	0.0	0%	2.2	12%	-	0%
Other	0.1	1%	2.3	13%	0.1	3%
Total Waste Generated[1]	15.8	100%	18.2	100%	4.6	100%

[1] Sewage sludge and ash were not included in the U.S. EPA waste characterization and are not reflected in the total waste generated

The data provided above suggests a few key things about waste generation at DoD installations.

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[11] (U.S. EPA, 2008)

[12] (U.S. Army Corps of Engineers, 2008)

- Component generation, such as wood waste, can vary considerably from base to base. Wood waste from Camp A was 72 percent of total waste generated, while it represented just 16 percent of total waste generated from Camp B. One possible explanation for the high wood waste fraction of the Camp A waste is that the camp was not fully established and was generating significant construction and shipping waste to bring in new materials. An established camp, like Camp B, may have less wood waste, but higher concentrations of other wastes, as it is more reliant on locally available materials and supplies and is not in active construction.
- Total generation at Army base camps are relatively consistent, but are approximately four times as high as the U.S. National Average.
- The total waste generation rates at the Army base camps are consistent with the projections made in Table 7 for the entire DoD, suggesting that the estimate is reasonable for projections within the DoD. Camp A waste generation rates were identical to the projected average of 15.8 pounds per capita per day.
- Certain fractions of the waste stream can vary considerably from Army base to Army base in both the relative (fraction of total) and the absolute (pounds per capita per day generated) basis.
    - Paper and Paperboard, and Wood generation rates showed the most relative and absolute variation.
    - Metals, Sewage Sludge, Ashes, and Other wastes showed great relative variation, but little absolute variation.
    - Food and Vegetation, Glass, Rubber and Leather, Textiles, and Plastic waste showed some relative variation, but were generally consistent on an absolute basis between camps and when compared with the U.S. EPA national average.
- Food waste generation rates for the two Army base camps were 1.0 and 1.5 pounds pcpd compared to the US average of 0.6 pounds pcpd. Army food waste generation was 7 to 8% of total MSW generation compared to 12% for the US. Total food waste generation by the DoD was estimated to range from 330,000 to 560,000 tons per year using the range of percentages in Table 8 and total MSW generation data in Table 7.

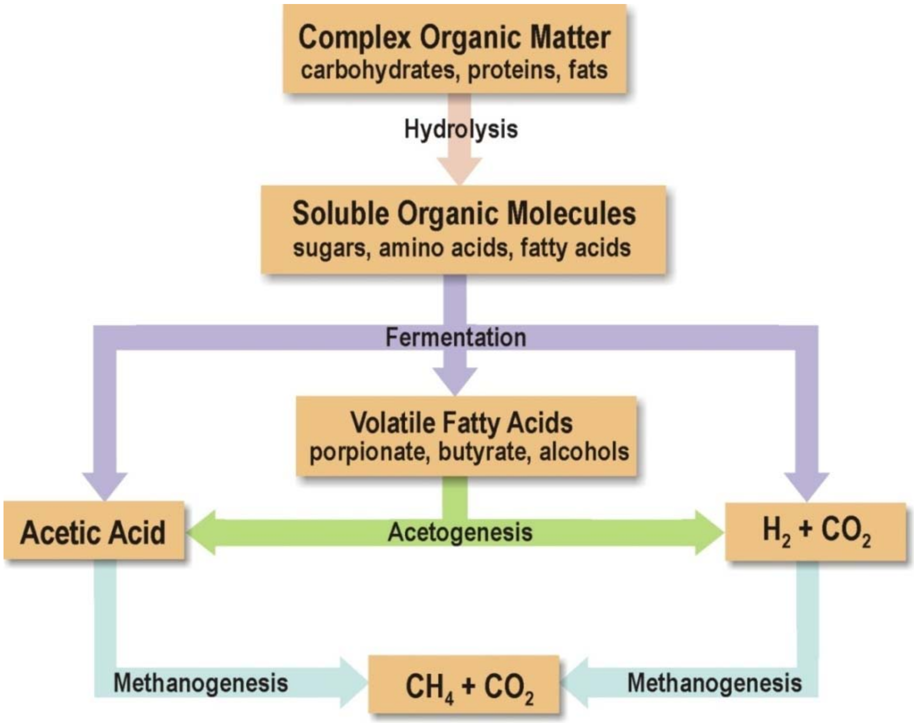
Conclusions from DoD Waste Characterization

The DoD waste characterization analysis was helpful to quantify the relative waste generation rates across installations. Based on the data provided by the different branches and based on the specific analysis performed by the Army Corps of Engineers, it is estimated that solid waste is generated at approximately 15.8 pounds per capita per day. Waste generation by specific component proved to be more difficult to estimate due to differences in waste tracking methodologies and installation activities. There does not appear to be enough data available from the DoD to make a detailed estimate of waste generation by component. Nevertheless, DoD food waste generation was estimated to be 330,000 to 560,000 tons per year.

Suitability of Waste Components for Anaerobic Digestion

Anaerobic digestion is an organic waste treatment technology that uses microbiological communities to break down complex organics to reduce the overall solids mass and volume while generating a biogas energy product. Regardless of the waste stream utilized, anaerobic treatment follows the same biological and chemical pathways using related microbial populations. The anaerobic treatment process is represented in Figure 1.[13]

Figure 1
Anaerobic Digestion Process


Complex Organic Matter
carbohydrates, proteins, fats
Hydrolysis
Soluble Organic Molecules
sugars, amino acids, fatty acids
Fermentation
Volatile Fatty Acids
porpionate, butyrate, alcohols
Acetic Acid
Acetogenesis
$H_2 + CO_2$
Methanogenesis
$CH_4 + CO_2$
Methanogenesis

Due to the relative uniformity of the anaerobic digestion process, and the substantial amount of data available from stable sewage sludge anaerobic digestion systems, general characteristics for digestible waste have been developed. These general characteristics are described below.

---

[13] (EPA, 2011)

Feedstock Characteristics

- **Organic:** The primary characteristic of a good digester feedstock is that it is organic in nature. Anaerobic digestion is biological process that utilizes organic compounds as an energy source. Inorganic compounds are not readily metabolized by the microbial population and are not appropriate for anaerobic digestion.

- **C:N Ratio:** The ideal carbon to nitrogen (C:N) ratio is between 20 and 30 for stable digestion. The higher carbon concentration helps provide sufficient organic matter for the microbiological community to feed on, while the lower nitrogen concentration provides a key nutrient at a low enough concentration to encourage growth while limiting ammonia toxicity. Anaerobic digestion of wastes with lower C:N ratios are possible, but ammonia toxicity becomes problematic and must be monitored carefully. Ammonia toxicity is relatively common when anaerobically digesting chicken waste, which has a C:N ratio between 5 and 10.[14] Digestion at higher C:N ratios is also possible, but it can be difficult to maintain due the absence of nitrogen, which is a rate limiting nutrient for the anaerobic bacteria.

- **Trace Nutrients:** Micronutrients including phosphorus, magnesium, iron, molybdenum, nickel and cobalt are essential for the stable growth of anaerobic populations.[15] In the absence of these micronutrients, the methanogenic archea are growth inhibited and digesters tend towards upsets as volatile fatty acids accumulate, the pH drops, and the microbiological community dies.

- **Absence of Inhibitory Compounds:** Inhibitory compounds such as disinfectants, antibiotics and heavy metals can negatively influence the digester population and result in digester upsets. The ideal digester feedstock will be free of inhibitory compounds. However, use of sanitizers and disinfectants is common and these products contain inhibitors such as quaternary ammonium compounds. Such compounds are found in anaerobic digester sludge and thus are tolerated within certain limits. The exact limits that are inhibitory is a current area of research and is not well defined.

Assessment and Conclusion on the Suitability of DoD Wastes for Anaerobic Digestion

To simplify the assessment of the available DoD waste streams, Table 9 comparing the component waste categories was developed based on the ideal feedstock characteristics discussed previously.

---

[14] (Speece, 1996)

[15] Ibid.

Table 9
Evaluation of DoD Waste Stream for Anaerobic Digestion

Component	**Organic Compound?**	**C:N Ratio**	**Trace Nutrients Present?**	**Inhibitor Compounds Present?**	**Suitable for Anaerobic Digestion?**
Paper and Paperboard	**Yes**	145 : 1	No	Maybe	No
Food	**Yes**	**19 : 1**	**Yes**	Maybe	**Yes**
Vegetation	**Yes**	14:1	**Yes**	Maybe	**Maybe**
Metals	No	<5 : 1	No	Yes	No
Glass	No	<5 : 1	No	**No**	No
Wood	**Yes**	250 : 1	No	Maybe	No
Rubber and Leather	No	40 : 1	No	Maybe	No
Textiles	No	12 : 1	No	Yes	No
Plastics	No	>500 : 1	No	Yes	No
Ashes	No	50 : 1	No	Yes	No

Based on the criteria in Table 9, only the food waste and vegetation waste streams are candidates for treatment through anaerobic digestion. Food waste is the best candidate and is well suited for biogas production. Vegetation may be a good amendment to be added to a food waste digestion process. In this case a compost product would be generated in addition to the biogas. All of the other waste streams are either inorganic, have insufficient carbon, nitrogen, or trace nutrients, or are known to have inhibitory compounds latent within the stream.

Typically, after a preliminary assessment of a candidate waste stream is completed, the candidate waste stream is subjected to lab and pilot scale tests to confirm its overall applicability and digestion characteristics. These lab and pilot scales are currently being completed for DoD food wastes as part of this project. Results from this analysis are forthcoming and will be reported in subsequent reports and presentations.

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Appendices

Table A
Complete United States Waste Stream Data

	Thousands of Tons								
Year	**1960**	**1970**	**1980**	**1990**	**2000**	**2004**	**2005**	**2006**	**2007**
Paper and Paperboard	29,990	44,310	55,160	72,730	87,740	86,450	84,840	85,350	83,010
Yard Trimmings	20,000	23,200	27,500	35,000	30,530	31,770	32,070	32,400	32,630
Food Scraps	12,200	12,800	13,000	20,800	26,810	29,410	30,220	31,040	31,650
Metals	10,820	13,830	15,510	16,550	18,910	19,980	20,060	20,660	20,750
Glass	6,720	12,740	15,130	13,100	12,760	12,890	13,320	13,520	13,580
Wood	3,030	3,720	7,010	12,210	13,110	13,890	14,080	14,100	14,210
Rubber and Leather	1,840	2,970	4,200	5,790	6,710	7,150	7,360	7,400	7,480
Textiles	1,760	2,040	2,530	5,810	9,440	10,980	11,380	11,870	11,920
Misc. Inorganic Wastes	1,300	1,780	2,250	2,900	3,500	3,650	3,690	3,720	3,750
Plastics	390	2,900	6,830	17,130	25,540	29,480	29,240	29,810	30,730
Other *	70	770	2,520	3,190	4,000	4,130	4,170	4,310	4,430
Total MSW Generated	88,120	121,060	151,640	205,210	239,050	249,780	250,430	254,180	254,140

	Percent of Total Generation								
Year	**1960**	**1970**	**1980**	**1990**	**2000**	**2004**	**2005**	**2006**	**2007**
Paper and Paperboard	34.0%	36.6%	36.4%	35.4%	36.7%	34.6%	33.9%	33.6%	32.7%
Yard Trimmings	22.7%	19.2%	18.1%	17.1%	12.8%	12.7%	12.8%	12.7%	12.8%
Food Scraps	13.8%	10.6%	8.6%	10.1%	11.2%	11.8%	12.1%	12.2%	12.5%
Metals	12.3%	11.4%	10.2%	8.1%	7.9%	8.0%	8.0%	8.1%	8.2%
Glass	7.6%	10.5%	10.0%	6.4%	5.3%	5.2%	5.3%	5.3%	5.3%
Wood	3.4%	3.1%	4.6%	6.0%	5.5%	5.6%	5.6%	5.5%	5.6%
Rubber and Leather	2.1%	2.5%	2.8%	2.8%	2.8%	2.9%	2.9%	2.9%	2.9%
Textiles	2.0%	1.7%	1.7%	2.8%	3.9%	4.4%	4.5%	4.7%	4.7%
Misc. Inorganic Wastes	1.5%	1.5%	1.5%	1.4%	1.5%	1.5%	1.5%	1.5%	1.5%
Plastics	0.4%	2.4%	4.5%	8.3%	10.7%	11.8%	11.7%	11.7%	12.1%
Other *	0.1%	0.6%	1.7%	1.6%	1.7%	1.7%	1.7%	1.7%	1.7%
Total MSW Generated -%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

	Pounds Per Capita Per Day (pcpd)								
Year	**1960**	**1970**	**1980**	**1990**	**2000**	**2004**	**2005**	**2006**	**2007**
Population, in millions	**180.7**	**205.1**	**227.2**	**249.5**	**282.2**	**293.2**	**295.9**	**298.8**	**301.6**
Paper and Paperboard	0.91	1.18	1.33	1.59	1.70	1.61	1.57	1.57	1.51
Yard Trimmings	0.60	0.62	0.66	0.77	0.59	0.59	0.59	0.59	0.59
Food Scraps	0.37	0.34	0.31	0.46	0.52	0.55	0.56	0.57	0.57
Metals	0.33	0.37	0.37	0.36	0.37	0.37	0.37	0.38	0.38
Glass	0.20	0.34	0.36	0.29	0.25	0.24	0.25	0.25	0.25
Wood	0.09	0.10	0.17	0.27	0.25	0.26	0.26	0.26	0.26
Rubber and Leather	0.06	0.08	0.10	0.13	0.13	0.13	0.14	0.14	0.14
Textiles	0.05	0.05	0.06	0.13	0.18	0.20	0.21	0.22	0.22
Misc. Inorganic Wastes	0.04	0.05	0.05	0.06	0.07	0.07	0.07	0.07	0.07
Plastics	0.01	0.08	0.16	0.38	0.50	0.55	0.54	0.55	0.56
Other *	0.00	0.02	0.06	0.07	0.08	0.08	0.08	0.08	0.08
Total MSW Generated -pcpd	2.7	3.2	3.7	4.5	4.6	4.7	4.6	4.7	4.6

** Includes electrolytes in batteries, fluff pulp, feces, and urine in disposable diapers. Details may not add to total due to rounding*

Waste Summary Data
US Navy
FY05 - FY09

	2005 (tons)	2006 (tons)	2007 (tons)	2008 (tons)	2009 (tons)		Average (tons)
Food	1,579	2,131	6,976	766	1,806		2,652
Glass	1,597	1,020	868	736	846		1,013
Metals	56,611	61,280	57,692	46,932	61,504		56,804
Other (non-food)	25,256	17,169	18,518	34,308	17,579		22,566
Paper & Paperboard	35,068	30,924	28,636	28,257	31,605		30,898
Plastic	1,677	1,413	1,942	1,673	3,244		1,990
Wood	24,558	10,754	12,089	20,110	12,478		15,998
Yard/Green Waste	11,263	2,781	4,116	7,232	2,102		5,499
Total Recycle by Cat	157,609	127,471	130,837	140,014	131,163		137,419
Composting	23,513	21,667	14,533	8,703	13,962		16,476
Recycled Antifreeze	287	240	90	219	206		209
Recycled Lead Acid Batteries	1,237	1,812	2,115	1,431	2,227		1,764
Recycled Used Motor Oil	8,498	5,134	2,385	4,158	4,341		4,903
Total Recycled	191,144	156,324	149,960	154,526	151,900		160,771
Landfilled	367,500	362,669	277,130	261,310	247,078		303,138
Incinerated	45,416	52,469	58,125	58,769	63,967		55,749
Landfilled Antifreeze	311	94	116	463	91		215
Landfilled Lead Acid Batteries	55	238	41	163	163		132
Landfilled Used Motor Oils	7,971	879	898	42	435		2,045
L_Oils(wte)		229	176	60	100		141
LR_Oils(wte)		3,402	3,408	2,571	3,677		3,265
Total Disposed	421,253	419,979	339,894	323,379	315,510		364,003
Total Waste	612,397	576,303	489,854	477,905	467,410		524,774
% Recycled	31%	27%	31%	32%	32%		31%
% Not Recycled	69%	73%	69%	68%	68%		69%
Food Waste % Rcyc	0.8%	1.4%	4.7%	0.5%	1.2%		2%
Food Waste % Total	0.3%	0.4%	1.4%	0.2%	0.4%		1%
F+Y+C % Rcyc	19%	17%	17%	11%	12%		15%
F+Y+C % Total	6%	5%	5%	3%	4%		5%
Number of Installatns	103	105	103	102	95		102

R_Anti	Recycled Antifreeze
R_LAB	Recycled Lead Acid Batteries
R_Oils	Recycyed Used Motor Oils
L_Anti	Landfilled Antifreeze
L_LAB	Landfilled Lead Acid Batteries
L_Oils	Landfilled Used Motor Oils

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Waste Summary Data
US Marine Corps
FY06 - FY09

	2006 (tons)	2007 (tons)	2008 (tons)	2009 (tons)		Average (tons)
Food	4,518	6,610	5,783	1,800		4,678
Glass	639	558	248	331		444
Metals	18,930	37,686	23,580	19,394		24,898
Other (non-food)	2,236	10,294	14,683	7,630		8,711
Paper & Paperboard	10,900	9,825	13,422	15,036		12,296
Plastic	490	771	422	648		583
Wood	14,796	14,520	14,741	22,037		16,524
Yard/Green Waste	2,293	1,289	1,867	2,124		1,893
Total Recycle by Cat	54,804	81,552	74,746	69,001		70,026
Composting	9,064	5,336	6,381	4,273		6,264
Recycled Antifreeze	373	102	325	399		300
Recycled Lead Acid Batteries	1,091	769	2,063	996		1,230
Recycled Used Motor Oil	1,506	1,840	1,025	2,340		1,678
Total Recycled	66,838	89,598	84,539	77,010		79,497
Landfilled	145,126	135,042	133,175	126,041		134,846
Incinerated	21,697	21,597	16,340	16,373		19,002
Landfilled Antifreeze	44	38	36	57		44
Landfilled Lead Acid Batteries	105	4	41	82		58
Landfilled Used Motor Oils	363	44	1	-		102
L_Oils(wte)	37	131	289	-		114
LR_Oils(wte)	759	477	1,237	1,537		1,002
Total Disposed	168,130	157,333	151,120	144,091		155,169
Total Waste	234,969	246,931	235,659	221,101		234,665
% Recycled	28%	36%	36%	35%		34%
% Not Recycled	72%	64%	64%	65%		66%
Food Waste % Rcyc	7%	7%	7%	2%		6%
Food Waste % Total	2%	3%	2%	1%		2%
F+Y+C % Rcyc	24%	15%	17%	11%		16%
F+Y+C % Total	7%	5%	6%	4%		5%
Number of Installatns	19	18	17	18		18

R_Anti	Recycled Antifreeze
R_LAB	Recycled Lead Acid Batteries
R_Oils	Recycyed Used Motor Oils
L_Anti	Landfilled Antifreeze
L_LAB	Landfilled Lead Acid Batteries
L_Oils	Landfilled Used Motor Oils

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Waste Summary Data
US Army
FY03 - FY08

	FY03 (tons)	FY04 (tons)	FY05 (tons)	FY06 (tons)	FY07 (tons)	FY08 (tons)		Average (tons)
Total SW Generated (Tons)	1,759,624	3,544,886	2,209,752	2,328,227	2,859,805	2,237,291		2,489,931
Landfill (Tons)	874,954	739,763	891,997	488,958	517,058	527,811		673,424
C&D Landfill (Tons)	167,919	1,156,898	244,038	366,339	389,730	358,406		447,222
C&D Diverted (Tons)	334,538	1,189,487	488,738	924,944	1,461,907	769,615		861,538
Total C&D Generated (Tons)	502,456	2,346,385	732,776	1,291,283	1,851,637	1,128,021		1,308,760
C&D Diversion (%)	67%	51%	67%	72%	79%	68%		66%
Non-WTE Incinerator (Tons)	28,922	23,244	39,115	51,012	47,701	32,666		37,110
WTE Incinerator (Tons)	63,774	50,357	47,521	41,858	45,987	50,014		49,919
Compost (Tons)*	16,707	14,723	11,846	9,950	11,140	9,073		12,240
Recycle (Tons)	599,442	1,556,464	969,108	1,357,477	1,842,471	1,251,036		1,262,666
SW Diversion (%)	39%	46%	47%	61%	66%	59%		53%
MSW Generated	1,223,252	1,150,971	1,367,642	944,750	964,533	1,041,349		1,115,416
MSW Diverted	253,751	331,837	425,073	362,806	354,745	432,668		360,147
Percent Diverted	21%	29%	31%	38%	37%	42%		32%
WTE	63,774	50,357	47,521	41,860	45,987	50,014		49,919
Commodities Paper	83,014	89,007	90,372	87,370	85,574	76,062		85,233
Commodities Other	115,099	160,403	241,432	192,341	201,569	124,603		172,574

* - equivalent to recycled yard waste which is considered equivalent to generated yard waste

7/7/2010

Based on data pulled from SWARWeb Reports

Waste Summary Data
US Air Force
FY02 - FY08

	FY02 (tons)	FY03 (tons)	FY05 (tons)	FY06 (tons)	FY07 (tons)	FY08 (tons)		Average (tons)
Solid Waste Composted (tons)	54,985	26,055	30,381	24,689	19,022	25,920		30,175
Solid Waste Mulched (tons)	43,503	57,226	42,061	40,538	50,564	18,122		42,002
Solid Waste Recycled (tons)	359,822	193,848	203,195	1,241,843	224,125	154,091		396,154
Solid Waste Reused (tons)	32,082	102,158	75,212	465,727	62,478	24,098		126,959
Solid Waste Donated (tons)	4,607	2,784	3,030	52,652	23,715	2,907		14,949
Total Diverted/Recycled SW(tons)	494,999	382,070	353,869	1,825,450	379,904	225,137		610,240
C&D Debris Diverted (tons)	1,567,537	694,474	1,647,490	1,863,864	974,963	1,409,634		1,359,660
Solid Waste Sent to Disposal Facilities (tons)	1,407,945	629,049	375,249	461,984	424,039	277,828		596,016
C&D sent to Disposal Facilities (tons)	458,742	179,627	236,149	271,803	322,582	329,449		299,725
Solid Waste Incinerated (tons)	-	-	35,663	33,568	36,290	25,887		21,901
C&D Incinerated (tons)	-	-	999	424	524	97		341
SW Disposed (incl Incineration)	1,407,945	629,049	410,912	495,552	460,329	303,715		617,917
SW Diversion Rate	26%	38%	46%	79%	45%	43%		50%
C&D Disposed (incl Incineration)	458,742	179,627	237,148	272,227	323,106	329,546		257,199
C&D Diversion Rate	77%	79%	87%	87%	75%	81%		82%
SW Incineration Rate	0%	0%	5%	1%	4%	5%		3%
SW Compost/Mulch Rate	20%	22%	20%	4%	18%	20%		12%
Total SW Generated	1,902,944	1,011,119	764,781	2,321,002	840,233	528,852		1,228,157
Total C&D Generated	2,026,279	874,101	1,884,638	2,136,091	1,298,069	1,739,180		1,659,726
Total Waste Generated	3,929,223	1,885,221	2,649,419	4,457,093	2,138,302	2,268,032		2,887,883
Total Waste Diverted	2,062,536	1,076,544	2,001,359	3,689,314	1,354,867	1,634,771		1,969,900
Total Waste Diversion Rate	52%	57%	76%	83%	63%	72%		68%

Appendix D: Treatability Study Report

TREATABILITY REPORT

Renewable Energy Production from DoD Installation Solid Waste by Anaerobic Digestion

Project Number: ER-200933

May 24, 2011

Prepared By:

CDM
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ACRONYMS

ADM1	Anaerobic Digestion Model No. 1
Alk	Alkalinity
AOAC	AOAC International
BMP	Biochemical Methane Potential
C	Celsius
CH4	Methane
CO2	Carbon Dioxide
COD	Chemical Oxygen Demand
ESTCP	Energy Science and Technology Certification Program
FOG	Fats, Oils, and Grease
FW	Food Waste
g	gram
GC-FID	Gas Chromatography-Flame Ionization Detector
HRT	Hydraulic Residence Time
kg	Kilogram
L	Liter
ND	Non-detection
ppm	Parts per million
QAC	Quaternary Amine Compound
RPD	Relative Percent Difference
sCOD	Soluble Chemical Oxygen Demand
SELR	Specific Energy Loading Rate
SRT	Solids Residence Time
STP	South Treatment Plant, Renton, Washington
tCOD	Total Chemical Oxygen Demand
TKN	Total Kjeldahl Nitrogen
TOC	Total Organic Carbon
TS	Total Solids
USAFA	United States Air Force Academy
VFA	Volatile Fatty Acid
VS	Volatile Solids

1.0 INTRODUCTION

The Department of Defense Environmental Security Technology Certification Program (ESTCP) is funding CDM to conduct a demonstration of anaerobic digestion for food waste treatment and energy recovery. CDM and ESTCP have selected the United States Air Force Academy (USAFA) as a suitable site for this demonstration. A treatability study was conducted using food wastes collected from Mitchell Hall at USAFA. The study was conducted in accordance with the March 11, 2010 Work Plan and the September 7, 2010 memorandum Response to Treatability Study Work Plan Comments (ER-0933). This treatability study involved the following tasks:

- Collection and characterization of multiple food wastes
- Analysis of food waste digestibility and energy yield in microcosm and bench-scale semi-continuous reactor tests
- Assessment of the utility of the specific energy loading rate (SELR) for design purposes
- Testing of food waste hydrolysis kinetics to provide data for calibration of the ADM1 model for use with food wastes

This report presents the methods, results, and conclusions from this treatability study.

2.0 FOOD WASTE CHARACTERIZATION

2.1 ABSTRACT

Fifteen food waste samples were collected from Mitchell Hall over the course of a five-day period (breakfast, lunch, and dinner), as well as one sample of grease trap waste from the underground oil-water separator adjacent to Mitchell Hall. These samples were characterized for chemical parameters relevant to anaerobic digestion and nutritional food analysis. The average COD of the food wastes was 1,400 g/kg dry weight, and the average VS/TS ratio was 0.85 which suggests that the wastes may be highly degradable.

2.2 SAMPLE COLLECTION

Two five-gallon buckets of grease trap waste were collected from the underground oil-water separator adjacent to Mitchell Hall. Dewatered, ground food waste samples were collected into sealable bags from Mitchell Hall pulper over five days for each meal (Table 2-1). Each sample was approximately 500 grams of material. Two five-gallon buckets of FW-004 (FW-B1 and FW-B2) and FW-011 (FW-B3 and FW-B4) were collected in addition to the normal samples. These food wastes were used for all of the respirometer studies in conjunction with the grease trap waste. Samples were refrigerated at USAFA after collection and shipped overnight to CDM on ice. After receipt, the samples were stored in a 4-6 °C refrigerated cold room until analysis.

Table 2-1 Food Waste Samples

Sample ID	Date Collected	Time Collected	Meal
FW-001	05/17/10	10:00	Breakfast
FW-002	05/17/10	13:00	Lunch
FW-003	05/17/10	19:00	Dinner
FW-004	05/18/10	9:00	Breakfast
FW-B1			
FW-B2			
FW-005	05/18/10	13:00	Lunch
FW-006	05/18/10	19:00	Dinner
FW-007	05/19/10	9:00	Breakfast
FW-008	05/19/10	13:00	Lunch
FW-009	05/19/10	18:30	Dinner
FW-010	05/20/10	9:00	Breakfast
FW-011	05/20/10	13:00	Lunch
FW-B3			
FW-B4			
FW-012	05/20/10	19:00	Dinner
FW-013	05/21/10	9:00	Breakfast
FW-014	05/21/10	13:00	Lunch
FW-015	05/21/10	18:30	Dinner
Grease Trap Waste	05/10/10	N/A	N/A

2.3 METHODS AND RESULTS

The directly-measured characteristics of the food wastes included chemical oxygen demand (COD), volatile solids (VS), total Kjeldahl nitrogen (TKN), total phosphorus, and the moisture, fat, and ash contents. The analytical methods used are outlined in Table 2-2. Sample FW-10 was analyzed in duplicate to assess precision. Characteristics derived from the analyses performed by the contract laboratory are outlined in Table 2-3. Tables 2-4 through 2-6 contain the characterization results, and Table 2-7 contains the average values of the food wastes for each characteristic. The COD analysis was performed in the CDM Bellevue Environmental Treatability Laboratory. Food wastes were homogenized and diluted with de-ionized water prior to analysis. Homogenization was achieved using an industrial blender to create a 10x diluted food waste slurry. Additional dilutions of the slurry were made as necessary to bring the waste within the analytical range of the method. The remaining characterizations were performed by a contract laboratory. Aliquots of each food waste type were dispensed into sample jars and shipped overnight on ice to the contract laboratory. Results were reported on a wet-weight basis but, where noted, they have been converted to dry-weight basis. Total organic carbon (TOC) was also analyzed, but the results were deemed unreliable and are not presented here.

Table 2-2 Directly Measured Food Waste Characteristics

Analysis	Method
Chemical Oxygen Demand	Hach Method 8000
Volatile Solids	Standard Method 2540E
Total Kjeldahl Nitrogen	AOAC Method 981.10
Total Phosphorus	AOAC Method 965.17
Moisture Content	AOAC 925.10
Fat Content	AOAC 922.06
Ash Content	AOAC 900.02A

Table 2-3 Derived Food Waste Characteristics

Analysis	Calculated From
Total Solids	Moisture, by difference
Protein	TKN, by conversion factor
Total Carbohydrates	Moisture, Protein, Fat and Ash, by difference
Calories	Carbohydrates, Protein and Fat, by 4:4:9 rule (contract laboratory standard method for food analysis; assumes Calorie content of 4Calories/gCarbohydrate, 4Calories/gProtein, and 9Calories/gFat)

Table 2-4 Total and Volatile Solids

FW Typw	Volatile Solids (% Wet Weight)	Total Solids (% Wet Weight)	VS/TS
FW-001	23	24	0.94
FW-002	24	26	0.93
FW-003	30	31	0.98
FW-004	19	20	0.94
FW-005	34	62	0.55
FW-006	14	23	0.63
FW-007	32	60	0.54
FW-008	30	56	0.54
FW-009	31	31	0.98
FW-010	16	16	0.97
FW-011	23	25	0.94
FW-012	23	23	0.98
FW-013	30	32	0.94
FW-014	26	27	0.99
FW-015	33	40	0.82
Grease trap waste	67	68	0.98

Table 2-5 Nitrogen, Phosphorus, and COD Content Results

FW Type	TKN (% Dry Weight)	Total Phosphorus (mg/kg Dry Weight)	COD (g/kg Dry Weight)
FW-001	7.0	1070	1630
FW-002	3.7	310	1450
FW-003	2.8	190	1130
FW-004	2.5	160	1880
FW-005	3.7	300	1430
FW-006	2.4	180	790
FW-007	5.5	180	820
FW-008	4.3	230	1100
FW-009	4.0	200	1140
FW-010	2.2	190	1630
FW-011	4.7	320	1810
FW-012	8.5	330	1550
FW-013	9.3	270	1130
FW-014	9.4	360	1170
FW-015	4.2	260	1700
Grease trap waste	0.06	40	1530

Table 2-6 Food Proximate Analysis Results

FW Type	Protein (% Dry Weight)	Fat (% Dry Weight)	Ash (% Dry Weight)	Total Carbohydrates (% Dry Weight)	Calories (kcal/100g Dry Weight)
FW-001	43	17	5.8	34	460
FW-002	23	14	3.9	59	460
FW-003	17	6.2	2.3	74	350
FW-004	16	13	3.0	69	450
FW-005	23	22	1.8	53	500
FW-006	15	6.7	2.2	76	430
FW-007	34	17	1.2	48	480
FW-008	27	21	1.8	50	500
FW-009	25	23	2.2	50	500
FW-010	14	3.7	3.7	79	400
FW-011	29	35	4.5	32	560
FW-012	54	26	2.6	17	520
FW-013	58	24	6.3	11	500
FW-014	59	17	4.5	19	470
FW-015	26	19	3.0	52	410
Grease trap waste	0.3	91	0.3	8.7	850

Table 2-7 Summary of Food Waste Characteristics

Analysis	Average of Food Wastes (not including FOG)	Standard Deviation	FOG
Volatile Solids (% Wet Weight)	26	6	67
Total Solids (% Wet Weight)	33	15	68
VS/TS	0.85	0.18	0.98
TKN (% Dry Weight)	4.9	2.5	0.06
Total Phosphorus (mg/kg Dry Weight)	300	220	40
COD (g/kg Dry Weight)	1400	340	1530
Protein (% Dry Weight)	31	16	0.3
Fat (% Dry Weight)	18	8	91
Ash (% Dry Weight)	3.2	1.5	0.3
Total Carbohydrates (% Dry Weight)	48	22	8.7
Calories (kcal/100g Dry Weight)	470	53	850

3.0 BIOCHEMICAL METHANE POTENTIAL

3.1 ABSTRACT

Biochemical methane potential tests (BMPs) were used to assess the anaerobic digestibility and methane production potential of the food waste samples collected from Mitchell Hall. In these tests, food waste was combined with anaerobic digester sludge, then incubated in sealed, anaerobic serum bottles at 37°C for 38 days. Biogas production was monitored regularly over the course of the experiment using the wet-syringe volume test method. Biogas composition was determined using GC-FID. On average, anaerobic digestion of the food wastes yielded 400 mL of methane per gram of food-waste COD, with a range of 190mL – 700 mL per gram of COD. The high average methane yield suggests that the food wastes were generally well-degraded, and that some of the food wastes may have stimulated additional methane production from the COD already present in the sludge inoculum. Wastes with a higher fat and protein content yielded more methane per gram of COD, which may be due in part to poor degradability of components of the carbohydrate fraction. The fat and/or protein may also have stimulated greater methane yield from the sludge inoculum.

3.2 METHODS

Biological methane potential tests were conducted on the waste samples described in section 2. For each test, 0.15L of anaerobic digester sludge from the King County South Treatment Plant (STP) in Renton, containing approximately 5.9 g COD, was combined with food waste to achieve a loading of approximately 3 g COD/L. The sludge and food waste were added to 250-mL serum bottles, which were then sealed with thick butyl rubber stoppers and aluminum crimp tops and purged with ultra-high-purity nitrogen gas for 2 minutes. The bottles were incubated at 37°C for 38 days.

This experiment tested 15 food waste samples from Mitchell Hall (one in duplicate), plus a sample of grease trap waste. In addition, duplicate bottles containing only digester sludge were used to determine baseline methane production from the sludge. Biogas production was measured using the wet-syringe volume test method. Sampling frequency varied over the course of the experiment, with more frequent sampling at the beginning of the test to correspond to the greater gas production rates anticipated during this period. Samples of the biogas were periodically analyzed by GC-FID, to determine the gas composition. Total methane production was calculated for each bottle, based on biogas production and composition data. The net methane production was calculated by subtracting the average methane production of the negative controls from that of the experimental bottles. The net methane yield was calculated by dividing the net methane production by the COD loading from the added food waste.

3.3 RESULTS

Figure 3-1 shows the net methane accumulation over time for the 17 experimental bottles. The average net methane accumulation for the two sludge-only controls define the zero-line of this figure. All the food wastes produced considerably more methane than the sludge-only controls over the course of the experiment, and none of the bottles experienced a lag before the onset of methane production.

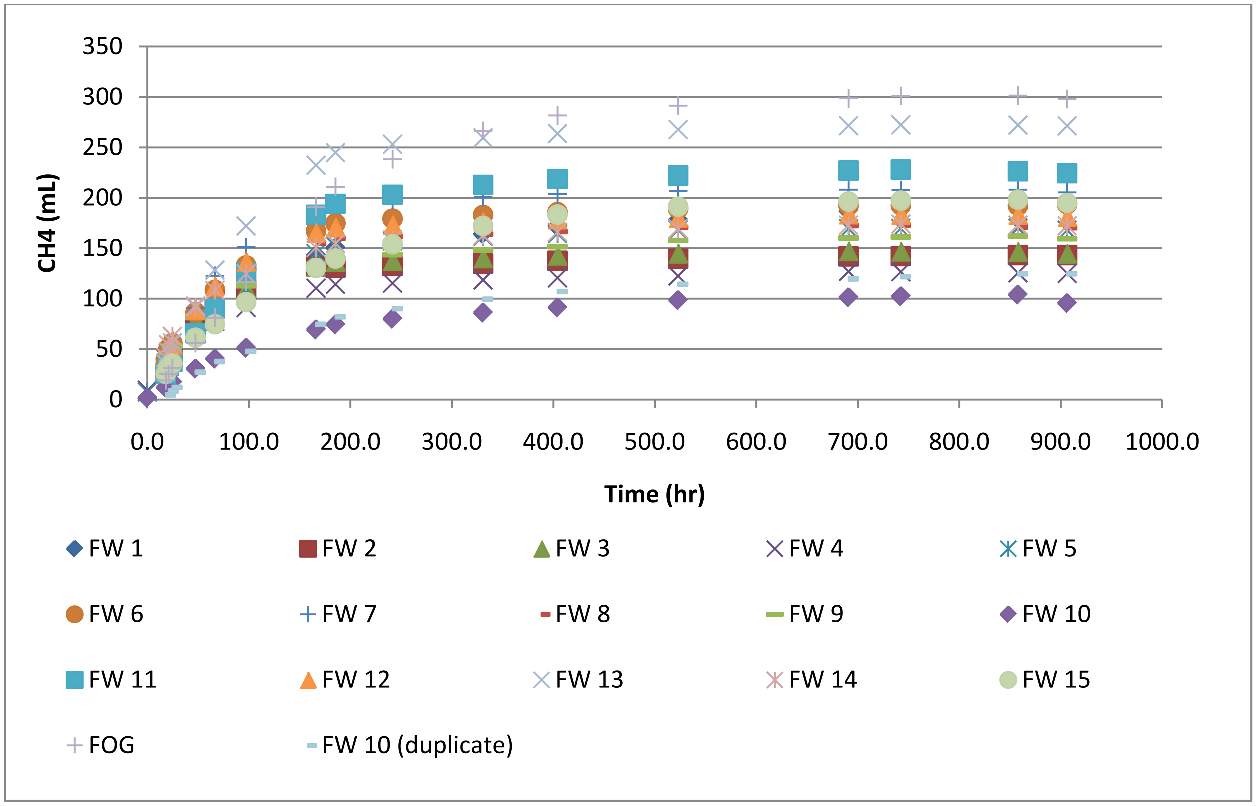


Figure 3-1 BMP Net Methane Accumulation

Table 3-1 shows the food-waste COD loading, the net methane production, and the net methane yield for each of the 17 bottles. The average of the 15 food wastes, not including the grease trap waste or the duplicate, is also contained in Table 3-1. The average net methane yield for the food wastes was 390mL/gCOD of food waste, with values ranging from 190 to 570 mL/gCOD. The yield from grease trap waste was much higher, at 700mL/gCOD.

Table 3-1 Food-Waste COD Loading, Net Methane Production, and Net Methane Yield from BMPs

Sample ID	FW COD load (g)	Net CH4 Production (mL)	Net CH4 Yield (mL CH4/g FW COD)
FW 1	0.49	220	460
FW 2	0.47	150	320
FW 3	0.49	150	310
FW 4	0.42	140	330
FW 5	0.49	200	400
FW 6	0.50	210	420
FW 7	0.46	220	470
FW 8	0.54	190	350
FW 9	0.46	180	380
FW 10	0.45	90	190
FW 11	0.46	230	490
FW 12	0.49	180	380
FW 13	0.49	280	570
FW 14	0.47	170	370
FW 15	0.50	190	390
Grease trap waste	0.46	320	700
FW 10 (duplicate)	0.48	110	230
Average ± std. dev.*	0.48 ± 0.03	190 ± 45	390 ± 90

* The average and standard deviation were calculated with neither the grease trap waste nor the duplicate of food waste 10.

Because of the wide range of methane yields observed in the BMP tests, the food waste characteristics reported in Section 2 were examined for any correlations with the methane yields. Of the food waste characteristics, the sum of the fat and protein contents was found to best explain the variation in the methane yields. The relationship between these factors is shown in Figure 3-2. Three food wastes were identified as outliers based on their unusually high residuals from a regression on all the samples: wastes 3, 12, and 14. These wastes are circled in Figure 3-2, and were excluded when calculating the regression shown in that figure. None of the tested food waste characteristics explains the deviation of these three from the pattern shown by the other wastes.

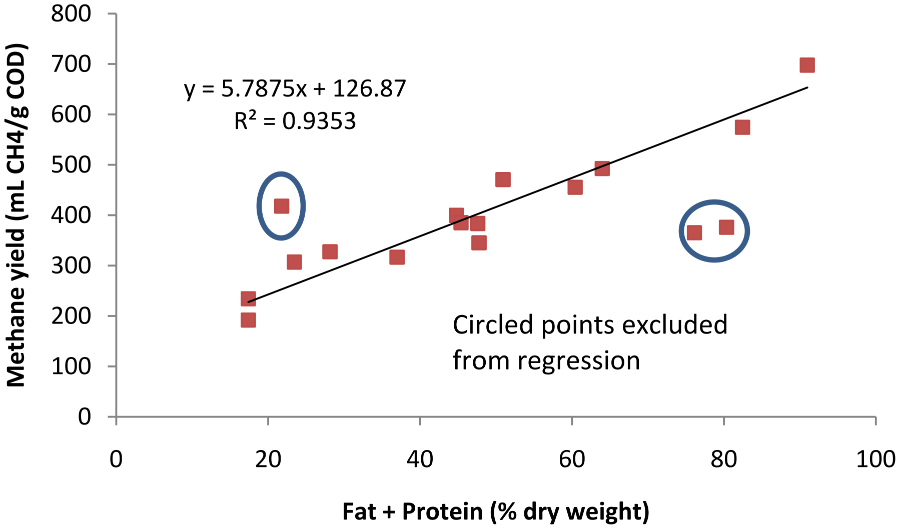


Figure 3-2 Methane Yield as a Function of Fat and Protein Content of the Wastes

4.0 SEMI-CONTINUOUS REACTOR TESTS

4.1 ABSTRACT

In this phase of the treatability study, food wastes from Mitchell Hall were digested in lab-scale, semi-continuous reactors. Initial attempts at digestion of these wastes were unsuccessful, as reactors repeatedly developed instability. Two possible causes of instability were hypothesized. The first cause identified was a low concentration of volatile solids (VS) in the reactors, resulting from dilution of the food waste prior to feeding the digester in combination with the high digestibility of the waste. The second cause identified was nutrient limitation caused by low levels of molybdenum, nickel, and cobalt. After these factors were corrected, stable reactor operation was achieved.

Several further experiments were conducted to define the limits of reactor operation. Addition of quaternary amine compounds (QACs) was tested because these compounds are contained in sanitizers used at Mitchell Hall. The QACs were found to cause reactor failure at concentrations about 2000 to 3000 mg QAC/kg of food waste solids. Multiple COD loading rates were tested, with and without the addition of grease trap waste from the Mitchell Hall. Digestion was successful at 4g COD/L/day both with and without the inclusion of grease trap waste comprising 10% of the total COD. Furthermore, food waste without grease trap waste was successfully digested at rates up to 10g COD/L/day. However, reactors started at 10g COD/L/day with 10% grease trap waste COD failed. Tests comparing grease trap waste to another fat source, canola oil, found that both fats were inhibitory when they accounted for 10% of a 10 gCOD/L/day loading the remainder being food waste. Both fats were successfully digested when they comprised only 5% of a 10g COD/L/day loading. This suggests that the grease-trap waste from Mitchell Hall did not contain any unusual inhibitory substances, and that similar inhibitory levels may be expected from other fat sources. Experiments with ramped loading rates demonstrated that 10% grease trap waste COD additions could be achieved at a 10g COD/L/day loading, if start-up occurred at either lower COD loadings rates or lower grease trap waste COD percentages followed by gradual increase of the relevant parameter.

The performance of stable reactors was compared at different loading rates of total COD and grease trap waste COD. Higher COD loading rates increased total methane production from a given reactor volume, but decreased the methane yield from the COD applied. At lower COD loading rates, grease trap waste addition increased methane production and methane yield by about 20%, but at higher COD loading rates the benefit of grease trap waste addition was less clear. VS destruction was greater at the lower COD loading rates, but was not apparently affected by grease trap waste. Some of these differences were attributable to differences in solids retention time (SRT). Lower COD loading rates were associated with longer SRTs because the feed COD and VS concentrations were kept constant.

The specific energy loading rate (SELR) was also examined. The SELR is analogous to the specific activity of an enzyme. Whereas the specific activity measures the substrate concentration per mass of enzyme per time, the SELR measures the energy loading per unit biomass per time. The SELR of the reactors was compared to measures of reactor stability and performance, to assess whether the reactors had a maximum SELR beyond which the capacity of the methanogenic biomass is exceeded. Reactors receiving a higher SELR generally had lower

methane yields and higher VFA/alkalinity ratios. Prior to trace nutrient supplementation, instability was observed at SELR values greater than approximately 0.2gCOD fed/g reactor VS/day. Following the addition of trace nutrients, reactors were stable at SELR values up to approximately 0.4gCOD fed/g reactor VS/day. These results suggest that the SELR may be a useful design parameter, but various factors can affect the acceptable SELR threshold.

4.2 METHODS

4.2.1 Food Waste Slurry

To ease in feed addition and help ensure a homogenized mixture the reactors were fed a food waste slurry. The feed slurry was prepared in an industrial blender by homogenizing food waste (with or without grease trap waste). Tap water was added to dilute the slurry to a target COD concentration (gCOD/L FW Slurry). This concentration was varied from 75 to 275gCOD/L over the course of the treatability study; the concentrations used in particular experiments are specified in the following sections. After trace nutrient deficiencies were identified (Section 4.3.1), a trace metals solution replaced a portion of the tap water in the slurry. This solution was made with de-ionized water and the compounds listed in Table 4-1. The nutrient solution was added to the food waste slurry at a concentration of 10mL/L. Final slurry consistency was similar to peanut butter and could be fed into reactors using a syringe.

Table 4-1 Trace Metals Solution for Addition to the Food Waste Slurry at a Concentration of 10mL/L.

Compound	Concentration (mg / 100mL)
$NiSO_4*6H_2O$	10.9
$Co(NO_3)_2*6H_2O$	13.6
$Na_2MoO_4*2H_2O$	16.6
H_3BO_3	150

Two standard feeds slurries were used for a variety of the experiments, USAFA Mix and USAFA grease trap waste Mix. USAFA mix was a 50-50 mixture (mass basis) of FW-004 and FW-011. In USAFA grease trap waste Mix, 10% of the COD was from grease trap waste and the balance of the COD came from the 50-50 mixture of FW-004 and FW-011.

4.2.2 Respirometer

Biogas accumulation, production rate and concentration were measured using the Columbus Instruments Respirometer System (Figure 4-1). The system in the used for this project has extended range methane and carbon dioxide sensors, a 40 channel expansion interface and ran version 2.0.0.9 of the Micro-Oxymax software.

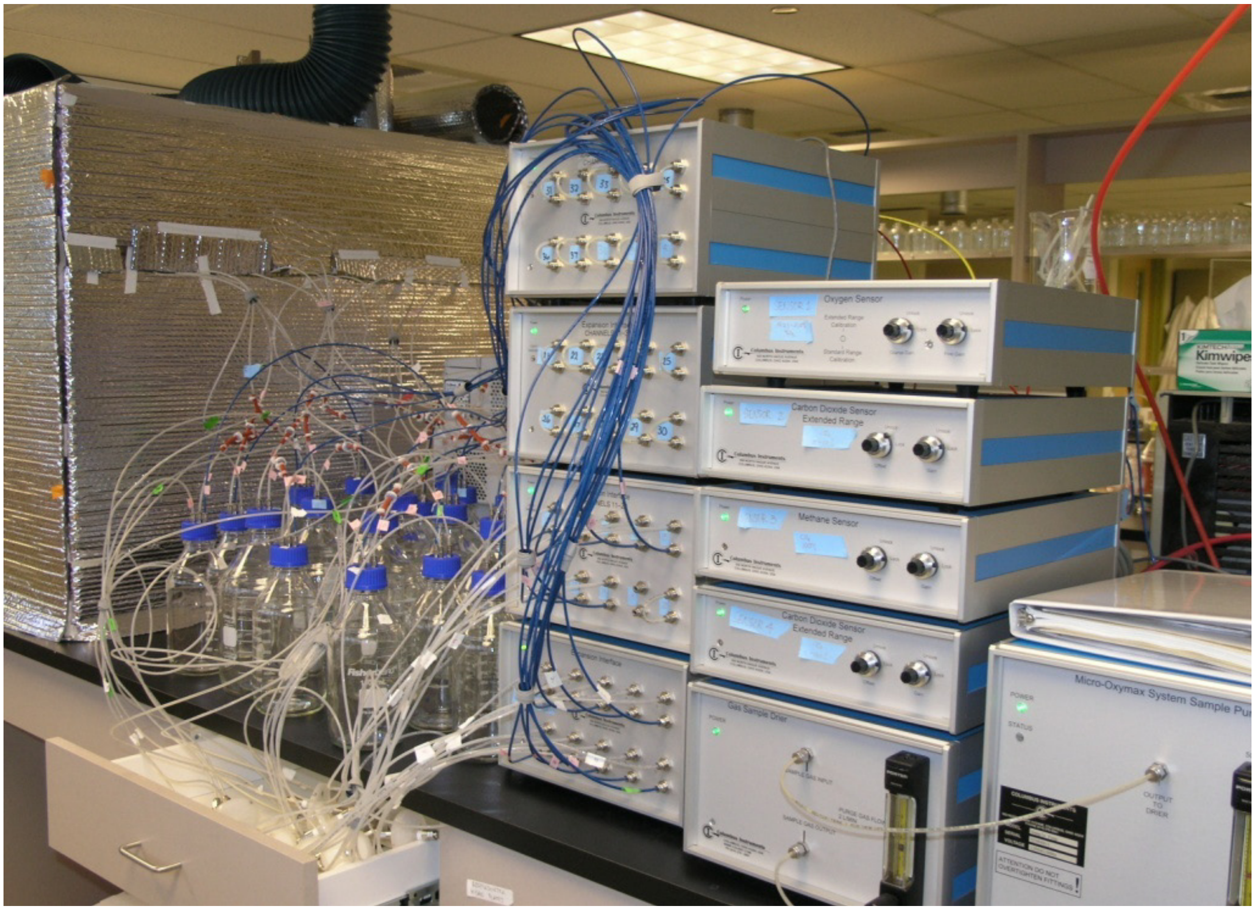


Figure 4-1 Columbus Instruments Respirometer System

As biogas is produced, the gas is collected in a glass sample collection bottle. The respirometer uses nitrogen to circulate the sample gas through the sensors to determine the gas concentration, temperature and pressure. The biogas volume, composition and production rate is calculated by the Micro-Oxymax software.

4.2.3 Carboy Configuration and Operation

The carboy bioreactors were consisted of a 20L Nalgene carboy and 3 port caps fitted with Swagelok and polycarbonate quick connects, seen in Figure 4-2.

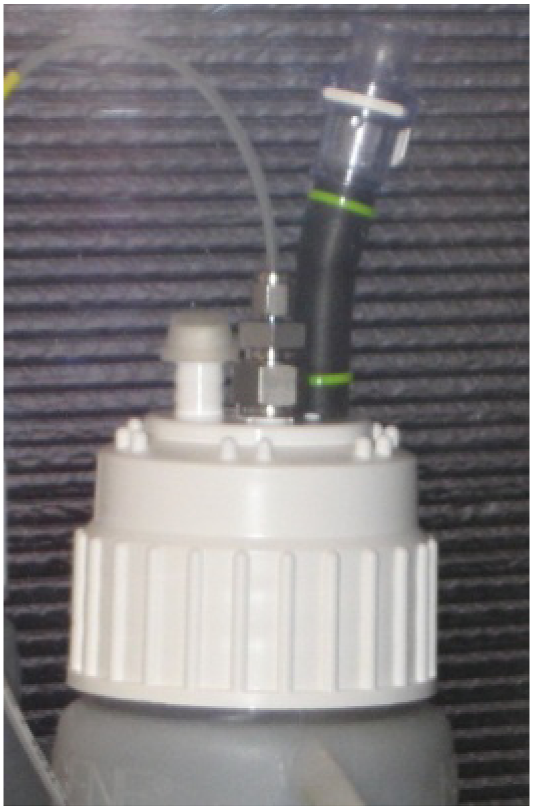


Figure 4-2 Carboy Cap with Headplate Connections

The three headplate connections are the sample port, gas line to the respirometer and feed port. The sample port is the hosebarb connection on the left of the headplate. A second hosebarb on the inside of the cap is connected with ½” tubing running beneath the liquid level. Samples were obtained by connecting tube lines to the outer hosebarb and pumping out sludge with a peristaltic pump. The metal Swagelok fittings at the center of the headplate connect to a gas line that carried accumulated gas to the respirometer via a separate gas reservoir. Food waste slurries were injected into the feed line using a syringe.

Reactor mixing was achieved using a shaker base in an incubator. Carboys were started from STP anaerobically digested sludge and maintained at a one-gallon working volume. The headspace of the carboys was flushed with high-purity nitrogen after inoculation and any time that the carboy was opened. Carboys were fed a 2 day feed load on Mondays and Wednesdays and a three day feed load Fridays. Samples were pulled just prior to feeding. The COD concentration of the feed slurry was adjusted over time in the range of 75 to 275g/L. The VS concentration varied in proportion to the COD concentration, from 35 to 135g/L, which allowed exploration of the effects of low VS loading. The TS concentration also varied, from 38 to 143g/L.

4.2.4 Glass Reactor Configuration and Operation

Reactors constructed from 2L media bottles, illustrated in figure 4-3, were used for the majority of the semi-continuous digester experiments. The large fitting on the headplate served as a feeding and sampling port. Catheter-tip syringes were inserted into the ¼” vinyl tubing for feeding and sampling; at all other times the tubing was held closed by a pinch-cock, as shown in the figure. The two small fittings were both for gas lines. One gas line connected to the respirometer via a gas reservoir. This line also had a quick-connect fitting, allowing the reactor to be disconnected from the gas reservoir during sampling and feeding. The other gas line connected to a tedlar bag. This bag was kept closed except during feeding and sampling. During sludge sampling, the bag was opened so that the sample volume withdrawn would be displaced by the biogas collected in the bag, rather than creating a vacuum that would lead to intrusion of ambient air. During feeding, the volume of feed added displaced the biogas back into the bag. Liquid sampling was conducted by inversion of the reactor, pictured in Figure 4-4.

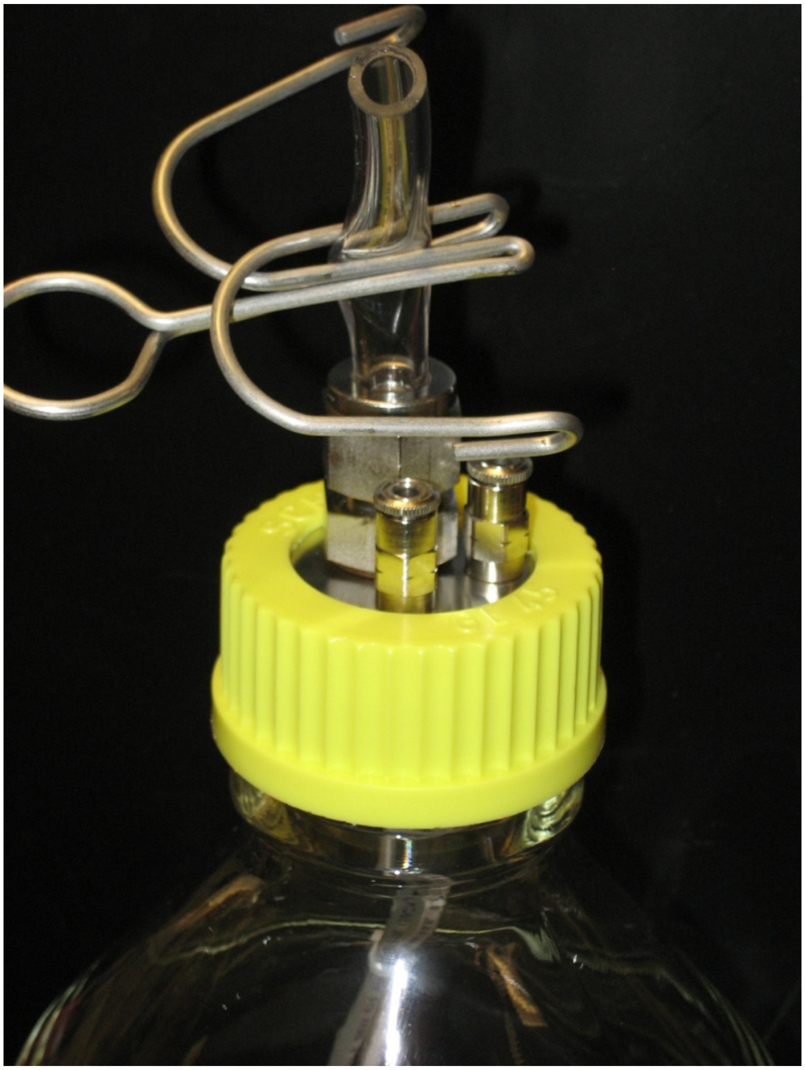


Figure 4-3 Configuration of 2L Semi-Continuous Reactor Bottle

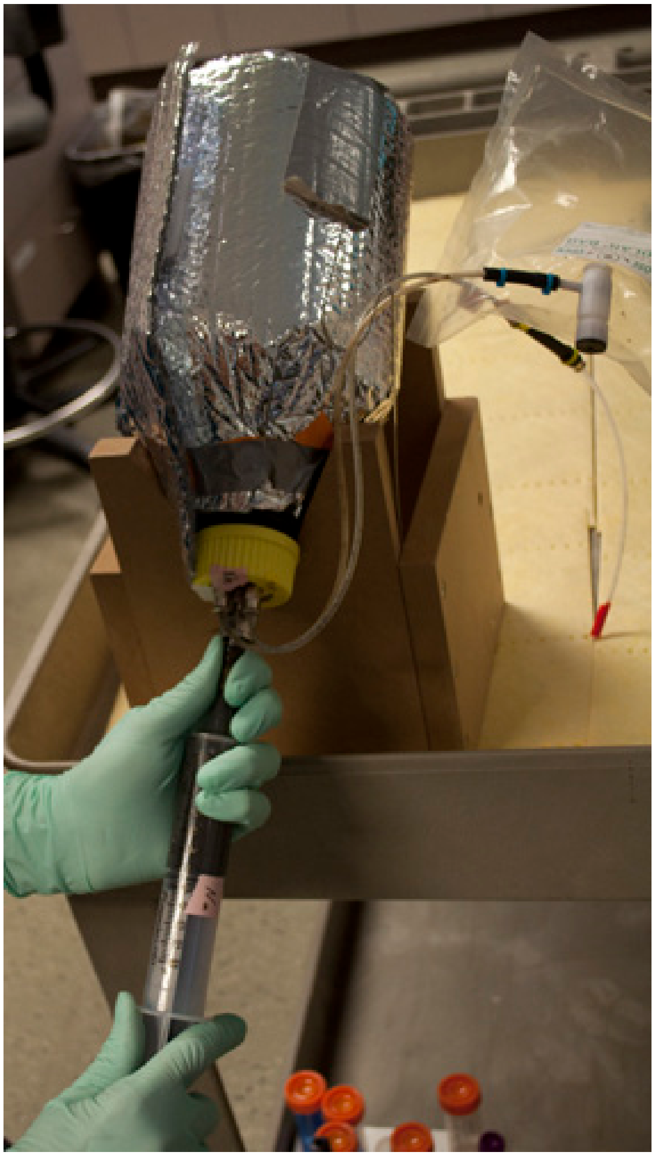


Figure 4-4 Sampling of 2L,Semi-Continuous Reactor

Reactors were inoculated with STP anaerobically digested sludge, then flushed with high-purity nitrogen to remove oxygen from the reactor headspace. Similarly to the carboys, the reactors were mixed on a shaking table in a 37°C incubator, as pictured in Figure 4-5. Sampling and feeding occurred on Monday, Wednesday, and Friday. On Monday and Wednesday the reactors were fed double the daily COD load and on Friday the reactors were fed triple the daily COD load, using feed slurries with a total COD concentration of 230 g/L. This COD concentration corresponded to VS and TS concentrations of about 140 g/L and 150 g/L, respectively. Sampling was conducted immediately prior to feeding. Samples were analyzed for pH and VFAs three times per week. COD, alkalinity, and TS and VS were analyzed weekly.

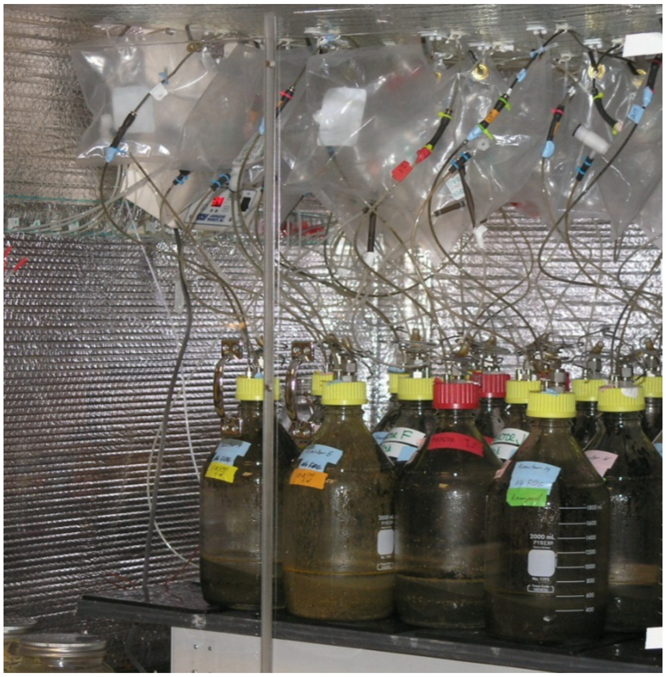


Figure 4-5 Reactors on Shaking Table in Incubator

4.2.5 Digestion Tests

4.2.5.1 QAC Inhibition

Seven reactors were used to determine the inhibitory concentration of QACs used in a sanitizer at USAFA Mitchell Hall. The reactors were fed a constant 6 g COD/L/day of mixed USAFA food waste. In addition, a the commercial QAC-containing sanitizer used at USAFA (Formula F362 No Rinse Sanitizer; State Chemical, Cleveland, Ohio) which contains 4.5% QACs by weight was added to the reactors at the concentrations shown in Table 4-2.

Table 4-2 QAC Inhibition Test Design

Reactor	QAC Concentration (mg QAC/kg feed TS)	Feed Load
UQ0	0	6 gCOD/L/day, USAFA Mix
UQ1	65	
UQ2	650	
UQ3	1300	
UQ4	1900	
UQ5	3200	
UQ6	6500	

4.2.5.2 Grease Trap Waste and COD Ramping

Tables 4.3 through 4.5 summarize the experimental conditions used to determine stable methods of starting up the digesters, evaluating potential toxicity of USAFA grease trap waste, and characterize steady state operating conditions.

Table 4.3 Experimental Conditions of Ramped Reactors

Reactor	Ramp Basis	Ramp Rate	Inoculum	Start Condition	Final Condition
1	COD Load	First order increase of COD loading over 53 days	STP Digested Sludge	4 gCOD/d/L of USAFA Mix	10 gCOD/d/L of USAFA Mix
2	COD Load	First order increase of COD loading over 53 days	STP Digested Sludge	4 gCOD/d/L of USAFA waste mix with 10% grease trap waste COD	10 gCOD/d/L of USAFA mix with 10% grease trap waste COD
3	COD Load	First order increase of COD loading over 53 days	STP Digested Sludge with Walnut Shell Grit	4 gCOD/d/L of USAFA Mix	10 gCOD/d/L of USAFA Mix
4	Grease trap waste concentration	First order increase of grease trap waste COD percentage over 35 Days	STP Digested Sludge acclimated to 10 gCOD/d/L of USAFA Mix	10 gCOD/d/L of USAFA Mix at 2% grease trap waste COD	10 gCOD/d/L of USAFA Mix at 10% grease trap waste COD
5	Grease trap waste concentration	First order increase of grease trap waste COD percentage over 24 Days	STP Digested Sludge acclimated to 10 gCOD/d/L of USAFA Mix	10 gCOD/d/L of USAFA Mix at 2% grease trap waste COD	10 gCOD/d/L of USAFA Mix at 10% grease trap waste COD

Table 4.4 Experimental Conditions for Evaluating Grease Trap Waste Inhibition

Reactor	Feed type	Feed loading
6	USAFA mix	10 gCOD/d/L
7	USAFA Mix with 5% canola oil COD	
8	USAFA Mix with 5% grease trap waste COD	
9	USAFA Mix with 10% canola oil COD	
10	USAFA Mix with 10% grease trap waste COD	

Table 4.5 Experimental Conditions for Longer-Term Steady State Operation

Reactor	Feed type	Feed loading
11	USAFA Mix	4 gCOD/d/L
12	USAFA Mix with 10% grease trap waste COD	4 gCOD/d/L
13	USAFA Mix	10 gCOD/d/L
14	USAFA Mix with 10% grease trap waste COD	10 gCOD/d/L

4.3 RESULTS

4.3.1 Instability Resulting from Low-VS Feed and Trace Nutrient Limitation

During preliminary operation of the carboy digesters, repeated instability was observed. Two factors were identified as probable contributors: insufficient feed-VS concentration, and trace nutrient limitation.

Figure 4-6 shows the relationship between the VS concentrations in the feed and VS in the reactors. These are plotted with the theoretical reactor effluent concentration, calculated by Equation 4-1. For these wastes, the undegradable VS fraction was assumed to be 15%, and the cell yield to be 0.12g biomass VS per 1g feed VS consumed.

$$\begin{aligned} Reactor\,VS = {} & Feed\,VS * undegradable\,VS\,fraction \\ & + Feed\,VS * degradable\,VS\,fraction * cell\,yield \end{aligned} \tag{4-1}$$

As predicted by the theory, lower VS concentrations developed in reactors receiving lower VS feed concentrations. The reactors being fed less than 5% VS developed instability in the form of elevated VFA/alkalinity ratios, lowered pH, and poor methane production. The COD load to these reactors was approximately 2.2gCOD/L/day which is not considered high. Higher VS concentrations developed in the sludge of reactors that received feed with a VS concentration of greater than 10%, and these reactors performed more stably. These reactors had COD loadings that ranged from 0.5 to 3.3gCOD/L/day. Thus low VS was concluded to be the cause of instability rather than COD loading. The specific energy loading rate (SELR) was calculated for these reactors and was also greater in the unstable region (less than 5% VS feed) than in the stable region (greater than 10% VS feed). These data indicate that the energy loading rate (i.e., g COD/d) was too great for the effective microbial population in the digester represented in terms of g digester VS. As a result of these observations, the feed VS was kept above 10% during further reactor operations.

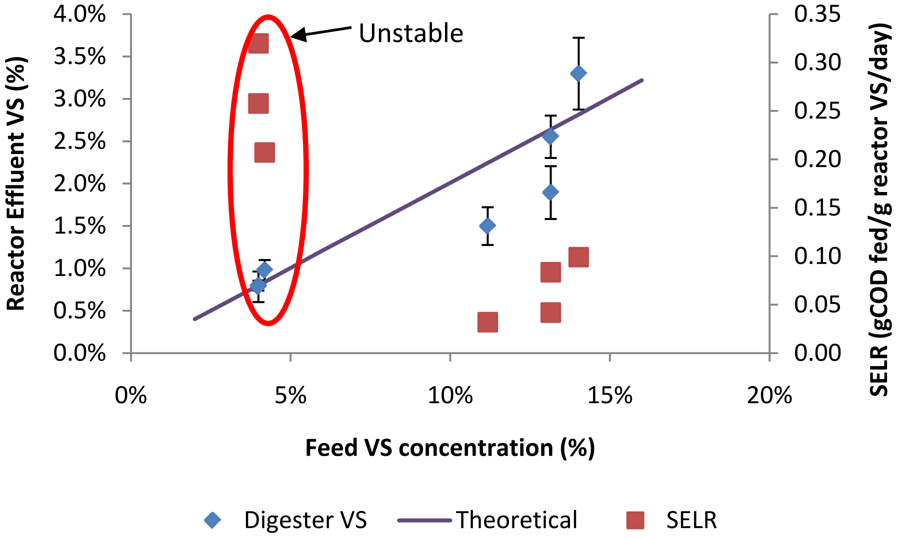


Figure 4-6 Reactor VS Concentrations, SELR, and Reactor Stability in Relation to Feed VS Concentration

Despite increased feed VS concentrations and increased digester VS concentrations, the reactors continued to experience some instability. As part of a process to identify causes of the instability, the trace metals content of the food waste was tested. Figure 4-7 compares the trace nutrient content of the food waste to required concentrations. The required concentrations in the food waste were calculated from literature values for nutrient levels required for the growth of methanogens and multiplying by 20. The factor 20 was used to account for concentration metals during volatile solids destruction and microbiological assimilation of the nutrients. The food waste was found to be deficient in nickel, cobalt, and possibly molybdenum. After the trace nutrient limitation was identified, these three nutrients were added to the feed. Boron was also added at a concentration of 11 mg/kg (dry-weight basis); although the need for this element is not well-established, it is recommended in some anaerobic culture media.

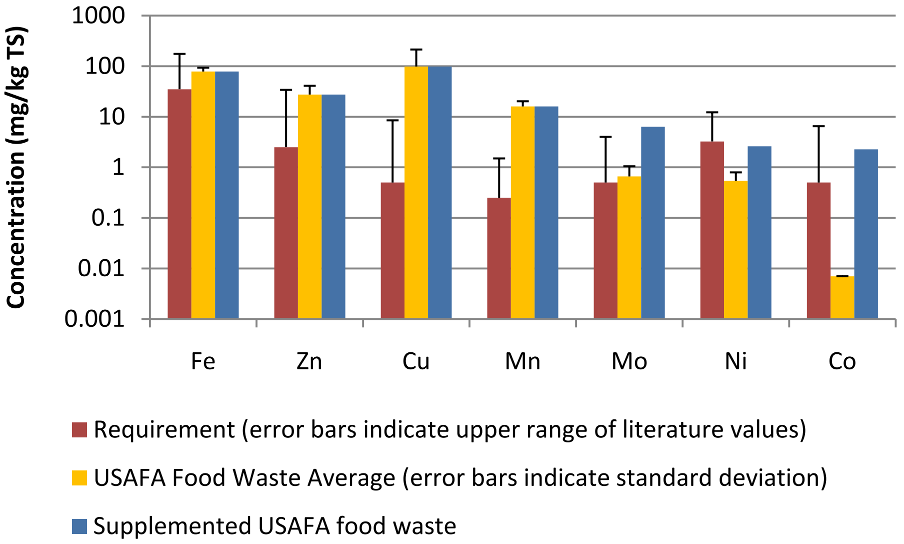


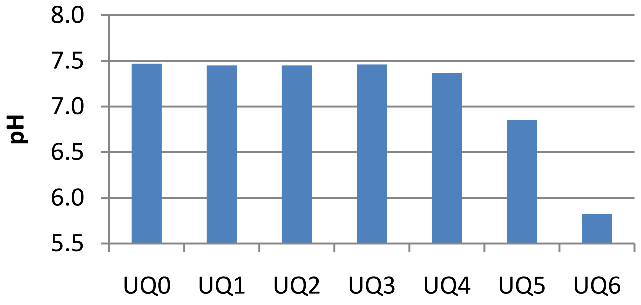
Figure 4-7 Comparison of Trace Metals Requirements

4.3.2 Effects of Quaternary Amine Compounds

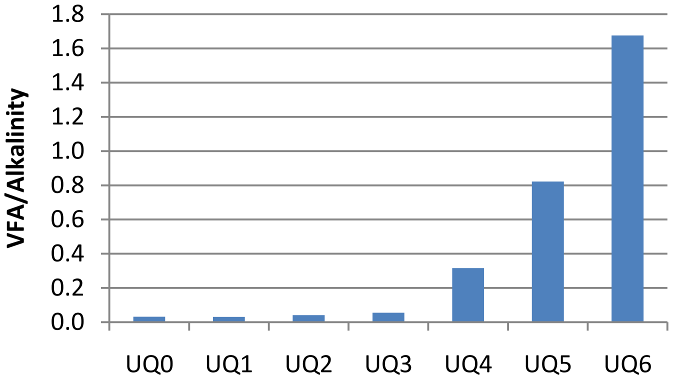
Because the food-waste collection system at Mitchell Hall uses a quaternary amine compound (QAC) sanitizer in the rinse-water, the effects of QAC additions to the food waste were studied. The concentrations of QAC applied were shown in Table 4-2.

This experiment demonstrated increasing inhibition at QAC concentrations above 2000mg QAC/kg food-waste TS. These results are illustrated in Figure 4-8. The reactors receiving the highest QAC concentration, UQ5 and UQ6, both failed before the experiment concluded. The other four experimental reactors maintained a pH similar to that of the control reactor throughout the experiment, although UQ4, with the third-highest QAC concentration (1,900 mg/kg TS), developed an elevated VFA/Alkalinity ratio indicative of possible instability.

A. Minimum Reactor pH



B. Maximum VFA/Alkalinity



C. Average Methane Yield

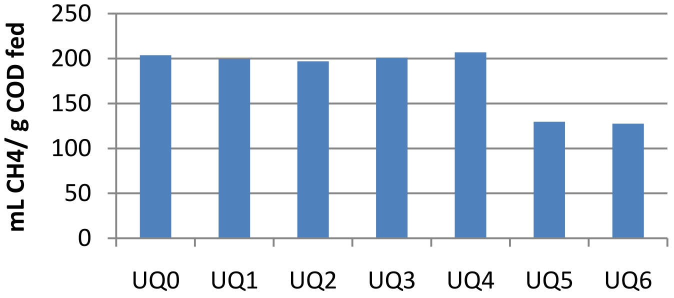


Figure 4-8 Effects of the addition of quaternary amine compounds (QAC) on reactor stability. (A): Minimum pH measured in each reactor during operation; (B) Maximum VFA/Alkalinity ratio; (C) Average methane yield.

4.3.3 Grease Trap Waste Inhibition and Digester Startup

During early tests of reactor loading, reactors started at a loading of 10gCOD/L/day failed when grease trap waste was included as 10% of the COD load. In contrast, reactors started at that same COD load but without grease trap waste were stable. In order to determine whether the grease trap waste from the grease traps at Mitchell Hall was inherently inhibitory, the performance of reactors receiving grease trap waste was compared to that of reactors receiving canola oil. Five conditions were compared in this test where all five received the USAFA food waste mix plus different amounts of grease trap waste or canola oil and the COD loading was kept constant at 10 g/L/d. As shown in Figure 4-9, the reactors receiving 10% of their COD as either grease trap waste or canola oil failed immediately: gas production was consistently low in these reactors, VFA accumulated rapidly, and pH dropped below 6.5 within one week of operation. In contrast, the reactors receiving 5% of their COD load as either grease trap waste or canola performed stably, and with methane production rates similar to those seen in the control with no grease trap waste or canola oil. These results clearly demonstrated that USAFA grease trap waste is not inherently inhibitory but elevated concentrations of any fat can be inhibitory when fed at a high COD loading rate.

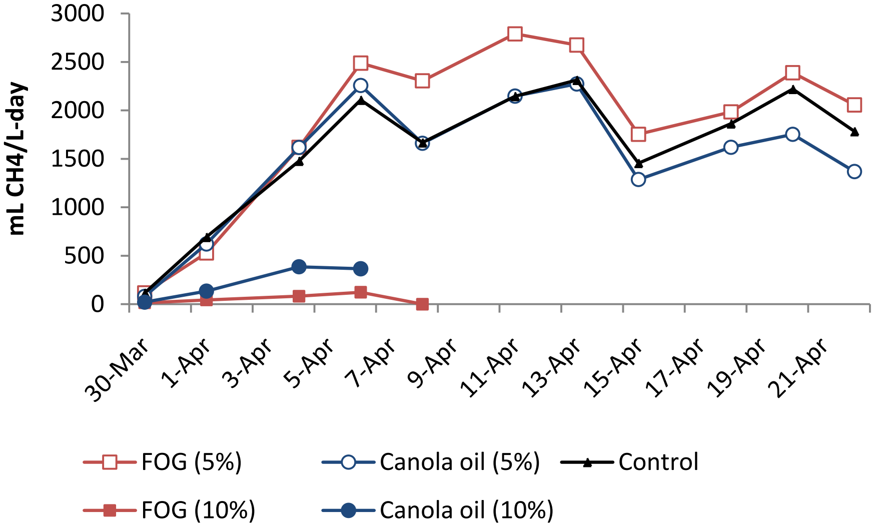


Figure 4-9 Methane production from reactors receiving grease trap waste and canola oil

Experiments were also performed to identify methods for startup of the digesters and how to attain stable operation with high COD loading rates and grease trap waste content. Four conditions were compared: immediate loading of 10gCOD/L/day without grease trap waste, immediate loading of 10gCOD/L/day with 10% grease trap waste, immediate loading of 10gCOD/L/day with ramping of grease trap waste from 0% to 10%, and ramping a 10% grease trap waste COD feed from 4gCOD/L/day to 10gCOD/L/day. The methane production rates from these reactors are shown in Figure 4-10. As expected based on results presented in Figure 4-9, immediate feeding of 10gCOD/L/d of USAFA food waste without grease trap waste was stable but inclusion of grease trap waste at this COD loading rate was unstable. Both ramping approaches (i.e., gradual increase of COD loading or grease trap waste percentage) led to stable digestion of a 10gCOD/L/day loading with 10% grease trap waste. These data demonstrate that stable digestion with 10% grease trap waste COD at a total COD loading rate of 10 g/L/d is possible, but startup must include one of the two ramping procedures.

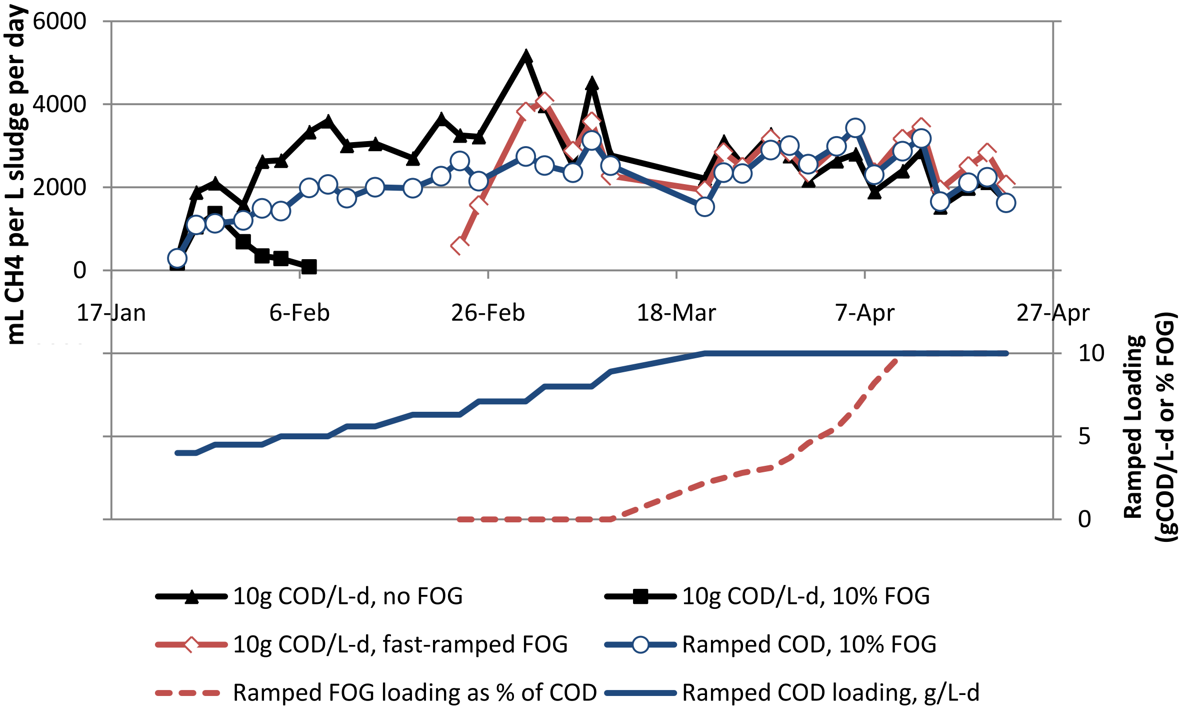


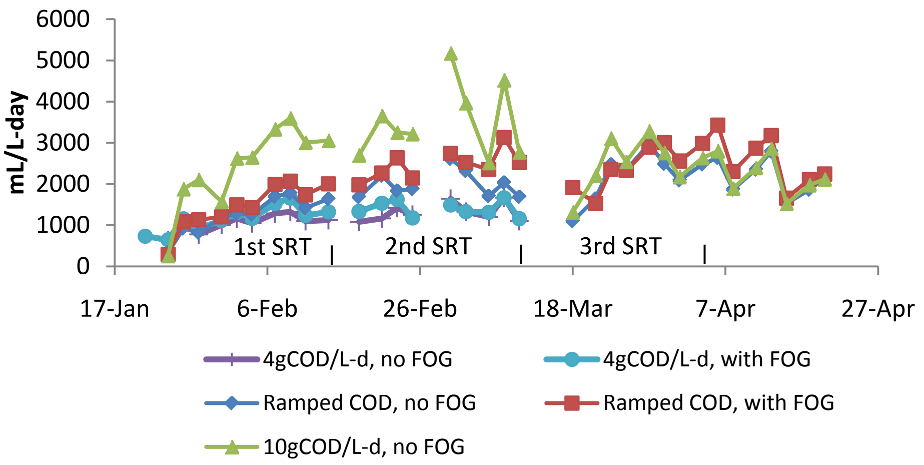
Figure 4-10 Methane production from ramped grease trap waste reactors

4.3.4 Performance of Reactors at Ramped and Stable Loading Rates

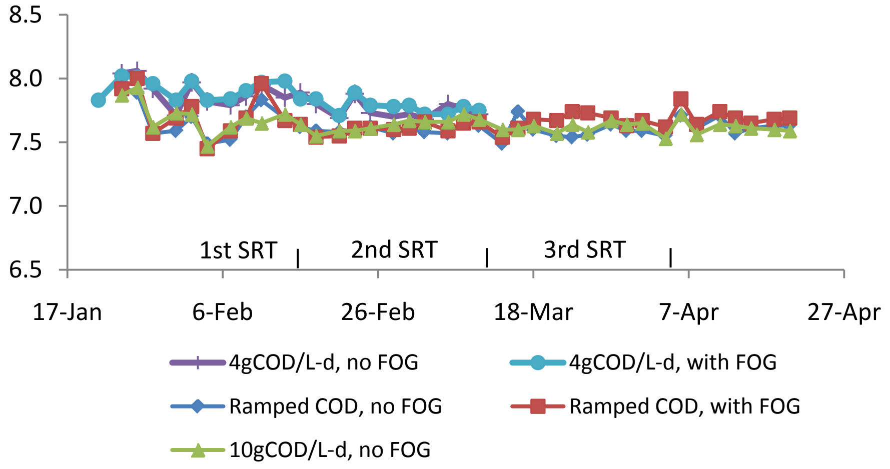
The performance of stable reactors was characterized at four different loading conditions: 4 gCOD/L/day with no added grease trap waste, 4gCOD/L/day with 10% of the COD from grease trap waste, 10gCOD/L/day with no added grease trap waste, and 10gCOD/L/day with 10% grease trap waste. As mentioned in section 4.3.2, immediate loading of 10gCOD/L/day with 10% grease trap waste resulted in reactor failure, so this condition was studied in reactors that had been acclimated to this loading condition through ramping. An additional reactor was ramped from 4gCOD/L/day to 10gCOD/L/day, without grease trap waste, to explore whether a ramped start-up resulted in better performance than immediate loading. The ramping process was completed in these reactors on 18 March, after which they were operated at a steady 10gCOD/L/day. Figure 4-11 shows several performance characteristics over time for reactors at steady and ramped loadings, with and without grease trap waste. Also shown are the elapsed SRTs for the 10gCOD/L/day loading rate.

Figure 4-11 (a) shows methane production, normalized to the working volumes of the reactors. Methane production was higher for the 10gCOD/L/day loading than for lower loadings, but it was also more variable during the first two SRTs. Some of this variability is likely to be associated with respirometer precision and accuracy, and will be discussed further in Section 6.2, but some of the variability might also indicate that the reactor had not yet fully adapted to that loading. Figure 4-11 (a) also shows that the ramped reactors, once reaching a 10gCOD/L/day loading, had similar methane production to the un-ramped 10gCOD/L/day reactor. Figure 4-11 (b) shows the pH of these reactors, all of which stabilized at pH of 7.6-7.7. The VFA/alkalinity ratios, shown in Figure 4-11 (c), remained below 0.1 for all the reactors, although the steady 10gCOD/L/day reactor and the ramped reactors tended to have higher values than the steady 4gCOD/L/day reactors. As shown in Figure 4-11 (d), the VS in the reactors remained between 2.5 and 3.3%, with slightly lower values in the 4gCOD/L/day reactor and during the early part of the ramping process. These data demonstrate that stable operation over a period of greater than 3 SRTs was observed in low and high COD loading rates both with and without grease trap waste.

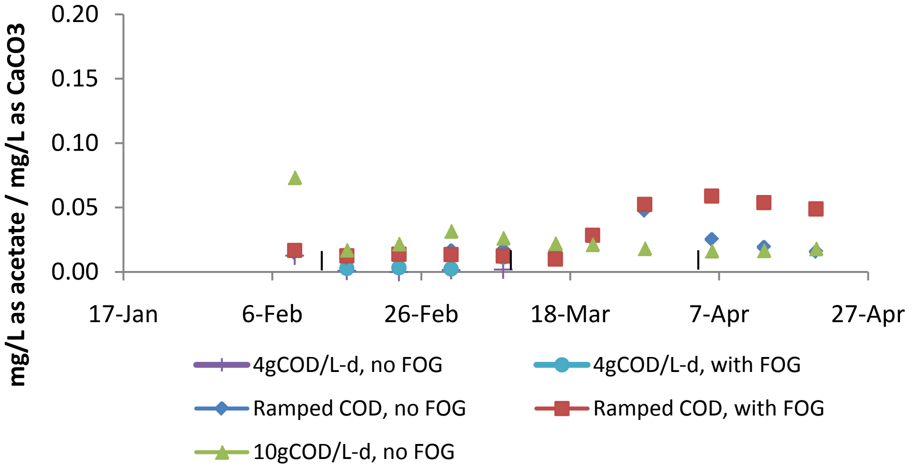
A. Methane production



B. pH



C. VFA/Alkalinity



D. VS

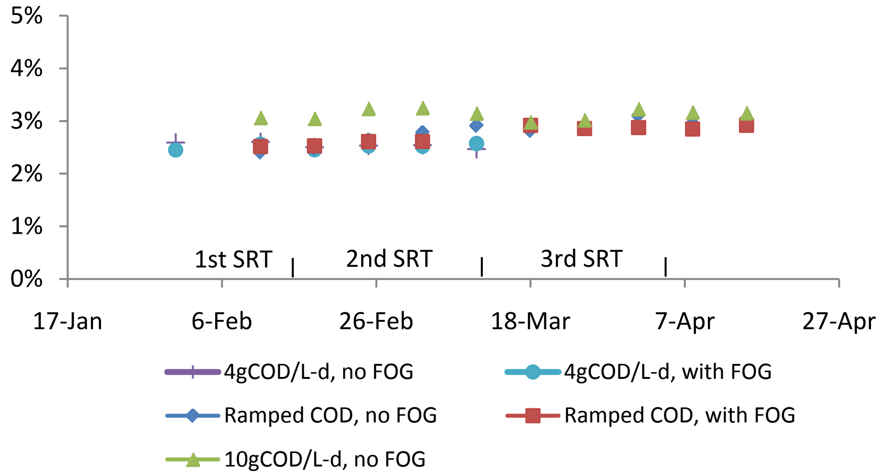
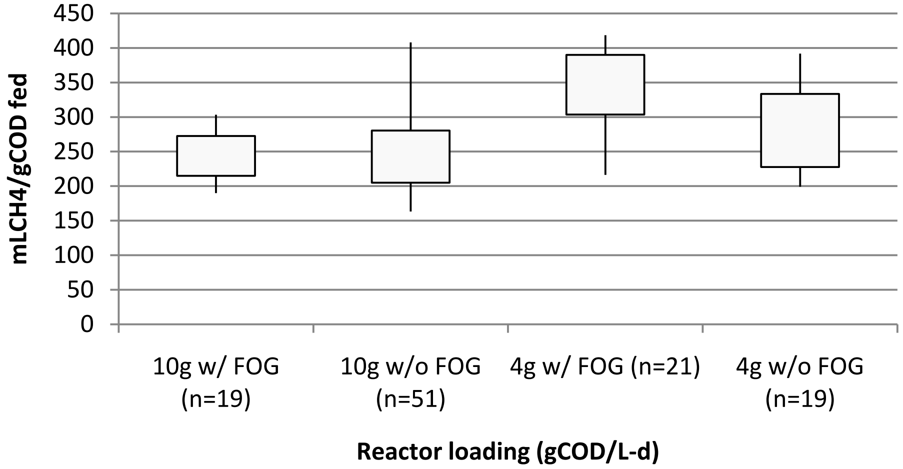


Figure 4-11 Reactor Performance by methane production, pH, VFA/acetate ratio and VS concentration over time (Ramping completed on 18 March)

Figure 4-12 summarizes the methane yields and VS destruction rates observed in reactors receiving steady loadings of either 4gCOD/L/day or 10gCOD/L/day, with and without grease trap waste. These values were calculated from the reactors that were included in Figure 4-11, as well as from reactors used in the grease trap waste ramping experiments. The methane yield was higher at lower COD loading rates. This is in contrast to the methane production, which is higher with higher loading rates. There was also an increased methane yield from grease trap waste additions with a 4gCOD/L/day loading, but that increase was not observed at a 10gCOD/L/day loading. The VS destruction rates were also increased in the 4gCOD/L/day reactors compared to the 10gCOD/L/day reactors, but grease trap waste addition had no apparent effect.


A. Methane yield

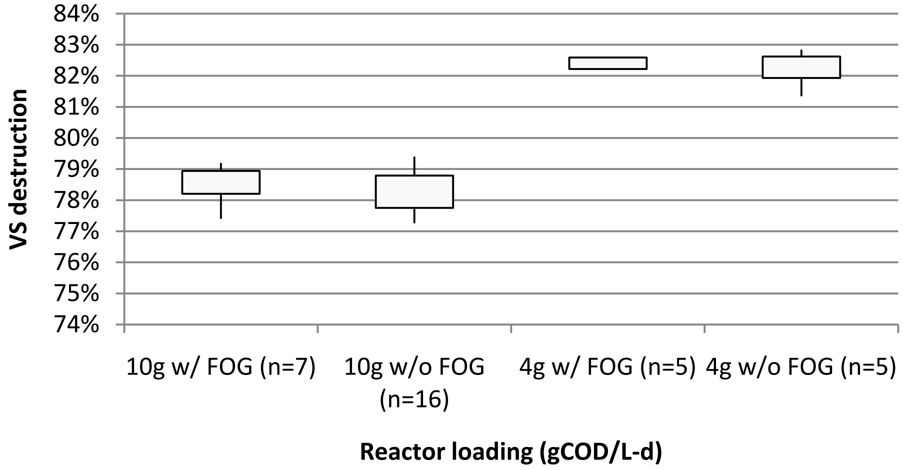
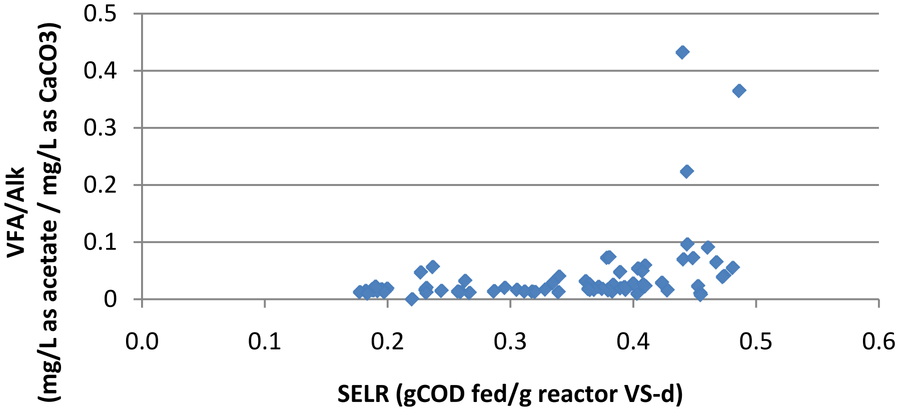

B. VS Destruction

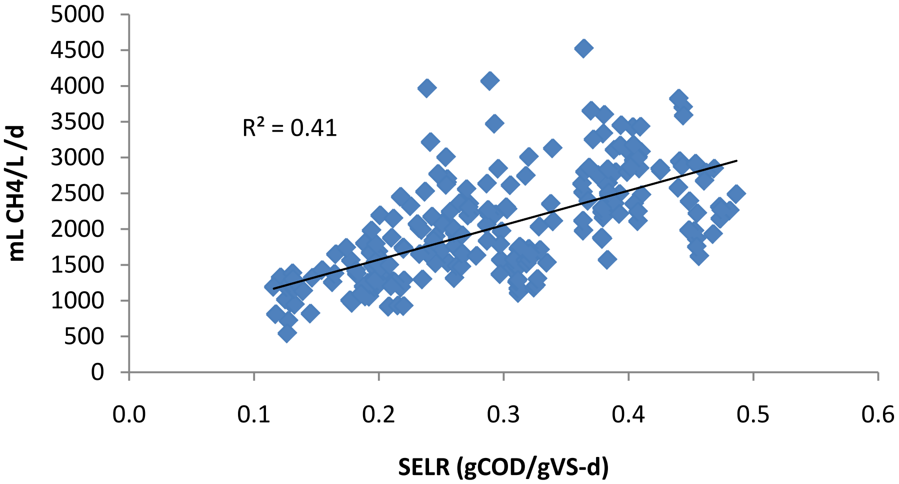
Figure 4-12 Reactor performance at steady loading rates. Boxes 25-75 percentile, whiskers 5-95 percentile.

In order to assess the utility of the specific energy loading rate (SELR) as a guideline for stable reactor loading rates, the VFA/alkalinity ratios observed during reactor operation were compared to the SELR. A VFA/alkalinity ratio of greater than 0.1 has been suggested as an indicator of reactor instability. The SELR was also compared to both the methane production and the methane yield. Figure 4-13 shows the relationship between SELR and these three factors, for reactors that were neither suffering acute inhibition from QAC addition nor receiving high grease trap waste loadings without acclimation. Reactors with an SELR of <0.4gCOD fed/g reactor VS/day generally maintained VFA/alkalinity values well below 0.1, although those loaded at more than 0.38 approached that threshold. At SELRs from 0.4 to 0.5, the VFA/alkalinity ratios were generally higher than at lower loadings, with a few excursions well above 0.1. Methane production increased with SELR, and methane yield decreased. These trends are similar to those seen with comparisons among loading rates. There was substantial variation in the relationships of methane production and methane yield to SELR. This variation reflects the day-to-day variability of the gas production data, but also suggests that other factors may be influencing gas production.

A. VFA/Alkalinity vs. SELR



B. Methane Production vs. SELR



C. Methane Yield vs. SELR

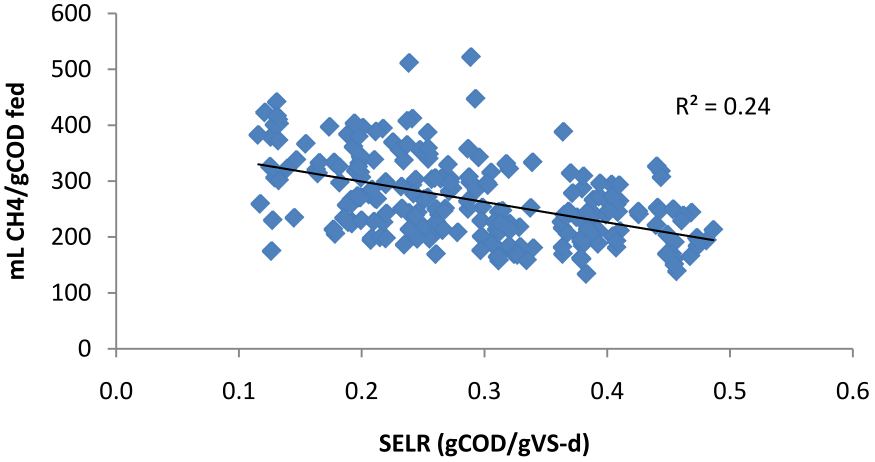


Figure 4-13 Reactor performance characteristics plotted against the specific energy loading rate (SELR). (A): VFA/alkalinity; (B): Methane production; (C): Methane yield.

Table 4-6 presents summary statistics for the steady state reactors at four conditions. These data formed the based for development of performance objectives for the demonstration.

Table 4-6 Summary Statistics for Steady State Digester Operation

Parameter	4 g COD /L/d w/o 10% FOG	4 g COD/L/d w/ 10% FOG	10 g COD/L/d w/o 10% FOG	10 g COD/L/d w/ 10% FOG
% Energy conversion	76 ± 10	92 ± 11	75 ± 16	74 ± 8
mL CH4/g VS load	450 ± 130	550 ± 140	410 ± 130	460 ± 80
mL CH4/g COD load	290 ± 70	350 ± 60	260 ± 80	250 ± 40
mL CH4/L/d	1200 ± 290	1400 ± 210	2600 ± 770	2600 ± 560
% CH4 in biogas	65 ± 1	66 ± 1	67 ± 4	70 ± 3
g COD/g VS/d (SELR)	0.16 ± 0.03	0.18 ± 0.03	0.33 ± 0.06	0.35 ± 0.07
g VS/L/d (volumetric loading)	2.6 ± 0.5	2.4 ± 0.4	6.3 ± 1.2	5.8 ± 1.2
g COD/L/d (volumetric loading)	4.1 ± 0.8	4.2 ± 0.7	10.2 ± 1.9	10.3 ± 1.9
VFA/Alk	0.01 ± 0.002	0.02 ± 0.003	0.03 ± 0.02	0.04 ± 0.02
% VS destruction	82 ± 1	82 ± 1	78 ± 1	78 ± 1
% TS destruction	78 ± 1	78 ± 1	75 ± 1	75 ± 1
SRT (d)	58 ± 12	58 ± 12	24 ± 6	23 ± 5

5.0 MODEL CALIBRATION AND HYDROLYSIS KINETICS OF FOOD WASTE AND GREASE TRAP WASTE

5.1 ABSTRACT

A batch test was run on the respirometer in order to determine the hydrolysis kinetics of two food wastes with and without 10% grease trap waste. Data collected in the hydrolysis test will be used to calibrate the Mathcad ADM1 model.

5.2 METHODS & MATERIALS

5.2.1 Acclimation Period

Three weeks prior to commencing the experiment four reactors of Renton Municipal Digestion sludge were started on a semi-continuous feed of 4.0 g COD/L/day of mixed food waste with 10% grease trap waste to develop acclimated inoculum. During the acclimation period the reactors were kept incubated at 37° C and fed on a Monday/ Wednesday/Friday schedule. Digester health was monitored by pH checks on feed days. Additional analysis was completed for informational purposes, including alkalinity, total and soluble COD, ammonia concentration, VFA analysis, total and volatile solids and conductivity.

5.2.2 Hydrolysis Test

Sludge from the four acclimation reactors was pooled and then split into five hydrolysis reactors for the experiment. Temperature, SRT, HRT, start volume and COD dose were constant for the five reactors. Each reactor was dose fed 12 gCOD/L at T = 0 according to the test conditions. Food waste source and composition were the variable test conditions, outlined in Table 5.1.

Table 5-1 Hydrolysis Test Conditions

Test Variable	Reactor 1	Reactor 2	Reactor 3	Reactor 4	Reactor 5
Food Waste Composition (% COD Basis)	FW-B1 100%	FW-B1 90%	FW-B3 100%	FW-B3 90%	FW-B1 100%
Grease trap waste (% COD Basis)	0%	10%	0%	10%	0%

Gas production rates and percentages were monitored at regular intervals using the respirometer. Reactors were sampled at specified time points and reactor volume changes were recorded over time so the gas production data can be normalized to the batch volume. Sample points and analyses performed are outlined in table 5-2.

Table 5-2 Hydrolysis Reactor Sample Schedule

Day	Time (hrs)	Analyses
1	Inoculum	TS, VS, VFA, sCOD, pH, Ammonia, Alkalinity
1	t=0 (post-feed)	TS, VS, VFA, sCOD, pH, Ammonia, Alkalinity
1	2, 4, 6, 8, 10	pH, VFA, sCOD, Ammonia
2	24, 28, 32	pH, VFA, sCOD, Ammonia
3	48	pH, VFA, sCOD, Ammonia
3	56	TS, VS, VFA, sCOD, pH, Ammonia, Alkalinity

5.3 RESULTS

A summary of the acclimation and hydrolysis reactors results are provided below. Interpretation of these data is not discussed at this time since calibration of the ADM1 model is required and will be conducted separately.

Table 5-3 Acclimation Reactor Analytics Summary

		ACC 1	**ACC 2**	**ACC 3**	**ACC 4**
pH	Average	7.6	7.7	7.7	7.6
	StDev	0.1	0.1	0.2	0.1
	Min	7.5	7.5	7.5	7.5
	Max	8.0	7.9	8.0	7.8
Alkalinity (mg/L as $CaCO_3$)	Average	12000	11000	11000	12000
	StDev	120	610	310	420
	Min	12000	11000	11000	11000
	Max	12000	12000	12000	12000
tCOD (mg/L as COD)	Average	42000	45000	45000	47000
	StDev	3200	28000	1700	8800
	Min	39000	43000	44000	39000
	Max	45000	48000	47000	56000
sCOD (mg/L as COD)	Average	1600	1500	1600	1500
	StDev	220	80	84	250
	Min	1400	1500	1600	1300
	Max	1900	1600	1700	1700
Ammonia (mg/L as N)	Average	2400	2400	2400	2400
	StDev	280	300	260	240
	Min	2200	2200	2200	2600
	Max	2600	2600	2600	2600
Volatile Solids (% Wet Weight)	Average	2.2%	2.2%	2.1%	2.1%
	StDev	0.0%	0.2%	0.1%	0.3%
	Min	2.2%	2.0%	2.0%	1.9%
	Max	2.2%	2.3%	2.2%	2.3%
Total Solids (% Wet Weight)	Average	3.1%	3.0%	2.9%	2.9%
	StDev	0.2%	0.2%	0.1%	0.5%
	Min	3.0%	2.9%	2.8%	2.6%
	Max	3.3%	3.1%	3.0%	3.2%
Conductivity (mS/cm)	Single Point	17	17	17	17

Table 5-4 Acclimation Reactor VFA Summary

		ACC 1	ACC 2	ACC 3	ACC 4
Acetate (ppm)	Average	109	89	88	82
	StDev	26	14	13	15
	Min	88	63	67	66
	Max	170	110	110	120
Propionate (ppm)	Average	14	4.7	4.4	2.5
	StDev	16	5.4	4.7	2.2
	Min	0	0	0	0
	Max	45	16	13	5.8
Isobutyrate (ppm)	Average	1.4	0	0	0
	StDev	2.4	0	0	0
	Min	0	0	0	0
	Max	6.4	0	0	0
Butyrate (ppm)	Average	1.5	0	0	0
	StDev	1.8	0	0	0
	Min	0	0	0	0
	Max	4.0	0	0	0
Isovalerate (ppm)	Average	6.9	3.6	3.2	3.4
	StDev	3.5	1.4	1.4	3.6
	Min	3.2	1.6	1.6	0
	Max	13.3	6.0	5.1	12.0
Valerate (ppm)	Average	0	0	0	0
	StDev	0	0	0	0
	Min	0	0	0	0
	Max	0	0	0	0

Table 5-5 Hydrolysis Reactor Summary

Reactor #	**1**	**2**	**3**	**4**	**5**
Feed Source (COD Basis)	100% FW-B1	90% FW-B1 10% grease trap waste	100% FW-B3	90% FW-B3 10% grease trap waste	100% FW-B1 (duplicate of Rx 1)
COD Load (gCOD/Day/L)	12	12	12	12	12
Total Methane Accumulation (mL)	1700	1700	1800	1900	1700
% Methane (Average)	65%	66%	67%	67%	66%
Total Carbon dioxide Accumulation (mL)	900	860	860	880	850
% Carbon dioxide (Average)	35%	34%	33%	33%	34%

Tables 5-6 Hydrolysis Reactor 1 Analytics

Sample Point	pH	sCOD (mg/L as COD)	Ammonia (mg/L as N)	Alkalinity (mg/L as $CaCO_3$)	% VS (% Wet Weight)	% TS (% Wet Weight)
Inoculum	7.8	1700	2400	12000	2.2%	2.9%
Post Feed	7.6	3900	2300	11000	2.9%	3.6%
T = 2 hr	7.5	3300	2500	-	-	-
T = 4 hr	7.6	3100	2600	-	-	-
T = 6 hr	7.6	3000	2200	-	-	-
T = 8 hr	7.6	2800	2300	-	-	-
T = 10 hr	7.6	2700	2300	-	-	-
T = 24 hr	7.6	2000	2400	-	-	-
T = 28 hr	7.7	1800	2600	-	-	-
T = 32 hr	7.7	2000	2700	-	-	-
T = 48 hr	7.6	1900	2700	-	-	-
T = 56 hr	7.6	1800	2800	12000	2.4%	3.1%

Tables 5-7 Hydrolysis Reactor 1 VFA Results

Sample Point	Acetate (ppm)	Propionate (ppm)	Iso-butyrate (ppm)	Butyrate (ppm)	Iso-Valerate (ppm)	Valerate (ppm)
Inoculum	105	2	ND	ND	4	ND
Post Feed	268	15	3	1	11	ND
T = 2 hr	512	63	9	11	20	2
T = 4 hr	519	95	13	20	24	7
T = 6 hr	460	108	16	15	27	6
T = 8 hr	348	114	17	3	26	2
T = 10 hr	196	118	20	ND	28	ND
T = 24 hr	82	2	ND	ND	2	ND
T = 28 hr	100	4	ND	ND	4	ND
T = 32 hr	107	3	ND	ND	4	ND
T = 48 hr	93	ND	ND	ND	2	ND
T = 56 hr	102	ND	ND	ND	3	ND

ND = Less than 1.5 ppm or non-detection

Tables 5-8 Hydrolysis Reactor 2 Analytics

Sample Point	pH	sCOD (mg/L as COD)	Ammonia (mg/L as N)	Alkalinity (mg/L as $CaCO_3$)	% VS (% Wet Weight)	% TS (% Wet Weight)
Inoculum	7.8	1800	2300	12000	2.3%	2.6%
Post Feed	7.6	3400	2300	11000	2.8%	3.5%
T = 2 hr	7.5	3200	2500	-	-	-
T = 4 hr	7.6	3000	2600	-	-	-
T = 6 hr	7.6	3000	2400	-	-	-
T = 8 hr	7.7	3000	2400	-	-	-
T = 10 hr	7.6	2900	2300	-	-	-
T = 24 hr	7.7	2000	2500	-	-	-
T = 28 hr	7.7	1900	2400	-	-	-
T = 32 hr	7.7	2100	2700	-	-	-
T = 48 hr	7.7	2100	2800	-	-	-
T = 56 hr	7.6	1800	2700	12000	2.3%	3.1%

Tables 5-9 Hydrolysis Reactor 2 VFA Results

Sample Point	Acetate (ppm)	Propionate (ppm)	Iso-butyrate (ppm)	Butyrate (ppm)	Iso-Valerate (ppm)	Valerate (ppm)
Inoculum	119	2	ND	ND	4	ND
Post Feed	269	12	2	ND	10	ND
T = 2 hr	502	64	9	12	22	3
T = 4 hr	444	70	10	16	21	4
T = 6 hr	409	71	10	19	21	5
T = 8 hr	362	100	16	30	30	11
T = 10 hr	337	90	17	16	30	9
T = 24 hr	123	4	3	ND	4	ND
T = 28 hr	119	ND	ND	ND	4	ND
T = 32 hr	118	2	ND	ND	4	ND
T = 48 hr	110	ND	ND	ND	4	ND
T = 56 hr	106	ND	ND	ND	3	ND

ND = Less than 1.5 ppm or non-detection

Tables 5-10 Hydrolysis Reactor 3 Analytics

Sample Point	pH	sCOD (mg/L as COD)	Ammonia (mg/L as N)	Alkalinity (mg/L as $CaCO_3$)	% VS (% Wet Weight)	% TS (% Wet Weight)
Inoculum	7.8	1800	2300	12000	2.3%	3.0%
Post Feed	7.6	2900	2300	11000	2.8%	3.6%
T = 2 hr	7.6	2900	2500	-	-	-
T = 4 hr	7.7	2700	2700	-	-	-
T = 6 hr	7.6	2600	2300	-	-	-
T = 8 hr	7.7	2500	2300	-	-	-
T = 10 hr	7.6	2500	2400	-	-	-
T = 24 hr	7.7	2300	2700	-	-	-
T = 28 hr	7.7	2100	2800	-	-	-
T = 32 hr	7.8	2100	2800	-	-	-
T = 48 hr	7.7	2000	2900	-	-	-
T = 56 hr	7.6	2100	3100	12000	2.3%	3.1%

Tables 5-11 Hydrolysis Reactor 3 VFA Results

Sample Point	Acetate (ppm)	Propionate (ppm)	Iso-butyrate (ppm)	Butyrate (ppm)	Iso-Valerate (ppm)	Valerate (ppm)
Inoculum	131	ND	ND	ND	4	ND
Post Feed	219	11	2	ND	9	ND
T = 2 hr	285	41	11	7	25	2
T = 4 hr	238	29	7	6	17	2
T = 6 hr	252	56	23	15	53	8
T = 8 hr	197	31	9	5	18	2
T = 10 hr	184	50	27	4	52	3
T = 24 hr	132	4	24	ND	27	ND
T = 28 hr	133	3	17	ND	14	ND
T = 32 hr	126	2	3	ND	4	ND
T = 48 hr	103	ND	ND	ND	4	ND
T = 56 hr	108	ND	ND	ND	4	ND

ND = Less than 1.5 ppm or non-detection

Tables 5-12 Hydrolysis Reactor 4 Analytics

Sample Point	pH	sCOD (mg/L as COD)	Ammonia (mg/L as N)	Alkalinity (mg/L as $CaCO_3$)	% VS (% Wet Weight)	% TS (% Wet Weight)
Inoculum	7.8	1800	2400	12000	2.3%	3.1%
Post Feed	7.6	2800	2400	11000	2.8%	3.6%
T = 2 hr	7.6	2900	2600	-	-	-
T = 4 hr	7.7	2900	2800	-	-	-
T = 6 hr	7.7	2800	2100	-	-	-
T = 8 hr	7.7	2900	2300	-	-	-
T = 10 hr	7.6	2800	2400	-	-	-
T = 24 hr	7.7	2500	2800	-	-	-
T = 28 hr	7.8	2400	2700	-	-	-
T = 32 hr	7.8	2400	3000	-	-	-
T = 48 hr	7.7	2200	2900	-	-	-
T = 56 hr	7.7	2200	3000	12000	2.4%	3.1%

Tables 5-13 Hydrolysis Reactor 4 VFA Results

Sample Point	Acetate (ppm)	Propionate (ppm)	Iso-butyrate (ppm)	Butyrate (ppm)	Iso-Valerate (ppm)	Valerate (ppm)
Inoculum	108	2	ND	ND	4	ND
Post Feed	202	16	4	ND	13	2
T = 2 hr	222	38	13	6	28	2
T = 4 hr	223	52	18	8	38	4
T = 6 hr	204	57	18	8	38	5
T = 8 hr	218	68	20	10	42	6
T = 10 hr	224	82	27	16	54	8
T = 24 hr	130	36	45	ND	79	ND
T = 28 hr	134	5	45	ND	84	ND
T = 32 hr	130	3	41	ND	83	ND
T = 48 hr	127	2	8	ND	76	ND
T = 56 hr	109	ND	ND	ND	78	ND

ND = Less than 1.5 ppm or non-detection

Tables 5-14 Hydrolysis Reactor 5 Analytics

Sample Point	pH	sCOD (mg/L as COD)	Ammonia (mg/L as N)	Alkalinity (mg/L as $CaCO_3$)	% VS (% Wet Weight)	% TS (% Wet Weight)
Inoculum	7.77	1810	2420	12000	2.3%	3.0%
Post Feed	7.59	3880	2430	11000	2.9%	3.6%
T = 2 hr	7.55	3470	2560	-	-	-
T = 4 hr	7.60	3270	2660	-	-	-
T = 6 hr	7.58	2953	2280	-	-	-
T = 8 hr	7.59	2913	2260	-	-	-
T = 10 hr	7.57	2720	2360	-	-	-
T = 24 hr	7.68	2060	2660	-	-	-
T = 28 hr	7.70	2080	2620	-	-	-
T = 32 hr	7.72	1860	2660	-	-	-
T = 48 hr	7.62	1880	2840	-	-	-
T = 56 hr	7.56	1690	2860	13000	2.4%	3.2%

Tables 5-15 Hydrolysis Reactor 5 VFA Results

Sample Point	Acetate (ppm)	Propionate (ppm)	Iso-butyrate (ppm)	Butyrate (ppm)	Iso-Valerate (ppm)	Valerate (ppm)
Inoculum	110	ND	ND	ND	4	ND
Post Feed	228	10	ND	ND	9	ND
T = 2 hr	488	61	8	9	19	3
T = 4 hr	474	83	9	16	18	5
T = 6 hr	458	122	14	9	27	5
T = 8 hr	314	123	15	2	25	2
T = 10 hr	191	129	19	ND	26	ND
T = 24 hr	127	5	6	ND	6	ND
T = 28 hr	121	4	ND	ND	5	ND
T = 32 hr	132	2	ND	ND	4	ND
T = 48 hr	126	2	ND	ND	5	ND
T = 56 hr	103	2	ND	ND	4	ND

ND = Less than 1.5 ppm or non-detection

6.0 QUALITY ASSURANCE

This section presents the deviations from the Work Plan and evaluation of the data quality.

6.1 DEVIATIONS FROM THE WORK PLAN

The following deviations from the work plan were made:

- HRT and SRT were varied as a function of COD loading. Varying them independently of COD loading would have required feeding a more diluted waste, which was determined to be detrimental to reactor operation.

- Carbon-to-nitrogen-to-phosphorus ratios were explored during the BMP tests, rather than reactor tests, but were not found to be predictive of digestibility within the range encountered. Although neither of these macro-nutrients was found to be limiting, trace nutrient concentrations were identified as an important limitation.

- Biomass carriers were tested in only one condition: ramped COD loading without grease trap waste. The performance of this reactor did not differ from that of the ramped reactor without walnut shells (data not shown).

- Pre-hydrolysis was not tested, as the high digestibility of the food waste rendered it unnecessary.

- Cycling of food/oil waste compositions has been deferred to the pilot demonstration.

- An explicit test of the effects of QACs at varying concentrations was added.

- A test comparing the Mitchell Hall grease-trap grease trap waste to canola oil was conducted to determine whether observed inhibitory effects were due to high lipid loading, or to an inhibitory factor unique to this grease trap waste source.

6.2 EVALUATION OF DATA QUALITY

Data precision was assessed by calculating the relative percent difference (RPD) of laboratory analyses, presented in Table 6-1. A single replicate was calculated for the Exova food waste characterization and BMP test. Multiple replicates were performed for the food waste characterization COD to ensure method precision, and the resulting average deviation is shown. Reactor Studies analyses were performed with approximately 20% replication, and the RPDs shown are the average values. All analyses meet the precision goal (RPD<35%) of the work plan.

Table 6.1: Summary of Analytical RPDS

Phase	Analysis	RPD Average
Food Waste Characterization	Chemical Oxygen Demand	2%
	Volatile Solids	10%
	Total Kjeldahl Nitrogen	1%
	Total Phosphorus	10%
	Moisture Content	3%
	Fat Content	12%
	Ash Content	7%
	COD (average)	7%
BMP	Methane Yield	19%
Reactor Studies (average)	pH	0.33
	Alkalinity	4.2
	tCOD	5.1
	sCOD	1.9
	TS	1.6
	VS	1.6
	NH4	7.3

The continuous respirometry analyses could not be performed in duplicate, so RPDs cannot be determined. However, certain factors were observed to affect the quality of the respirometry data. The gas composition sensors malfunction when exposed to excessive pressures. These pressures develop when gas production is very high relative to the headspace and sample bottle volume. This can occur if the sludge is too active (e.g. from a high COD loading rate), the working volume is too great, the headspace volume is insufficient, and/or the sampling interval is too long. However, gas composition measurements are also inaccurate if gas production is too low, so an optimization process was necessary to arrive at a good combination of working volume, sample-bottle size, and sampling interval for the different COD loading rates. Therefore the methane production values should be used primarily for comparison among different treatments, rather than as indicators to absolute values for various design parameters.

7.0 CONCLUSIONS

7.1 BMP TESTS

7.1.1 General Degradability of Mitchell Hall Food Wastes

The average net methane yield from the food wastes tested was 400mL CH4/gCOD loaded, which suggests that the wastes tested were highly degradable by anaerobic digestion. There were no major inhibitory effects apparent, as none of the bottles experienced a lag before the onset of methane production.

7.1.2 Methane Yield Correlated to Fat and Protein Content

The methane yield was quite variable between the wastes, and it was found that there was a correlation with the fat and protein content of the food waste. Several factors may have contributed to this correlation. Lignocellulose and some other types of carbohydrates are poorly degradable, so the fat and protein may have represented a more highly-degradable fraction. Furthermore, in standard analytical procedures for food the fat, protein, and ash contents of the material are analyzed; the remainder is assumed to be carbohydrates but these are not measured directly. Therefore, certain non-food materials, such as plastics, would be included in the carbohydrate fraction. The presence of such recalcitrant organics would reduce the apparent methane yield, and would also contribute to the apparent correlation between methane yield and the fat and protein content.

7.1.3 High Fat Content and grease trap waste Addition may Enhance Digestion

Many of the wastes tested produced yields above 400mL CH_4/gCOD, which is the theoretical value for full conversion (Tchobanoglous *et al.*, 2003). The grease trap waste produced the highest yield, with 700mL CH4/gCOD. This supports the readily-degradable nature of this waste, but more importantly suggests that it enhanced digestion of the sewage sludge inoculum. Recent studies have shown enhanced methane yields from the addition of high-fat wastes to sewage sludge (Kabouris *et al.*, 2009; Luostarinen *et al.*, 2009; Davidsson *et al.*, 2008). However, digestion of high-fat wastes can be problematic as well as beneficial. Degradation of fats produces long-chain fatty acids, which are potentially-toxic intermediates. Excessive loading of fats has been observed to lead to the inhibition of anaerobic digestion (Koster and Cramer, 1987; Hatamoto *et al.*, 2007). Therefore, tests to determine the acceptable grease trap waste loadings were included in the semi-continuous reactor tests, described in Section 4.

7.2 SEMI-CONTINUOUS REACTOR STUDIES

The semi-continuous reactor studies demonstrated successful digestion of food wastes from Mitchell Hall at a variety of loadings, with and without the addition of grease trap waste. This phase of the treatability study also identified several critical operational parameters.

7.2.1 Supplemental Co, Ni and Mo Addition

Trace metals analysis revealed that these food wastes are deficient in cobalt and nickel, and perhaps molybdenum. These three elements are required for enzymatic cofactors, and are among the trace metals that have been identified as critical to successful anaerobic digestion (Speece, 1996).

7.2.2 High Volatile Solid Concentrations Necessary in Feed

Feeding waste at a high VS concentration proved necessary for stable reactor operation. The food wastes were highly degradable, with VS destruction rates greater than 75%. Feeding the waste at VS concentrations seen in traditional anaerobic sludge digestion resulted in reactor solids concentrations too low to support stable operation. Reactor performance improved when the food waste VS concentrations were kept at greater than 10%.

7.2.3 Inhibition at High QAC Concentrations

Experiments demonstrated inhibition above 2000 mg QAC/kg Food Waste TS. Estimates suggest that the QAC concentrations at Mitchell Hall may approach this threshold, so assessment of QAC inhibition during the demonstration is necessary.

7.2.4 Multiple Approaches to Reactor Start Up

Reactor performance data suggest guidelines for successful start-up of food waste digestion from a sewage-sludge digester inoculum. No special acclimation of the inoculum was needed during reactor start-up for low COD loadings (4gCOD/L/day) with or without grease trap waste. The stability of high COD loaded reactors (10gCOD/L/day) depended on the presence of grease trap waste. Reactors started at high load without grease trap waste showed transiently elevated VFA/alkalinity ratios. This suggests there might be an unstable period during which the reactor would by vulnerable to further upset. Reactors started at high a COD load with 10% of COD from grease trap waste did not develop stable digestion. However, the experiments demonstrated that stable performance at high COD loadings with and without grease trap waste is achievable with a period of reactor acclimation through ramping.

7.2.5 High COD Loads Achievable Through Ramping

Stable digestion was achieved at COD loadings up to 10gCOD/L-d, with and without grease trap waste. Successful start up was demonstrated both by ramping the grease trap waste concentration from 2 to 10% and ramping the load of a 10% grease trap waste reactor from 4 to 10 gCOD/L/day.

7.2.6 Grease Trap Waste Effects Dependent on the Concentration and COD Load

Beneficial effects were seen during BMPs in conditions of a low COD load with high lipid contents. Some negative effects were observed with grease trap waste addition at high COD in the reactor studies. Starting newly-inoculated reactors with a 10gCOD/L/day loading was successful when a grease trap waste-free food-waste or low grease trap waste concentration (less than or equal to 5% of the COD) mix was used. Including grease trap waste as 10% of the COD at start-up led to reactor failure. Similar effects were seen when canola oil was used in place of grease trap waste, indicating that the failure was attributable to lipid loading in general rather than to any inhibitory factor unique to the grease trap waste from the Mitchell Hall grease traps. The breakdown of fats is known to produce long-chain fatty acids, which are potentially-inhibitory intermediates. These results show that while addition of fats may have beneficial effects either the percent of COD from grease trap waste or total COD load must be low at reactor start up.

7.2.7 Performance Trade Offs With COD Load

Comparison of performance between reactors operated at steady loadings of 4gCOD/L/day and 10gCOD/L/day showed that there was a trade-off between the methane production per reactor volume and COD. Reactors with high COD loading had a higher methane production per reactor volume, while the greater methane yield per COD loading occurred at the lower loading rate. There was also greater VS destruction at the lower loading rate. This was likely due, at least in part, to the longer SRT of the low load reactors, as it varies inversely with the loading rate when the feed concentration is kept constant.

The loading rate also changed the effects of grease trap waste addition. In reactors receiving 4gCOD/L/day, grease trap waste addition increased the methane yield, but no such increase was observed in reactors receiving 10gCOD/L/day. Grease trap waste did not apparently affect the VS destruction rate at either COD loading rate, which suggests that for these wastes the higher methane yields were a function of greater grease trap waste digestibility, rather than enhanced VS destruction.

7.2.8 Utility of SELR

Within the range tested, SELR had a weak positive correlation to methane production, but a weak negative correlation to methane yield. Reactor stability was found to decrease at higher SELRs, although the acceptable threshold appeared to be affected by factors such as trace nutrient limitation. For nutrient-supplemented reactors that were not subjected to inhibitors (e.g. QAC addition or high loadings of grease trap waste without prior acclimation), SELRs above 0.4 were associated with elevated VFA/alkalinity ratios. This suggests that the SELR may be a useful design parameter for determining safe loading levels.

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Appendix E: ADM1 Model Development

Anaerobic Digestion of Food Waste: Mechanistic Modeling, Hydrolysis Kinetics, Digester Stability, and Biomethane Production Efficiency

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INTRODUCTION

Anaerobic digestion has commonly been used in municipal wastewater treatment facilities to destroy solids produced from the wastewater treatment process. Methane biogas production from solids destruction and no aeration energy requirement are major benefits compared to aerobic digestion of solids. More recently anaerobic digestion has been considered for other community wastes including food wastes (Gabb, 2008), fat, oils and grease waste (Li et al. 2002, Stoll and Gupta 1997), and food processing and rendering wastes (Muller et al., 2009) because of its ability to produce a beneficial energy product from these waste materials. Feasibility studies performed on food waste from the United States Air Force Academy (USAFA) have shown high energy conversion efficiency of organic solids to biomethane and indicate that this is a feasible and economically promising technology for disposal of food wastes from military establishments and other institutions.

Dynamic simulation models for activated sludge systems have been developed by an International Water Association (IWA) Task Group (Gujer et al. 1999, Henze et al. 1999) and have been commonly accepted and applied for design and operational analysis on a number of commercial platforms. Similarly a comprehensive dynamic simulation model for anaerobic digestion, termed ADM1, has been developed by another IWA Task Group (Batstone et al. 2002) and has been generally accepted for its application to anaerobic digestion of municipal sludge. ADM1 has also been applied to other wastes such as grass silage, pig slurry, microalgae, and other combined wastes (Fezzani and Ben Cheikh 2008, Girault et al. 2011, Koch et al. 2010, Mairet et al. 2011). An important aspect of anaerobic digestion is maintaining stable operation under variable loads with a suitable balance between carbon processing from fermentation bacteria and utilization of the acetate and hydrogen produced by the more sensitive methanogenic bacteria. The ADM 1 model provides a useful tool to evaluate the effects of transient loadings and operating conditions on digester performance and stability.

In contrast to relatively frequent and constant feeding patterns normally used for municipal sludge digestion, the feeding patterns for anaerobic digesters of food wastes at military installations may be intermittent with significant loading spikes every two to three days. The goal of this study was to apply the ADM1 model for anaerobic digestion of food waste so that the effect of design and feeding strategies could then be evaluated for subsequent pilot plant testing and demonstration and full-scale applications. In addition, the ADM1 model was incorporated into Mathcad15 to provide a relatively inexpensive available software package for other users. Anaerobic digestion of USAFA food waste was studied in laboratory digesters and in bottle tests and provided information for model calibration.

The calibrated model was then used to evaluate the effect of different operating conditions for the pilot plant demonstration of food waste digestion. Of particular interest were digester responses to loading rate increases and periods of starvation or reduced loading rate. The effect of waste composition, hydrolysis characteristics, feeding strategy, and endogenous decay rate were also evaluated with the calibrated model.

CHAPTER I: ADM1 MODEL DESCRIPTION

The Anaerobic Digester Model 1 (ADM1) was selected as the model platform to describe anaerobic digestion of food waste. ADM1 is the product of a collaborative effort by the International Water Association (IWA) Task Group for Mathematical Modeling of Anaerobic Digestion Processes, and, has been applied for a broad range of anaerobic process applications (Batstone et al. 2002). While adjustments to the model were needed to account for this new application, the overall model structure was maintained. This chapter provides an overview and process description of the “default ADM1”, followed by the specific changes that were made to address food waste digestion, denoted as the “modified ADM1.” All of the information regarding the ADM1 model is in reference to the work presented by Batstone et al. (2002).

ADM1 describes the fate of organic substrates in anaerobic digestion on a chemical oxygen demand (COD) basis using a system of differential and algebraic equations. The COD is conserved in the conversion of particulate feed to its soluble intermediates, and eventually to final products of methane gas and biomass. Michaelis-Menten and first order kinetic rate equations describe how fast the COD conversions occur. The COD conversion steps of the default ADM1 is described in Figure 1. Petersen matrices from Batstone (2002) describing all of the soluble and particulate dynamic state variables for the default ADM1 are in Appendix A.

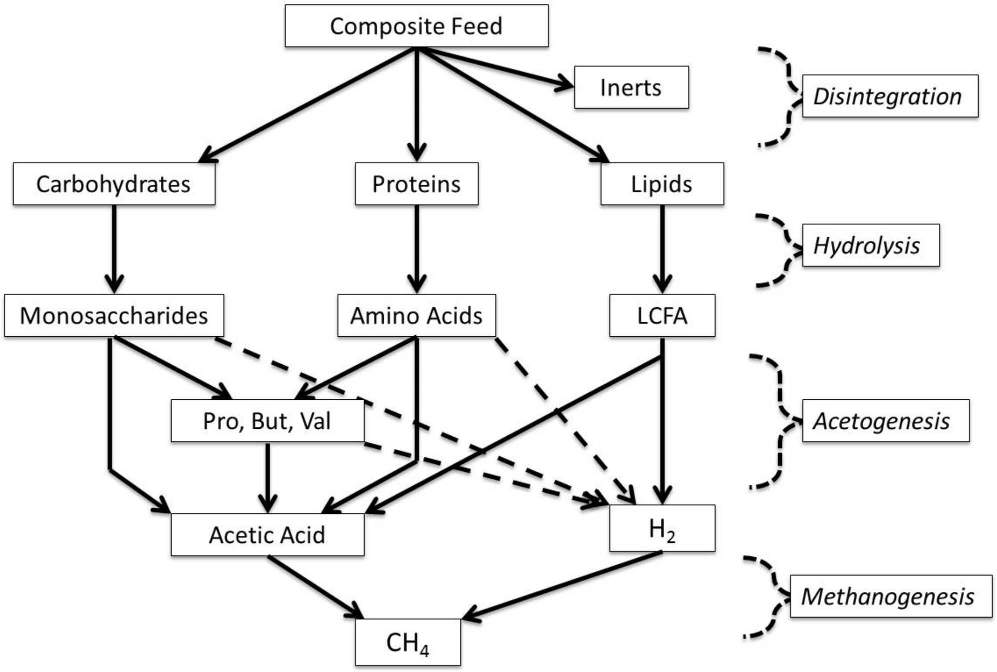

Composite Feed
Inerts
Disintegration
Carbohydrates
Proteins
Lipids
Hydrolysis
Monosaccharides
Amino Acids
LCFA
Pro, But, Val
Acetogenesis
Acetic Acid
H_2
Methanogenesis
CH_4

Figure 1. Flowchart of COD conversion pathways in the ADM1

The first step described by the ADM1 is disintegration, which is defined as the breakdown of composite particulate COD material into particulate carbohydrates, proteins, and lipids components, as well as soluble and particulate inert material. This step is a physical mechanism, and was included in the ADM1 to allow the use of individual hydrolysis rates for the particulate carbohydrate, protein, and lipid substrates.

The particulate substrate components produced by disintegration are then solubilized in a hydrolysis step. This enzymatic process converts complex particulates into their corresponding soluble monomers. Monosaccharides, amino acids, and long chain fatty acids comprise the soluble products of hydrolysis for carbohydrates, proteins, and lipids, respectively and are the substrates for acidogenesis and acetogenesis. Although hydrolysis is complex and has many steps, it is described by a simple first order kinetics model in ADM1.

Next, the soluble monomers are fermented to volatile fatty acids (VFAs) in an acidogenesis step. The ADM1 includes propionate, butyrate, and valerate as intermediate VFAs. Substrate utilization is determined by Michaelis-Menten kinetics in the ADM1 for all of the post hydrolysis processes:

$$R_S = \frac{k_m S X}{K_s + S} \tag{1}$$

where:

R_s = substrate utilization rate, gCOD/L-d

k_m = maximum specific substrate utilization rate, gCOD/g biomass COD-day

S = substrate concentration, gCOD/L

X = biomass concentration utilizing substrate, S, g biomass COD/L

Ks= half-velocity coefficient, gCOD/L

The acetogenesis step describes the degradation of higher molecular weight organic acids to acetate, hydrogen, and carbon dioxide. In order to maintain thermodynamically favorable acetogenesis reactions, hydrogen must be kept at a low concentration by the hydrogen-utilizing methanogens.

Methanogenesis is the last step of anaerobic digestion. Two types of methanogens are considered in the ADM1 model: acetoclastic and hydrogen-utilizing methanogens. Acetoclasts cleave acetate into methane and carbon dioxide, while hydrogen-utilizers form methane by combining hydrogen and carbon dioxide. Two main genera of acetoclasts are *Methanosarcina* and *Methanosaeta* and the ADM1 suggests their presence is mutually exclusive in anaerobic digesters. The more common occurring *Methanosaeta* (Zinder, 1993) with their corresponding ADM1 Michaelis-Menten kinetic coefficients were assumed for this digester application. All of the suggested parameter values for the default ADM1 are provided in Appendix B.

The ADM1 also includes dynamic calculation of the inorganic carbon and nitrogen concentrations in the digester. These equations are used in conjunction with acid-base equilibria and a charge balance to calculate the digester pH, and soluble CO_2, HCO_3, and ammonia concentrations. The inorganic carbon (HCO_3 and CO_2) concentrations are determined by a carbon balance and acid-base equilibrium. Soluble inorganic carbon enters the system through hydrolysis of the composite feed, and leaves through advection, volatilization of CO_2, reduction to CH_4, and uptake by biomass. The carbon content (moleC/gCOD) of each component of the digester must be known in order to implement the balance. The total soluble inorganic carbon is calculated using the carbon balance equation, and acid-base speciation equations determine the fractions of inorganic carbon as HCO_3 and CO_2. The inorganic nitrogen is calculated in the same way, but the volatilization of NH_3 is negligible so it is not included in the balance. Algebraic acid-base equilibria equations are used to determine the fraction of acids in ionic form. A charge balance, comprised of the ionized VFAs, NH_4^+, H^+, HCO_3^-, and OH^-, is used to calculate the pH. The inorganic carbon and nitrogen balances, acid-base equilibria, and charge balance equations are critical to the ADM1, as the performance and stability of digesters are greatly affected by pH, alkalinity, and ammonia. These parameters are also frequently measured in digesters, and can be used to compare model predictions to digester performance, or to calibrate the ADM1 to a particular application.

Another critical component of anaerobic digestion included in the ADM1 is liquid-gas transfer. Soluble hydrogen, CO_2, and methane are produced in anaerobic digesters, and exit the digester as dissolved components in the digester liquid and as a flux from the liquid to the gas phase. Therefore, a gas-flux term is included for soluble inorganic carbon, methane, and hydrogen in the model. The ADM1 dynamically calculates specific mass transfer rates for these gasses using their liquid concentration, partial pressure, Henry's constant, and an overall mass transfer coefficient, k_La. The k_La depends on mixing and temperature, and the ADM1 suggests that this parameter can be estimated from comparison to other systems with a known k_La. The ADM1 liquid-gas equations are presented in Appendix C.

The internal recycling of COD through biomass decay is also tracked by the ADM1. Biomass decay is assumed to follow first order kinetics with respect to the biomass concentration and the rate of COD production rate is proportional to the biomass decay rate as the cells release substrates which are then available for anaerobic metabolism. The released COD is treated as an addition to the particulate composite feed material. The composition of the decay products is therefore the same as the composite feed. This presents an issue when applying the ADM1 to other applications, as the feed source composition may be different from that for biomass. However, because of the low biomass yield in anaerobic processes (<5% of the feed COD), the error introduced by assumptions of a similar recycled COD composition is relatively small.

The ADM1 includes inhibition modeling in order to better describe digester response under stressed conditions. There are many forms of inhibition considered by the ADM1. The anaerobic microbial community is sensitive to pH and ammonia and hydrogen concentrations. LCFAs and VFAs can also be inhibitory at elevated concentrations. Nitrogen deficiency in digesters is also considered. The ADM1 incorporates empirical, competitive, and non-competitive forms of inhibition models to account for the effect of these inhibitors. The models decrease the rate of a given anaerobic process by multiplying the rate equation by an inhibition factor, I, where $0 \leq \mathrm{I} \leq 1$.

pH inhibition is modeled based on experimental pH boundaries where either 50% inhibition or complete inhibition occur. These boundaries are unique to each group of microbes in the anaerobic community. Two empirical equations are used which determine the inhibition factor for any given pH:

Empirical Upper and Lower Inhibition:

$$\mathrm{I} = \frac{1 + 2\times 10^{0.5(\mathrm{pH_{LL}} - \mathrm{pH_{UL}})}}{1 + 10^{(\mathrm{pH} - \mathrm{pH_{UL}})} + 10^{(\mathrm{pH_{LL}} - \mathrm{pH})}} \qquad (2)$$

where:

I = Inhibition factor ($0 \leq \mathrm{I} \leq 1$)

pH = digester pH

$\mathrm{pH_{LL}}$ = lower pH limit where the group of organisms is 50% inhibited

$\mathrm{pH_{UL}}$ = upper pH limit where the group of organisms is 50% inhibited

Empirical Lower Inhibition Only:

$$I = \begin{cases} e^{\left[-3\left(\frac{pH - pH_{UL}}{pH_{UL} - pH_{LL}}\right)^2\right]} & \text{if } pH \leq pH_{UL} \\ 1 & \text{if } pH > pH_{UL} \end{cases} \qquad (3)$$

where:

pH_{LL} = lower pH limit where the group of organisms is completely inhibited

pH_{UL} = upper pH limit where the group of organisms is not inhibited

The ADM1 provides both types of pH inhibition functions to give flexibility to the user. The upper and lower equation is useful in strongly buffered systems where upper pH inhibition is more likely to occur, and the lower only equation in low pH systems. An example of the selection of the pH_{LL} and pH_{UL} values for each equation is provided for acetate-utilizing methanogens: For upper and lower inhibition, pH_{LL} of 6.5 and pH_{UL} of 7.5 are where 50% inhibition occurs, and no inhibition occurs at the optimal pH of 7. For lower only, the methanogens will be completely inhibited below the pH_{LL} of 6 and not inhibited above the pH_{UL} of 7.

Hydrogen and free ammonia (NH_3) inhibition are both modeled in the ADM1 using a non-competitive inhibition equation that is based only on the inhibitor concentration and an inhibition constant.

$$I = \frac{1}{1 + \frac{S_I}{K_I}} \qquad (4)$$

where:

S_I = inhibitor concentration, gCOD/L

K_I = inhibition constant, gCOD/L

Hydrogen inhibition is included for fatty acid, propionate, and C_4 compound utilization. The suggested inhibition constants, K_I, vary from 4×10^{-6} - 1×10^{-5} gCOD/L depending on the group of syntrophic hydrogen producing or utilizing organisms. The ADM1 notes that other conditions such as pH, weak acids, and acetate concentration can affect the thermodynamic inhibition level.

Weak acids and bases in their non-ionic form can move freely through cell membranes and cause inhibition (Henderso.Pj 1971). The ADM1 chose to include NH_3 inhibition, but exclude other weak acids and bases. NH_3 ($pK_a = 9.25$) is the main free base in anaerobic digesters, and relevant concentrations can be present in strongly buffered systems. Other weak acids such as HAc, HPr, HBu, and HVa have low pK_a values (4.7-4.9), so the free forms of these acids predominate at low pH. NH_3 inhibition is included only for acetate utilizing organisms in the ADM1, and the suggested K_I is 1.8×10^{-3} M.

The final type of inhibition included in the ADM1 is inorganic nitrogen deficiency, which is modeled as a secondary substrate required for all other substrate uptake. The model is designed to inhibit uptake when $S_{IN} \approx 0$, and follows the form of Equation (4).

The ADM1 task group decided to omit some processes that were not encountered frequently enough to include them in a broadly applicable anaerobic digestion model. These processes include glucose alternative products, sulfate reduction and sulfide inhibition, weak acid and base inhibition, LCFA inhibition, homoacetogenesis, and solids precipitation.

CHAPTER II: ADM1 MODIFICATIONS FOR FOOD WASTE DIGESTION

ADM1 was modified for this food waste digestion application with consideration to model calibration needs and lab results, and the need to provide stable model computation under transient load simulations. The modified ADM1 includes different hydrolysis and endogenous decay equations, simplified pH calculations and inhibition equations, and consideration of the food waste protein composition.

Modeling of the initial disintegration and hydrolysis of biodegradable particulate COD (bpCOD) is critical to describing the behavior of anaerobic digesters. Because of the importance of hydrolysis in anaerobic digestion, a literature review was done on hydrolysis models and a wide range of approaches were found. Previous applications and successes of each model were considered as well as their applicability to food waste hydrolysis in order to select a feasible model that could be calibrated to laboratory data on food waste digestion in this study.

While it is understood that hydrolysis is a complex, multi-step process, a simple first-order model is most commonly used to describe solids hydrolysis in anaerobic digestion (Eastman and Ferguson 1981, Pavlostathis and Gossett 1988, Siegrist et al. 2002, Vavilin et al. 1996). The rate of change of the particulate material is directly proportional to the particulate concentration.

$$\frac{dX_c}{dt} = -kX_c \qquad (5)$$

where:

X_c = concentration of particulate feed (mg/L)

k= first order kinetic rate coefficient (day^{-1})

t = time (day)

The surface area of the feed solids has also been identified as the parameter that controls the particulate hydrolysis rate (Hobson 1987, Mshandete et al. 2006). Sanders et al. (2000) and Palmowski and Mueller (2000) used a first order model to describe surface area dependent hydrolysis.

$$\frac{dX}{dt} = -kA \quad (6)$$

where:

X = mass of particulate feed (mg)

A = particle surface area (m^2)

k= surface based hydrolysis constant (mg/m^2-d)

t = time (day)

A complication of applying this model is that the feed solids must be characterized in terms of the available surface area, which typically requires particle size distribution measurements. The more heterogeneous the feed source, the wider the distribution of particle sizes that are likely present. In addition, the particulate mass, surface area, and particle size distribution are all interrelated, making the relationship even more difficult to characterize.

One common variation on the first order hydrolysis models, which is used in ADM1, is fractionation of the feed solids composition to account for its particulate protein, carbohydrate, lipid, and inert components, and to apply a separate first order coefficient to each (Miron et al. 2000).

$$\frac{dX_{ch}}{dt} = -k_{ch}X_{ch} \quad (7)$$

$$\frac{dX_{pr}}{dt} = -k_{pr}X_{pr} \quad (8)$$

$$\frac{dX_{li}}{dt} = -k_{li}X_{li} \quad (9)$$

where:

X_{pr}, X_{ch}, X_{li} = particulate protein, carbohydrate, and lipid COD concentrations that come from the composite feed material, X_c, with known fractions of proteins, carbs, and lipids

k_{pr}, k_{ch}, k_{li} = first order rate coefficient for proteins, carbohydrates and lipids (gCOD/gX-d)

The hydrolysis rate coefficient values summarized in the parameter review appendix in the ADM1 (Batstone et al. 2002) vary widely from 0.04 – 106 day^{-1}, 0.01 – 2.7 day^{-1}, and 0.01 – 0.4 day^{-1} for k_{ch}, k_{pr}, and k_{li} respectively. This suggests that these values need to be calibrated to the specific feed source and operating conditions in order to more accurately model hydrolysis. Calibration requires tracking the particulate degradable protein, carbohydrate, and lipid substrates during testing, which is a difficult analytical task.

Considering the feed as a combination of readily biodegradable, slowly degradable, and non-degradable components allows more flexibility in calibrating hydrolysis when these components appear to exist (Hobson 1983). Using this approach, Straub (2006) implemented a rapidly and slowly biodegradable dual hydrolysis model within the ADM1 and found this model more suitable for simulating lab-scale and pilot-scale data in dynamic batch operation at elevated solids loadings with wastewater treatment plant primary and secondary waste sludge. The dual hydrolysis model assumes the hydrolysis rates for proteins, carbohydrates, and lipids are the same as they are not distinguished as different fractions in the model. The simple first order dual hydrolysis model is shown as follows:

$$\frac{dX_{rh}}{dt} = -k_{rh}X_{rh} \qquad (10)$$

$$\frac{dX_{sh}}{dt} = -k_{sh}X_{sh} \qquad (11)$$

where:

X_{rh}, X_{sh} = particulate rapidly and slowly hydrolysable COD (gCOD/L), where the feed material, X_c, is composed of some fraction of X_{rh} and X_{sh}.

k_{rh}, k_{sh} = first order rate coefficients for rapidly and slowly degradable particulate components, gCOD/gX-d.

Some models account for the effect of the biomass concentration. A Michaelis-Menten model assumes that in addition to the particulate concentration, the hydrolysis rate is also proportional to the biomass concentration.

$$\frac{dS}{dt} = -kX\left(\frac{S}{K_S + S}\right) \qquad (12)$$

where:

K_s= half saturation constant (mg/L)

S= particulate organic concentration (mg/L)

X = biomass concentration (mg/L)
k = maximum specific hydrolysis rate (mgS/mgX-day)

In a modification of the Michaelis-Menten model, a Contois function based model assumes that the particulate organic to biomass ratio as more important than particulate concentration alone in controlling the particulate hydrolysis rate. Noike (1985) expressed cellulose degradation using this model and calculated biomass concentration by subtracting the insoluble saccharides from the volatile suspended solid concentration.

$$\frac{dS}{dt} = -kX\left(\frac{S/X}{K_c + S/X}\right) \qquad (13)$$

where:
K_c= Contois half saturation constant (mg/L)
S= particulate organic concentration (mg/L)
X = biomass concentration (mg/L)
k = maximum specific hydrolysis rate (mgS/mgX-day)

Vavillin et al. (1996) argued that first order models are less effective than the Contois model at low SRTs.. To calibrate biomass dependent models, the active biomass must be obtained through measurement or estimation based on substrate utilization rates. Estimating the fraction of biomass active in particulate hydrolysis can be a difficulty in using the Michaelis-Menten or Contois models.

The dual hydrolysis model was found to be a simple and most practical approach for describing food waste hydrolysis in the modified ADM1. The data collected during hydrolysis degradation tests exhibited similar behavior to that seen in the work done by Straub (2008), with municipal sludge. There were two relatively distinct particulate degradation characteristics; a fast initial first-order degradation followed by a slower apparent first-order degradation, which is characteristic of the dual hydrolysis model (Figure 2).

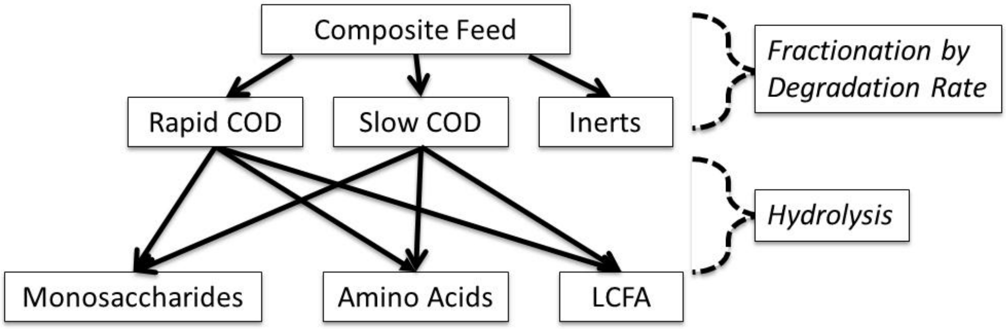


Figure 2. Partitioning and fate of particulate COD in the dual-hydrolysis model in the modified ADM1

For organizational purposes and to maintain the structure of the model, the composite particulate feed variable, X_c, was retained in the dual hydrolysis model. The fractionation or "disintegration" of feed to rapid, slow, and inert components occurs instantly in the model, so that this step has no effect on the hydrolysis rate. X_c can be thought of as a placeholder feed particulate COD input parameter which instantaneously converts to rapid, slow, and inert COD fractions.

The dual hydrolysis model can account for different hydrolysis kinetics for the protein, carbohydrate, and lipid fractions of the feed solids by changing the proportions of these components in the partitioning of the influent COD between the rapid and slowly degraded portions. The overall composition of the composite feed as protein, carbohydrate, and lipid COD cannot be changed, so for a given composite feed composition the following equalities must be maintained:

$$f_{pr,xc} = f_{rh,xc} f_{pr,rh} + f_{sh,xc} f_{pr,sh} \qquad (14)$$

$$f_{ch,xc} = f_{rh,xc} f_{ch,rh} + f_{sh,xc} f_{ch,sh} \qquad (15)$$

$$f_{li,xc} = f_{rh,xc} f_{li,rh} + f_{sh,xc} f_{li,sh} \qquad (16)$$

where:

$f_{pr,xc}$, $f_{ch,xc}$, $f_{li,xc}$ = fraction of protein, carbohydrate, and lipids in the particulate feed COD, X_c

$f_{rh,xc}$, $f_{sh,xc}$ = fraction of rapidly and slowly hydrolysable COD in the particulate feed COD, X_c

$f_{pr,rh}$, $f_{ch,rh}$, $f_{li,rh}$ = fractions of protein, carb, and lipid in rapid hydrolysable COD respectively

$f_{pr,sh}$, $f_{ch,sh}$, $f_{li,sh}$ = fractions of protein, carb, and lipid in slow hydrolysable COD respectively

Because we did not have data that could support changing the relative hydrolysis rates of protein, carbohydrates, and lipids in the food wastes, their composition in the rapidly and slowly hydrolysable feed COD were kept the same. Beyond the hydrolysis step, the remaining biological conversion processes in the model were left unchanged.

Another very significant deviation from the default ADM1 structure was in the determination of the digester H^+ concentration. The default ADM1 combines a charge balance, inorganic carbon balance, and acid-base equilibrium of the carbonate system to calculate $[H^+]$, $[HCO_3^-]$, and $[CO_{2(aq)}]$. A different more straight forward approach was used to determine the digester H^+ concentration and was based on calculating the bicarbonate concentration as a function of the NH_4^+ concentration in the digester. In anaerobic digesters, bicarbonate production is directly proportional to the ammonia production through the deamination of amino acids (Tchobanoglous et al. 2003).

$$NH_3 + H_2O + CO_2 \xrightarrow{\text{yields}} NH_4^+ + HCO_3^- \qquad (17)$$

With a pKa of 9.25, ammonia is almost entirely found as NH_4^+ at relevant digester pH (≈94% as NH_4^+ at pH = 8 and ≈99.4% at pH = 7). The modified ADM1 replaces the inorganic nitrogen term directly with NH_4^+, and solves the bicarbonate concentration by subtracting the molar VFA concentrations from the NH_4^+ concentration. The CO_2 is calculated from the difference of total inorganic carbon and bicarbonate in the system. The acid-base equilibrium between CO_2 and HCO_3^- was then used to determine the pH. The same pH prediction was obtained from simulations using the modified and default ADM1 models. The benefit of this simplification is that it allows the model to converge on solutions under dynamic conditions that caused model failure using the default equations.

Another aspect considered to be very relevant for modeling anaerobic digestion of food waste is the carbon and nitrogen content of the amino acids produced from protein hydrolysis. The nitrogen content of amino acids is critical, as this parameter dictates ammonia production in the ADM1, which in turn controls the bicarbonate concentration and pH in the digester. The carbon content of the amino acids is also important because it affects the inorganic carbon balance, which affects CO_2 content in the biogas. The default ADM1 suggests a value of 0.007 mole N/g COD for N_{aa}, but does not provide the basis for this estimation. The mole N/ g amino acid COD (N_{aa}) and COD is unique for each of the known twenty amino acids. The average nitrogen and carbon contents of the list of amino acids provided in the ADM1 are 0.0094 moles N/g COD and 0.0319 moles C/g COD respectively. In lieu of measurements of the carbon and nitrogen content in food waste fed to anaerobic digestion, the modified ADM1 assumes the average value for nitrogen and carbon contents of the twenty amino acids.

The modified ADM1 for food waste digestion considered how particulate COD released from biomass decay is recycle back to the system. In the default ADM1, particulate cell debris produced from cell decay is treated as an addition to the feed particulate COD with the same protein, carbohydrate, lipid and inert fractions. This approximation may be suitable for digesters fed sludge produced from domestic wastewater treatment, but in the case of food waste the biomass debris composition can be very different from that of the feed material. An additional variable for the products of endogenous decay (X_{ed}) was implemented to act as a separate feed with its separate defined composition description. The X_{ed} production rate is determined in the same way as in the default ADM1, but it is then instantly partitioned based on the composition of the cell to soluble sugars, amino acids, fatty acids, and particulate inerts. This modification does not have a large impact on simulation results, because the biomass yield is <5% of the feed COD, but it more accurately describes the flow of COD in the ADM1 for food waste applications.

The rate of protein, carbohydrate, lipid addition from biomass decay is based on the biomass debris production rate, its relative composition, and conversion factors of cell protein, carbohydrate, and lipids to COD. The majority of the cell is composed of protein on a dry weight basis, but there are some carbohydrates and lipids present, as well as DNA and RNA (

Table 1).

Table 1. Typical cell composition on a dry weight basis (Rittmann and McCarty, 2001)

Component of Cell	% (as dry weight)
Protein	50-60
Carbohydrate	10-15
Lipid	6-8
DNA	3
RNA	15-20

The COD conversion values used for carbohydrates and lipids were determined on glucose and palmitic acid respectively and are 1.07 gCOD/gCarb (Miron et al., 2002) and 2.88 gCOD/gLipid (Eastman and Ferguson 1981). Hattingh et al (1967) noted that the ratio of 6.25 g Pr/g N commonly applied in the literature is not appropriate for anaerobic biomass and instead recommended a ratio of 5.15 g Pr/g N. When this number is combined with the average N_{aa} determined above, a value of 1.47 g COD/ g protein is obtained. Sanders et al (1996) used a similar conversion of 1.5 g COD/ g protein. In order to be consistent with the nitrogen content of amino acids on a COD basis, and because of Hattingh's work specifically addressing the protein content of anaerobic sludge, 1.47 g COD/g protein was used for conversions in the modified ADM1. Assuming an inert fraction of 0.25, the range of dry weight values from

Table 1 and COD conversion values the fractions of protein, carbohydrate, lipid, and inert COD composition of biomass debris from endogenous decay was estimated at 0.55, 0.09, 0.11, and 0.25 respectively.

The modified ADM1 has the ability to quantify the existing digester sludge conditions prior to changing from one feed type to another. The existing sludge will contain unhydrolyzed bpCOD, characterized by preexisting rapidly and slowly degradable COD (X_{rh0} and X_{sh0}), with different characteristics than the new feed. This ability is relevant to the pilot plant digester startup, which involves seeding the digesters with sludge from the USAFA digester fed municipal waste sludge.

The modified ADM1 also includes the ability to account for the digester being fed more than one feed source with different composition and hydrolysis characteristics. Codigestion applications could involve municipal sludge digestion plus food waste or other sources. The model can easily be expanded to include as many feed sources as needed. This study did not use any secondary feed sources, so it was not utilized for our simulations.

The default ADM1 includes various inhibition functions to describe the effect on process rates in the model depending on digester conditions. The modified ADM1 has identified pH inhibition of acetoclastic methanogens to be the most critical of these inhibition functions. Inhibitory effects for these organisms are typically seen when the pH drops below 7. Other organisms do not experience inhibition until lower pH values are seen. The methanogenic populations also play a role in controlling VFA and hydrogen concentrations, making them critical to other metabolic processes and the stability of anaerobic digesters (Eldem et al. 2004).

The default ADM1 handles pH inhibition using a piecewise function which cannot be dynamically solved. The modified ADM1 replaces the piecewise function with a continuous “S-curve” function.

$$I = A + \frac{C}{\left(1 + Te^{-B(pH - M)}\right)^{1/T}} \quad (18)$$

where:

I= inhibition factor ($0 \le I \le 1$)

A = lower asymptote

C = upper asymptote

M = variable controlling the pH corresponding to the upper maximum

B = variable controlling the steepness of the curve

T = variable controlling where maximum inhibition occurs - nearer the lower or upper asymptote.

Optimizing these values to fit the piecewise empirical pH inhibition function at pH below 7.0 for acetoclastic methanogens from the default ADM1 provided a continuous inhibition function with an excellent fit of $R^2 = 0.9996$ (Table 2). The curve in Figure 3 describes the inhibition function that was included in the modified ADM1 as a dynamic variable, which is multiplied by the acetate uptake rate function to determine the effective rate of acetate utilization.

Table 2. S-curve parameters for approximating the ADM1 piecewise low pH inhibition function for acetoclastic methanogens

Variable	Fitted Value
A	0
C	1
T	2.01
B	8.67
M	6.57

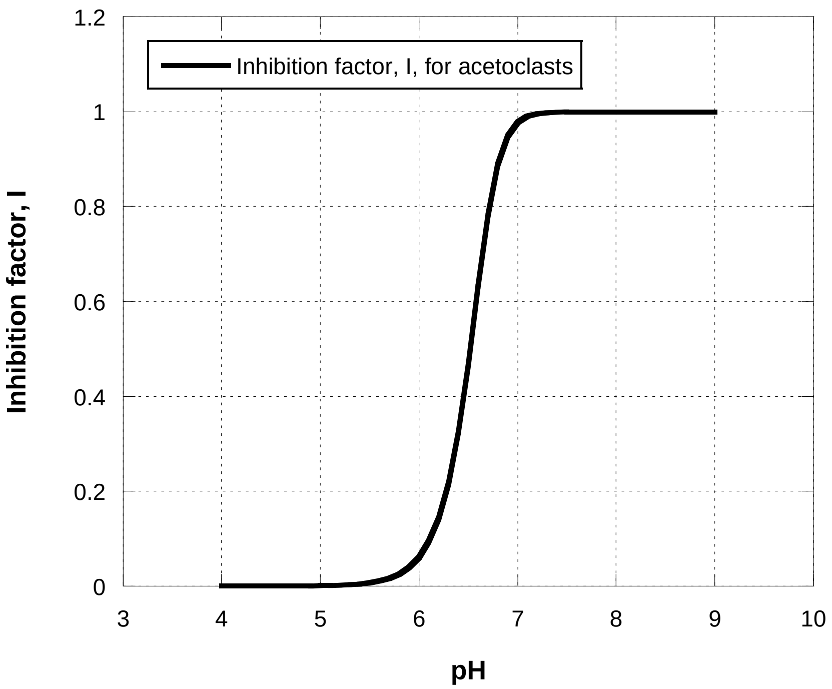


Figure 3. Inhibition factor, I, vs. pH for inhibition of acetoclastic methanogens used in the modified ADM1

The modifications to the default ADM1 were initially made to tailor the model to better describe important food waste characteristics for anaerobic digestion. These were replacing the disintegration/hydrolysis model with a dual hydrolysis model and more careful consideration of the carbon and nitrogen contents of amino acids in food waste. Other changes involving the feed composition include routing the products of endogenous decay through a new variable, X_{ed}, and the addition of preexisting digester bpCOD variables X_{rh0} and X_{sh0}. Changing the mechanism for calculating the $[H^+]$ concentration and making the pH inhibition function continuous were less about addressing food waste digestion, and more about ensuring model stability for transient loading simulations. Petersen matrices including the dual hydrolysis model, preexisting bpCOD variables, and modified endogenous decay model are in Appendix D.

CHAPTER III: MODEL IMPLEMENTATION

This section describes how the modified ADM1 in Mathcad is applied for a single stage continuously stirred tank reactor (CSTR). The same approach will also describe both batch and semi-batch mixed reactors. The general mathematical approach is provided first, followed by an implementation example for a batch reactor.

Mathcad combines equations, text, and graphics in a user friendly interface which can solve complex systems of differential equations. The anaerobic digester liquid phase, gas phase, and acid-base equilibrium equations are implemented as a differential and algebraic equation (DAE) system within Mathcad. Mathcad solves the DAE using an ordinary differential equation (ODE) solver. This solver dynamically detects the most appropriate solving method to be used for the system. The methods that can be applied using the ODE solver are Adams-Bashforth, fixed-step Runge-Kutta, adaptive-step Runge-Kutta, and Radau algorithm.

The mass balance equations for each component of the ADM1 are written as a combination of the advection terms for a CSTR and the sum of the specific kinetic rates for each process that affects said component. The following equation shows the general mass balance for a soluble component but the same equations can be applied to the particulate components in the liquid phase, $X_{liq,i}$.

$$\frac{dS_{liq,i}}{dt} = \frac{qS_{in,i}}{V_{liq}} - \frac{qS_{liq,i}}{V_{liq}} + \sum_{j=1-21} \rho_j \nu_{i,j} \tag{19}$$

where:

$S_{liq,i}$ = soluble component of i in the liquid phase, gCOD/L or mol/L

q = flow rate (assuming $q_{in} = q_{out}$)

$\sum_{j=1-21} \rho_j \nu_{i,j}$ = sum of the specific kinetic rates for process j multiplied by $v_{i,j}$ as defined in Appendix D.

The differential equation for Sva is provided here as an example and can be compared with the Petersen matrices in Appendix D as a guide for writing the remaining differential equations:

$$\frac{dS_{va}}{dt}=\frac{q(t)S_{in,va}}{V_{liq}}-\frac{q(t)S_{va}}{V_{liq}}+\left(1-Y_{aa}\right)f_{va,aa}k_{m,aa}\frac{S_{aa}}{K_{S,aa}+S_{aa}}X_{aa}-k_{m,c4}\frac{S_{va}}{K_{S,c4}+S_{va}}X_{c4}\frac{1}{1+{S_{bu}}/{S_{va}}} \quad (20)$$

where:

$S_{va,(aa,bu)}$ = concentration of total soluble valerate, amino acids, and butyrate respectively in the digester, gCOD/L.

Y_{aa} = yield of biomass on amino acids, $gCOD_X/gCOD_S$

$f_{va,aa}$ = fractional yield of valerate by catabolism of amino acids

$k_{m,aa,(c4)}$ = Monod maximum specific uptake rate for amino acids and C_4 compounds respectively, $gCOD_S/gCOD_X$-d

$K_{S,aa,(c4)}$ = half saturation values for amino acids and C4 compounds respectively, $gCOD_S/L$

The only exception for writing the soluble differential equations is for the soluble components that also exit the reactor in the gas phase as well as in the liquid flow. Liquid/gas transfer rates, $\rho_{T,i}$, must be subtracted from the differential equations for soluble H_2, CH_4, and CO_2 to account for transfer to the gas phase.

The gas phase mass balance equations are similar to the liquid phase equations, but there are no advective inflow terms and the gas transfer rate must be included for each gas.

$$\frac{dS_{gas,i}}{dt}=-\frac{q_{gas}S_{gas,i}}{V_{gas}}+\rho_{T,i}\frac{V_{liq}}{V_{gas}} \quad (21)$$

where

q_{gas} = gas flow rate, L_{gas}/d, more details in Appendix C

$\rho_{T,i}$ = specific gas transfer rate, mol gas/ L-day, more details in Appendix C

The V_{liq}/V_{gas} term is needed because the gas transfer rate is dependent on the liquid volume.

To determine the inorganic carbon states in the ADM1, the following acid-base equilibria equations are included as algebraic constraints in the DAE system:

$$S_{IC}-S_{CO_2}-S_{HCO_3^-}=0 \quad (22)$$

$$S_{HCO_3^-} - \frac{K_{a,CO_2} S_{IC}}{K_{a,CO_2} + S_{H^+}} = 0 \qquad (23)$$

where:

S_{IC} = total soluble inorganic carbon concentration (mol/L)

$K_{a,CO2}$ = acid-base equilibrium coefficient for CO_2/HCO_3^-

S_{H+} = H^+ concentration (mol/L)

All of the liquid phase, gas phase, and acid-base equilibria equations are written in a solve block in Mathcad. A solve block is a defined region of space within Mathcad that lets the ODE solver know which variables it is solving and how they are related to one another. The other key component of a Mathcad solve block is some form of boundary conditions. The boundary conditions used for the implementation of ADM1 are the values when time = 0 (initial conditions). These values (gCOD/L or mol/L) have a very significant impact on the model results, particularly over small time intervals, making their determination critical for accurate simulations. For instance, the initial reactor biomass concentrations are necessary to determine if substrates will increase with time in the digester following feeding. Because ADM1 uses Michaelis-Menten kinetics, the initial conditions for the soluble components are also important in determining the initial substrate uptake rates. As was the case for the lab scale digesters used in this study, food waste digesters or codigesters are often seeded with sludge from a preexisting anaerobic digester. Ideally, if sufficient operating and performance data is available for the seed digester, it can be modeled with ADM1 to provide a best estimate of the initial conditions to use in the solve block. The initial conditions of the seed digester may be largely unknown in some cases. When this is the case, estimates can be made by using conditions from known digesters with similar characteristics.

Once the solve block is setup, the ODE solver, Odesolve, is called for some user defined time interval and number of steps, where the step size is equal to the time interval divided by the number of steps. Mathcad then solves each dynamic variable in the DAE system, and uses a spline function to interpolate between each point to achieve a continuous result over the time interval. The step size therefore needs to be sufficiently small to capture variation over short time periods. After solving the DAE system, the user can make any desired calculations using the results. The calculations can be setup in advance, referencing the solver solutions as newly defined variables, or be made as needed after the solver has been run.

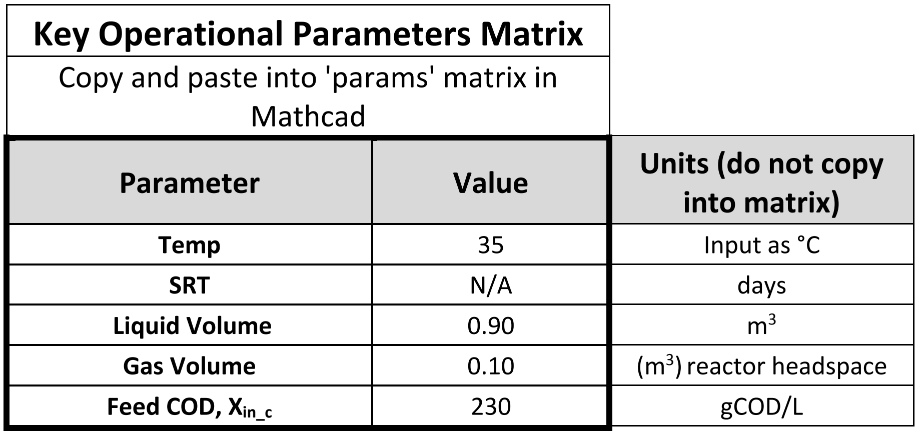
The ADM1 solution is dependent on the inputs provided by the user. Some of these inputs include kinetic rate coefficients, flowrate, COD concentration, feed composition, inhibition constants, temperature, reactor initial conditions, and reactor volume. The more accurately the user defines the system with these inputs, the more useful the model outputs will be. Because of the vast number of inputs required by ADM1, organization and ease of modification are both important for modeling under various operating conditions.

In order to make the ADM1 as user friendly as possible within Mathcad, the input values for every aspect of the model are defined in Microsoft Excel tables (Table 3 - Table 10). Mathcad is compatible with Excel, in that the user may copy Excel tables into Mathcad sheets, and vice versa. In the Mathcad ADM1 file, all of the input variables are defined by referencing Excel compatible tables. When the user wants to make changes to any inputs, they only need to make the changes to the values in Excel, and copy the corresponding tables to the inputs section of the Mathcad file. By saving the Excel inputs file for any defined input conditions, the user can easily recreate those conditions in Mathcad simply by copying the tables back into their model file. This compatibility is very useful because anyone with access to the Excel inputs file template can define a set of conditions to be modeled. Example input tables are provided in conjunction with a simulation example of a single batch feeding to a laboratory scale anaerobic reactor. The reactor is fed food waste with a known composition and COD concentration. The reactor is batch fed over a one hour period with an amount that corresponds to an average daily loading rate of 12gCOD/L-d for the week. The user is interested in the response of the reactor for the first 24 hours following the feeding.

Each of the following input tables are copied into Mathcad from their corresponding Excel table:

The Key Operational Parameters Table defines the temperature, SRT, working and gas volumes, and feed COD concentration (Table 3). The only operational parameter not included in this table is the flow rate, q, because it must be uniquely defined for the given feeding strategy of the simulation.

Table 3. Key Operational Parameters Table as defined in Excel for the batch feed example



Key Operational Parameters Matrix

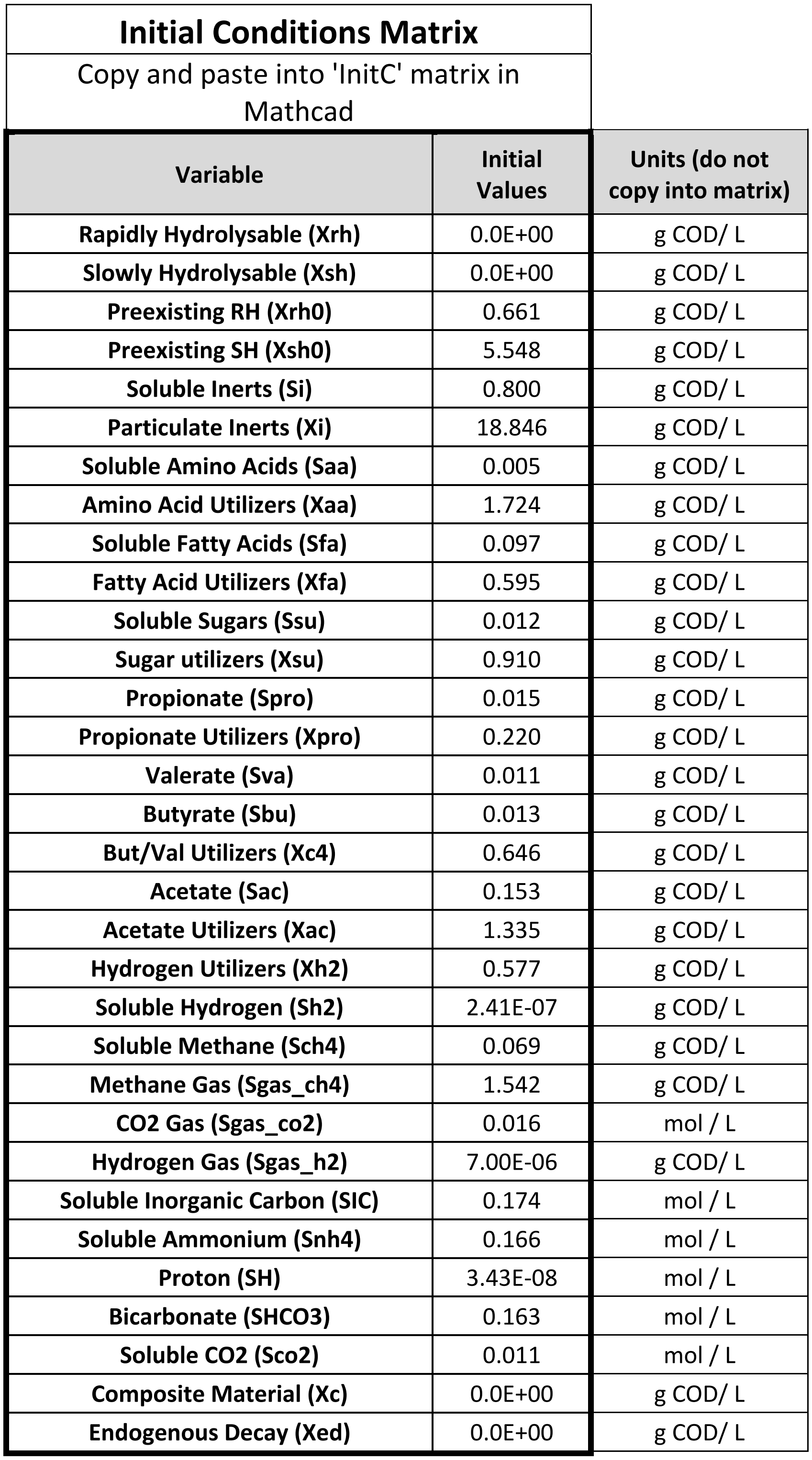
Copy and paste into 'params' matrix in Mathcad

Parameter	Value	Units (do not copy into matrix)
Temp	35	Input as °C
SRT	N/A	days
Liquid Volume	0.90	m^3
Gas Volume	0.10	(m^3) reactor headspace
Feed COD, X_{in_c}	230	gCOD/L

Mesophilic conditions at 35^0C are assumed for this example. The SRT is not relevant for this 24 hour batch test, so it will not be used in the determination of the feed volume. The reactor volume is 1 m^3 (0.9 m^3 liquid working volume, and 0.1 m^3 of gas volume). The feed concentration was determined in preliminary lab tests for the food waste to be 230 g COD/L. The bold outlined section of Table 3, and the remaining input tables denotes what is to be copied into Mathcad. The ADM1 Mathcad file has variable definitions already written that reference these tables. Once the tables have all been copied into the program the variables will all be defined within Mathcad.

The Initial Conditions Table defines the boundary conditions at time = 0 to be used in the ODE solve block (Table 4).

Table 4. Initial Conditions Table as defined in Excel for the batch feed example



Initial Conditions Matrix

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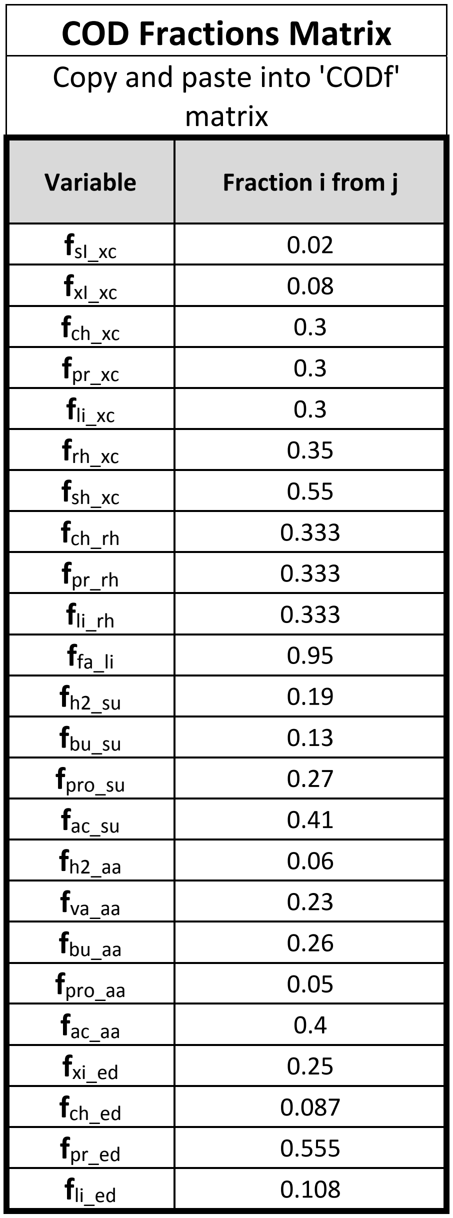
Variable	Initial Values	Units (do not copy into matrix)
Rapidly Hydrolysable (Xrh)	0.0E+00	g COD/ L
Slowly Hydrolysable (Xsh)	0.0E+00	g COD/ L
Preexisting RH (Xrh0)	0.661	g COD/ L
Preexisting SH (Xsh0)	5.548	g COD/ L
Soluble Inerts (Si)	0.800	g COD/ L
Particulate Inerts (Xi)	18.846	g COD/ L
Soluble Amino Acids (Saa)	0.005	g COD/ L
Amino Acid Utilizers (Xaa)	1.724	g COD/ L
Soluble Fatty Acids (Sfa)	0.097	g COD/ L
Fatty Acid Utilizers (Xfa)	0.595	g COD/ L
Soluble Sugars (Ssu)	0.012	g COD/ L
Sugar utilizers (Xsu)	0.910	g COD/ L
Propionate (Spro)	0.015	g COD/ L
Propionate Utilizers (Xpro)	0.220	g COD/ L
Valerate (Sva)	0.011	g COD/ L
Butyrate (Sbu)	0.013	g COD/ L
But/Val Utilizers (Xc4)	0.646	g COD/ L
Acetate (Sac)	0.153	g COD/ L
Acetate Utilizers (Xac)	1.335	g COD/ L
Hydrogen Utilizers (Xh2)	0.577	g COD/ L
Soluble Hydrogen (Sh2)	2.41E-07	g COD/ L
Soluble Methane (Sch4)	0.069	g COD/ L
Methane Gas (Sgas_ch4)	1.542	g COD/ L
CO2 Gas (Sgas_co2)	0.016	mol / L
Hydrogen Gas (Sgas_h2)	7.00E-06	g COD/ L
Soluble Inorganic Carbon (SIC)	0.174	mol / L
Soluble Ammonium (Snh4)	0.166	mol / L
Proton (SH)	3.43E-08	mol / L
Bicarbonate (SHCO3)	0.163	mol / L
Soluble CO2 (Sco2)	0.011	mol / L
Composite Material (Xc)	0.0E+00	g COD/ L
Endogenous Decay (Xed)	0.0E+00	g COD/ L

The initial conditions were determined by running a simulation of the seed anaerobic digester until steady state was achieved. These values are read into the solve block to act as the boundary conditions needed for the ODE solver.

The COD Fractions Table defines the fraction of COD that is produced from a given substrate, $f_{product,substrate}$ (Table 5). This table also defines the composition of the feed material (the fraction of COD as rapidly hydrolysable, slowly hydrolysable, and inert from the composite feed material).

Table 5. COD Fractions Table as defined in Excel for the batch feed example



COD Fractions Matrix

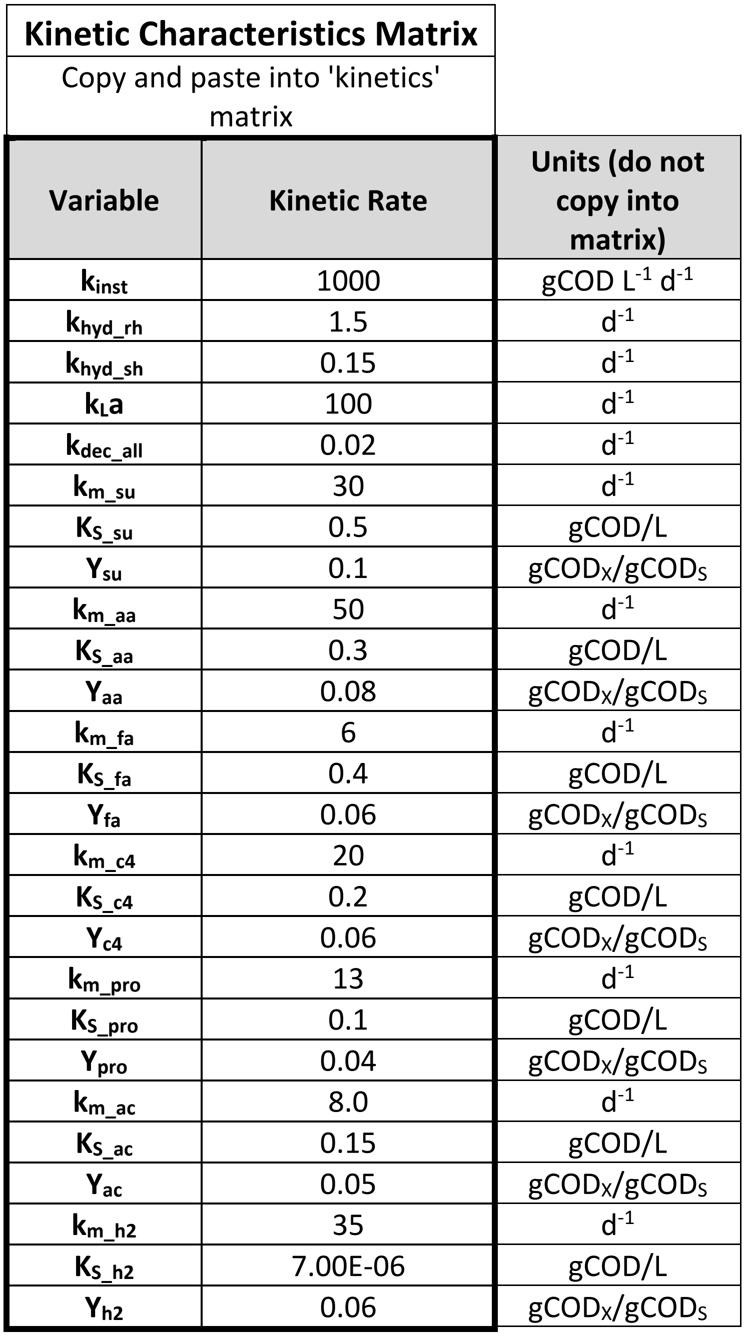
Copy and paste into 'CODf' matrix

Variable	**Fraction i from j**
f_{sI_xc}	0.02
f_{xI_xc}	0.08
f_{ch_xc}	0.3
f_{pr_xc}	0.3
f_{li_xc}	0.3
f_{rh_xc}	0.35
f_{sh_xc}	0.55
f_{ch_rh}	0.333
f_{pr_rh}	0.333
f_{li_rh}	0.333
f_{fa_li}	0.95
f_{h2_su}	0.19
f_{bu_su}	0.13
f_{pro_su}	0.27
f_{ac_su}	0.41
f_{h2_aa}	0.06
f_{va_aa}	0.23
f_{bu_aa}	0.26
f_{pro_aa}	0.05
f_{ac_aa}	0.4
f_{xi_ed}	0.25
f_{ch_ed}	0.087
f_{pr_ed}	0.555
f_{li_ed}	0.108

The first ten rows of the COD fractions table need to be defined by the user to best represent the digester feed COD. For this example, the composite material is composed of 10% inerts (2% soluble and 8% particulate) and 30% each carbohydrates, proteins, and lipids as COD. Batch hydrolysis experiments were performed to determine that this particular feed can be considered 35% rapidly hydrolysable, 55% slowly hydrolysable and 10% inert. The fraction of carbohydrates, lipids, and proteins in the slowly hydrolysable COD are calculated from the overall fractions in the composite feed, X_c, and the fractions in the rapid COD using equations 14, 15, and 16. These balances ensures that the overall amount of carbohydrate, lipid, and protein COD fed to the digester is conserved. In this example, as well as other model simulations, the fractions of carbohydrates, lipids, and proteins in the rapidly hydrolysable portion of the feed are the same as in the composite feed excluding the inert fraction. The calculations for the corresponding fractions in the slow COD will therefore be equal to the rapid fractions.

The Kinetic Characteristics Table defines the various first order kinetic rates such as the rapid hydrolysis rate and Monod maximum specific uptake rates, as well as the half saturation values and yields needed to determine the overall kinetic rate equations for substrate uptake (Table 6).

Table 6. Kinetic Characteristics Table as defined in Excel for the batch feed example



Kinetic Characteristics Matrix

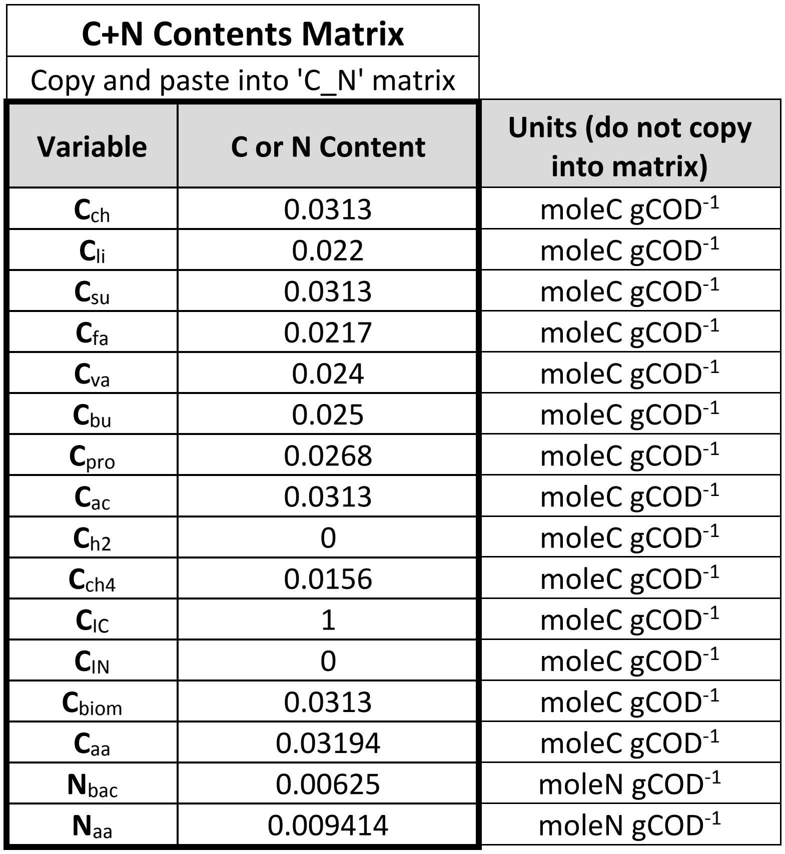
Copy and paste into 'kinetics' matrix

Variable	Kinetic Rate	Units (do not copy into matrix)
k_{inst}	1000	gCOD L^{-1} d^{-1}
k_{hyd_rh}	1.5	d^{-1}
k_{hyd_sh}	0.15	d^{-1}
k_La	100	d^{-1}
k_{dec_all}	0.02	d^{-1}
k_{m_su}	30	d^{-1}
K_{S_su}	0.5	gCOD/L
Y_{su}	0.1	$gCOD_X/gCOD_S$
k_{m_aa}	50	d^{-1}
K_{S_aa}	0.3	gCOD/L
Y_{aa}	0.08	$gCOD_X/gCOD_S$
k_{m_fa}	6	d^{-1}
K_{S_fa}	0.4	gCOD/L
Y_{fa}	0.06	$gCOD_X/gCOD_S$
k_{m_c4}	20	d^{-1}
K_{S_c4}	0.2	gCOD/L
Y_{c4}	0.06	$gCOD_X/gCOD_S$
k_{m_pro}	13	d^{-1}
K_{S_pro}	0.1	gCOD/L
Y_{pro}	0.04	$gCOD_X/gCOD_S$
k_{m_ac}	8.0	d^{-1}
K_{S_ac}	0.15	gCOD/L
Y_{ac}	0.05	$gCOD_X/gCOD_S$
k_{m_h2}	35	d^{-1}
K_{S_h2}	7.00E-06	gCOD/L
Y_{h2}	0.06	$gCOD_X/gCOD_S$

Like the COD fractions matrix, the kinetic rates matrix is also a combination of user defined and ADM1 default values. k_{inst} operationally transfers the influent composite feed material into rapid, slow, and inert fractions as well as the products of endogenous decay into soluble sugars, amino acids, and fatty acids. As long as this rate is set to a value much higher that all of the other kinetic rates, it can be assumed the transfer occurs instantly in the model. The values of X_c and X_{ed} are therefore always zero in the model. The k_{hyd_rh} and k_{hyd_sh} values are determined experimentally from the same tests used to determine the fractions of rapid and slowly hydrolysable COD in the composite material. The k_La, in this example, assumed to be 100 d^{-1}, also has to be estimated by the user.

The Carbon and Nitrogen Contents Table defines the carbon and nitrogen contents as moleC/gCOD or moleN/gCOD of each component in the model (Table 7).

Table 7. Carbon and Nitrogen Contents Table as defined in Excel for the batch feed example



C+N Contents Matrix

Copy and paste into 'C_N' matrix

Variable	C or N Content	Units (do not copy into matrix)
C_{ch}	0.0313	moleC $gCOD^{-1}$
C_{li}	0.022	moleC $gCOD^{-1}$
C_{su}	0.0313	moleC $gCOD^{-1}$
C_{fa}	0.0217	moleC $gCOD^{-1}$
C_{va}	0.024	moleC $gCOD^{-1}$
C_{bu}	0.025	moleC $gCOD^{-1}$
C_{pro}	0.0268	moleC $gCOD^{-1}$
C_{ac}	0.0313	moleC $gCOD^{-1}$
C_{h2}	0	moleC $gCOD^{-1}$
C_{ch4}	0.0156	moleC $gCOD^{-1}$
C_{IC}	1	moleC $gCOD^{-1}$
C_{IN}	0	moleC $gCOD^{-1}$
C_{biom}	0.0313	moleC $gCOD^{-1}$
C_{aa}	0.03194	moleC $gCOD^{-1}$
N_{bac}	0.00625	moleN $gCOD^{-1}$
N_{aa}	0.009414	moleN $gCOD^{-1}$

The carbon and nitrogen contents of most components are straightforward, and taken as default values provided by the ADM1. The values for amino acids are more difficult to determine, as discussed in the modified ADM1 description. For this example, the average carbon and nitrogen content for amino acids as mole/gCOD were used.

The Acid Base Equilibria Table defines the pK and temperature adjustment θ values for relevant acid-base pairs found in digesters (Table 8). The following temperature adjustment equation is used for equilibrium and Henrys constants:

$$K_2 = K_1 e^{\theta(T_2 - T_1)} \tag{24}$$

where:

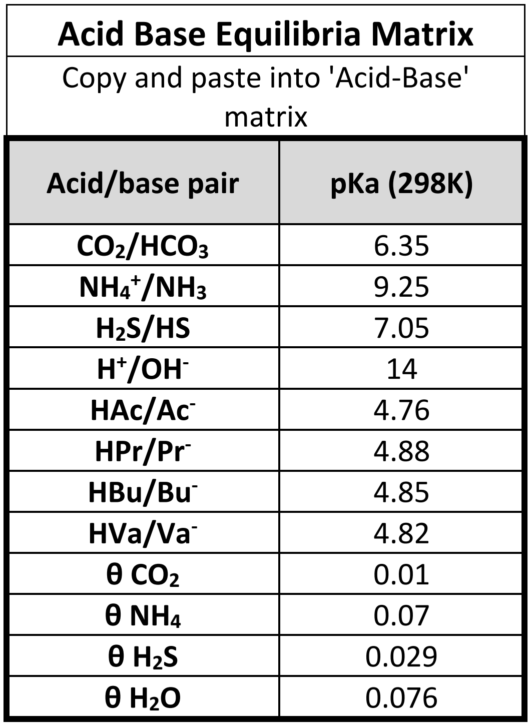
K_1 = equilibrium or Henrys constant at T_1

K_2 = equilibrium or Henrys constant at T_2

T_1 = temperature at which K_1 is defined, Kelvin

T_2 = temperature at which K_2 is to be defined, Kelvin

Table 8. Acid Base Equilibria Table as defined in Excel for the batch feed example



Acid Base Equilibria Matrix

Copy and paste into 'Acid-Base' matrix

Acid/base pair	pKa (298K)
CO_2/HCO_3	6.35
NH_4^+/NH_3	9.25
H_2S/HS	7.05
H^+/OH^-	14
HAc/Ac^-	4.76
HPr/Pr^-	4.88
HBu/Bu^-	4.85
HVa/Va^-	4.82
θ CO_2	0.01
θ NH_4	0.07
θ H_2S	0.029
θ H_2O	0.076

The Henry’s Constants Table defines the Henry’s gas constants (bar M^{-1}) and θ values for CO_2, CH_4, and H_2 gases (Table 9).

Table 9. Henrys Constants Table as defined in Excel for the batch feed example

Henrys Constants Matrix Copy and paste into 'Henry' matrix		
Variable	**Value**	**Units (do not copy into matrix)**
K_{H_CO2}	0.035	mol bar^{-1} L^{-1} (at 298)
K_{H_CH4}	0.0014	mol bar^{-1} L^{-1} (at 298)
K_{H_H2}	0.00078	mol bar^{-1} L^{-1} (at 298)
θ_{KH_CO2}	-0.02629	
θ_{KH_CH4}	-0.01929	
θ_{KH_H2}	-0.00566	

The Henrys constants and acid-base equilibria information is unlikely to be changed from the default values. The main reason they have been included instead of just defining them directly within Mathcad is for consistency.

The Seed Digester Table defines the composition and kinetic characteristics of the preexisting bpCOD in the digester prior to a change in feed type (Table 10).

Table 10. Seed Digester Table as defined in Excel for the batch feed example

Seed Digester Matrix Copy and paste into 'digester' matrix		
Variable	**Value**	**Units (do not copy into matrix)**
k_{hyd_rh0}	2.2	d^{-1}
k_{hyd_sh0}	0.25	d^{-1}
f_{rh_xc0}	0.37	
f_{sh_xc0}	0.39	
f_{sI_xc0}	0.01	
f_{xI_xc0}	0.23	
f_{ch_rh0}	0.26	
f_{pr_rh0}	0.53	
f_{li_rh0}	0.21	

The seed digester information is necessary to differentiate the composition of what is in the digester initially, before a feed with some other composition is introduced. The variables all have the same names as those in the other tables, but are denoted with a ‘naught’ subscript, 0. The seed digester information should always be the same as the values used to simulate the initial conditions of the current simulation. In this case, these values would be plugged into the kinetic rate and COD fraction tables during the preceding steady state simulation. When the new simulation is run, the hydrolysis of X_{rh0} and X_{sh0} will proceed based on the kinetics and composition in the seed digester matrix, instead of using the kinetics and composition of the new feed material.

Defining Operational Characteristics

After the model inputs are provided the final consideration for running the model is to define the feeding strategy of the digester. The flow rate, q, must be defined in the model to correspond to the feeding strategy of the digester. For a continuously fed digester, q can be defined as V_{liq}/SRT. If the digester is batch fed, like our implementation example, then q is equal to the volume of feed COD that must be given to the digester to achieve some desired nominal loading rate (gCOD/L-d). In this example the feed concentration is 230 gCOD/L, and we want to achieve a 12 gCOD/L/day loading rate for our 0.9 m^3 working volume. This means 47 L of food waste will be fed to achieve the equivalent loading rate. As stated in the simulation description, our interval of interest is 1 day. This means q must be defined as function of time over a 1 day period. If the batch feeding were to take place over 1 hour, we can say that q(t) = 0.047 m^3/hr for the first hour, and 0 L/hr for the next 23 hours. Therefore, a composite function for q(t) is written in Mathcad to simulate the batch feeding.

$$q(t) = \begin{cases} 0.047, & 0 \le t < 1 \\ 0, & \text{Otherwise} \end{cases} \tag{25}$$

Once q is defined, the Mathcad function Odesolve can be called to solve the system:

$$[\text{solutions}] = \text{Odesolve}([\text{vector}], x, b, [\text{intvls}]) \tag{26}$$

where:

[solutions] = vector of solutions for all the function names in [vector]

[vector] = vector of function names for the system of differential equations
x = name of the variable of integration. In the ADM1 this is time, t
b = terminal point of the integration interval
[intvls] (Optional) = integer number of discretization intervals used to interpolate the solution function. The number of solution points is the number of intvls + 1. The default value of intvls is 1000.

The terminal point of the integration interval in this example is 24 hours. The default value of 1000 was used for [intvls]. If the user is interested in a series of batch feeds, the values at the end of the integration interval for the first batch feed simulation are input as the initial conditions of a new simulation for the second feeding. The second simulation can redefine q(t) and the terminal point of the integration interval to describe the new batch feed, and this process can be repeated for any number of feeds.

Outputs

The results from a single simulation using the ADM1 are vast, so the user must decide what information they are trying to get, and how best to organize and utilize this information. By default, running the Odesolve function in Mathcad will not output any information to the user. It is up to the user to query Mathcad for the desired information.

One can divide the outputs from a simulation into two types of results: primary and secondary. The primary results are the values for every dynamic variable contained in the solve block at every instant in the chosen time interval. Secondary information is anything calculated from the primary data, and often times are the most useful simulation outputs. If the user is interested in the total VFA concentration in mg/L, it is more beneficial to predefine a variable for total VFA concentration that is calculated from the primary data (S_{ac}, S_{pro}, S_{bu}, and S_{va}), than to calculate it separately after each simulation.

After the DAE has been solved, Mathcad can be queried for the value of any variable (primary or secondary) at some specific time of interest, or as a table containing many points in time. The user can define output tables containing the information they deem valuable to a simulation. In Mathcad, equations defining secondary variables in terms of the solve block (primary) variables can be written into the file before the simulation has been run. These secondary variables can be presented as graphs or tables, just as the primary results.

Once the user knows what kind of information they want as outputs, they have to format how the information will be displayed by Mathcad. The compatibility between Mathcad and Excel is useful for organizing the results from simulations. For this example, we will assume the user is interested in how the acetate concentration changes in the digester over the one day interval. The user can define a variable for acetate concentration in mg/L, (Ac_{mg_L}), which can be calculated from the primary acetate concentration as gCOD/L. A matrix can then be defined that gives the acetate concentration every fifteen minutes for the 24 hour interval. The first column is the time in hours and the second column is the acetate concentration in mg/L. The following equations in Mathcad will create the table of acetate concentrations.

$$i := 0..24 \times 4 \tag{27}$$

$$Acetate\_Table_{i,1} := \frac{i}{4} \tag{28}$$

$$Acetate\_Table_{i,2} := Ac_{mg\_L}\left(\frac{i}{4}\right) \tag{29}$$

where:
i = range variable of integers from 0 to 24×4, where 24 is the number of hours and 4 is the number of intervals per hour that will be defined in the table (every 15 minutes).
$Acetate\_Table_{i,1}$ = the time value at each interval (i/4) assigned to the ith row of the 1st column. This is simply a vector from 0 to 24 by intervals of 0.25 in the first column of Acetate_Table.
$Acetate\_Table_{i,2}$ = the acetate concentration in mg/L at each interval (i/4) assigned to the ith row of the 2nd column.

This matrix, and any defined in this fashion can be copied directly out of Mathcad and into Excel. The outputs from an ADM1 Mathcad simulation are completely customizable and up to the user. Predesigning output tables for Excel can maximize the value of model simulations by getting the exact information the user needs as quickly and efficiently as possible.

CHAPTER IV: MODEL CALIBRATION

Hydrolysis is the rate limiting step in the conversion of particulate material to methane in anaerobic digestion (Eastman and Ferguson 1981, Pavlostathis and Gossett 1988, Vavilin et al. 1996),in that it initiates the conversion of COD to methane, and under stable digester operating conditions the concentration of degradable particulate COD is higher than the soluble degradable COD and VFA COD. It is therefore a critical step in the prediction of solids destruction and methane production by anaerobic digestion simulation models. Laboratory tests were carried out to provide kinetic information of food wastes hydrolysis for the ADM1 application to food waste digestion.

Five laboratory scale anaerobic digesters maintained in the CDM laboratory and four batch bottle tests were used to estimate the hydrolysis kinetics of selected food waste samples from the USAFA. A number of food waste samples from the USAFA were collected and characterized in terms of Volatile Solids/Total Solids (VS/TS) ratios and protein, carbohydrate, and lipid fractions. Two of these with the greatest differences in protein, carbohydrate, and lipid composition were selected for experimental use (Table 11). The food waste analyses did not determine the inert portion of the COD. Comparison between ultimate degradability studies by Newton (1999) of municipal sludge and laboratory scale food waste digesters was used to estimate the inert fraction of food waste. For 62 day degradability tests of primary and waste activated sludges from South Wastewater Treatment Plant (WWTP) in Renton, WA, Newton found 87% and 61% ultimate degradability respectively. Conversely, 70-90% COD conversion of food waste batch feedings was typical over 2-3 day intervals, suggesting the food wastes were highly degradable. An initial estimate of 10% inert COD in the food waste was made based on the laboratory digester data, but preliminary model fitting and simulations proved this assumption was too high. An inert assumption of 6% provided the best fitting of VS destruction, methane production, %CH_4, ammonia, and alkalinity.

Table 11. Properties of USAFA food wastes used in laboratory digesters and batch bottle tests for hydrolysis kinetics

Waste Name	Composition (% of COD)				VS/TS
	Protein	Carbohydrate	Lipid	Inert	
FW-004	17	51	26	6	0.94
FW-011	24	17	53	6	0.94
FW-MIX	20	35	39	6	0.94

Long-term laboratory anaerobic reactors and shorter term anaerobic reactors used for batch experiments were maintained with one of the three feeds described in Table 11, with and without 10% FOG (fats, oil and grease) as COD, and operated at different average COD loading rates between 4 and 10 g COD/L-d (Table 12). The reactors were 2.0 L bottles with a 0.5 L working volume. The working volume was kept at 0.5 L by withdrawing a volume equal to the following feed volume. The reactors were inoculated with anaerobic digester sludge from South Wastewater Treatment Plant (WWTP) (Renton, WA) and maintained at 37°C. The reactors were batch fed equal volumes three times a week (M, W, and F) with food waste at a constant concentration of 230 g COD/L. The average daily COD loading rate was set by the volume of food waste fed. The long term reactors were operated for 45-55 days and the batch test reactors were fed food waste for 26 days at 4gCOD/L-d, followed by a single batch test feeding at 12.0 gCOD/L. The 4gCOD/L-d loading rate during the 26 day acclimation period of the batch test reactors corresponded to average daily feed volumes that were 1.7% of the working volume (equivalent to a 57.5 day SRT).

Table 12. Laboratory experimental conditions for long-term digesters operation and batch bottle tests (T = 37°C, V = 0.5 L, Inoculated with anaerobic digester sludge from King County South WWTP at Renton, WA)

Reactor Name	Feed	Loading Rate (gCOD/L-d)	Average SRT (d)	Duration of Reactor Operation (d)
Longterm-1	FW-MIX	4	58	45
Longterm-2	FW-MIX	Ramped 4 - 10*	41	44
Longterm-3	FW-MIX + 10% FOG	4	58	47
Longterm-4	FW-MIX + 10% FOG	Ramped 4 - 10*	41	45
Longterm-5	FW-MIX	10	24	55
Batch-1	FW-004	-	-	31
Batch-2	FW-004 + 10% FOG	-	-	31
Batch-3	FW-011	-	-	31
Batch-4	FW-011 + 10% FOG	-	-	31

* Ramping occurred steadily throughout the entire duration of reactor operation

The parameters used to monitor and observe the performance of the laboratory anaerobic reactors are summarized in Table 13. These performance parameters provide the necessary data for model calibration and verification. The methane gas, VFA production, and soluble COD (sCOD) are the primary data used to evaluate hydrolysis kinetics, as they can be used to estimate the change in biodegradable particulate COD (bpCOD) in the reactors. The batch reactors were sampled more frequently in order to better describe the digester response immediately following feedings.

Table 13. Data collection parameters, sample frequency, and analytical methods for anaerobic digesters used for hydrolysis kinetics evaluation

Analyte	Collection Frequency		Method
	Long term	Batch	
Methane gas	continuous	continuous	Respirometry
VFAs	3/week	10 over 56hrs	GC-FID
pH	3/week	10 over 56hrs	pH probe
Alkalinity	~1/week	2 over 56hrs	Titration
Ammonia	-	10 over 56hrs	Colorimetric
%VS, %TS	~1/week	2 over 56hrs	Gravimetric
sCOD	-	10 over 56hrs	Colorimetric

The respirometry system from Columbus Instruments provided biogas accumulation, production rate, and concentration data continuously during testing. Gas was collected in a glass sample collection bottle. Nitrogen was used to circulate the sample gas through sensors to determine gas concentration, temperature, and pressure. Micro-Oxymax software calculated biogas volume, composition, and production rate.

Acetate, propionate, butyrate, iso-butyrate, valerate, and iso-valerate concentrations were measured in reactor samples following Method 5560D (APHA, 2005). The VFA samples were obtained by centrifugation and 0.45µm syringe filtration of 0.5 mL of centrate sample volume. A drop of 5.65 N sulphuric acid was added to each sample in a GC vial to fully protonate the acids. Analysis was performed using a Shimadzu gas chromatograph with flame ionization detection (GC-FID).

The objective was to use the long term and batch reactor data in conjunction with a hydrolysis model that could accurately describe solubilization of bpCOD in order to quantify the hydrolysis kinetics of the USAFA food waste. The first order, dual-hydrolysis model described above was deemed appropriate because of the two distinct regions found in methane production vs. time curves for both long term and batch reactors (Example in Figure 4).

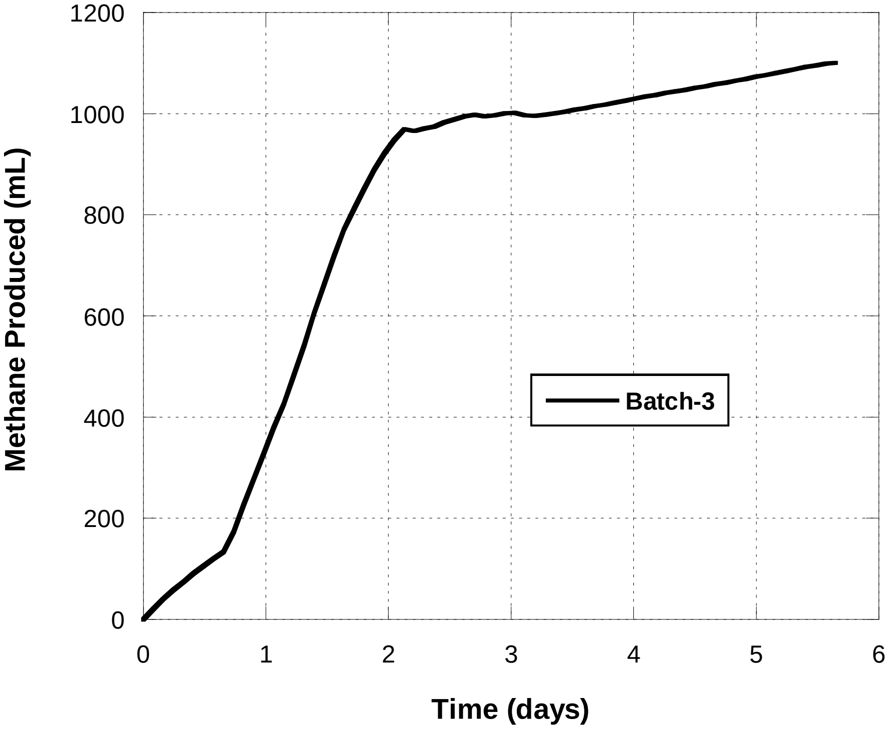


Figure 4. Cumulative methane production (adjusted to standard conditions) vs. time in batch test with Batch-3 reactor at 37^{0}C showing an initial rapid and final slower methane production rate

The dual hydrolysis model considers the reactor bpCOD to have both rapidly and slowly degrading fractions as described in Equations (10) and (11). The solubilization of each of these components is described independently using first order kinetics. By fitting this model to experimentally derived bpCOD data, the kinetic rate coefficients could be determined. The bpCOD remaining in the reactor as a function of time, hydrolysis rate coefficients, and fractions of rapid and slow bpCOD is:

$$X_c(t) = X_{c0}\left[f_{rh,xc}e^{(-k_{rh}t)} + f_{sh,xc}e^{(-k_{sh}t)}\right] \qquad (30)$$

where:

$X_c(t)$ = concentration of bpCOD at any time, t (gCOD/L)

t = time (days)

The process for determining the rapid and slow kinetic rate coefficients began with analysis of the batch reactor data. In order to calibrate the dual-hydrolysis model to food waste, experimental bpCOD concentration vs. time curves had to be synthesized from the available data. For the batch tests, the amount of bpCOD hydrolyzed in a given interval was determined by the sum of accumulative methane and VFA production as COD minus the non-VFA sCOD (nvsCOD). The nvsCOD is calculated by subtracting the VFA concentration as COD from the total sCOD concentration. If the VFA and sCOD concentrations were to remain constant during the test, the hydrolysis of bpCOD would simply be calculated using methane production, but because the hydrolysis products change during the test they were accounted for in the calculation.

$$\Delta \mathrm{bpCOD_{hyd}} = \left(\mathrm{CH_{4_{COD,t2}}} - \mathrm{CH_{4_{COD,t1}}}\right) + \left(\mathrm{VFA_{COD,t2}} - \mathrm{VFA_{COD,t1}}\right) + \left(\mathrm{nvsCOD_{t2}} - \mathrm{nvsCOD_{t1}}\right) \quad (31)$$

where:

$\Delta \mathrm{bpCOD_{hyd}}$ = amount of bpCOD hydrolyzed between t_1 and t_2, gCOD

$\mathrm{CH4_{COD}}$ = methane COD, gCOD

$\mathrm{VFA_{COD}}$ = VFA COD, gCOD

nvsCOD = non-VFA soluble COD, gCOD

The hydrolyzed bpCOD is subtracted from the initial bpCOD concentration in the reactor just after feeding to determine the reactor bpCOD concentration. The initial bpCOD concentration was estimated by the g bpCOD fed divided by the batch reactor volume. Preexisting bpCOD concentration in the reactors prior to feeding was unknown and was not included in the calculation. The effect of this simplification is discussed below. The fractions of rapid and slow bpCOD were also needed to calibrate the dual-hydrolysis model. These were estimated using the experimental bpCOD concentration vs. time curves for the batch tests (Figure 5). An exponential trend line was created using the slowly hydrolyzing portion of the bpCOD concentration curve. A significant fraction (0.96) of the rapid bpCOD had been hydrolyzed 45 hours after feeding, so the trend line was generated from the data after 45 hours had elapsed. The value for this trend line at time equal to zero was used to estimate the amount of slow bpCOD. The fraction of slow bpCOD was determined by dividing this value by the bpCOD fed, and the rapid bpCOD fraction was determined by difference.

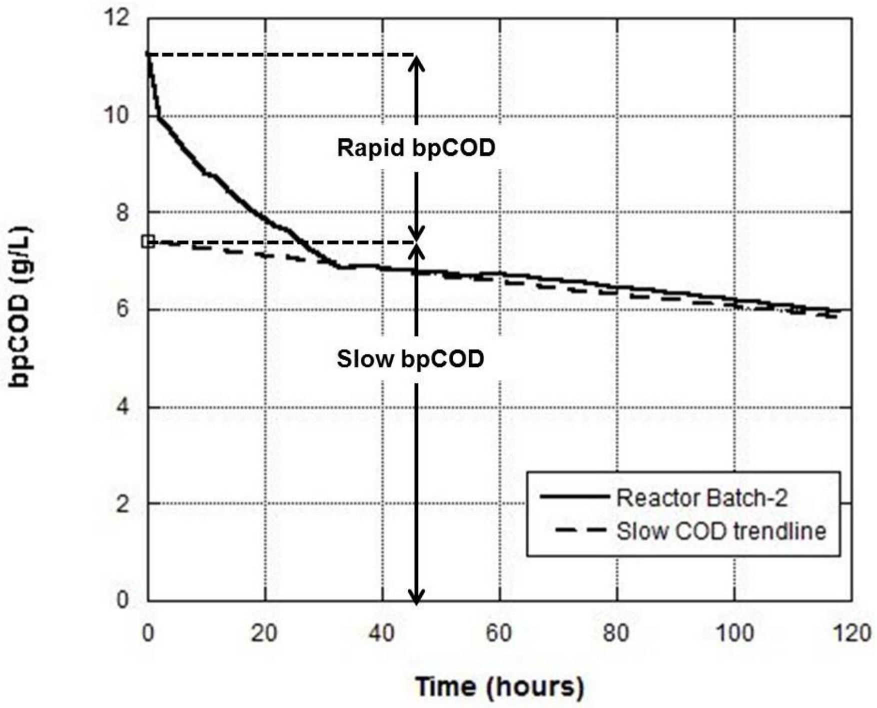


Figure 5. Determination of rapid and slow hydrolyzing bpCOD fractions using an exponential fit to the bpCOD concentration after 45 hours.

The hydrolysis rate coefficients were determined by minimizing the sum of the square error between the experimental bpCOD concentration vs. time curve and the dual-hydrolysis model (Figure 6). This was achieved using Microsoft Excel solver function; the rapid and slow hydrolysis rates were allowed to vary in order to solve for the smallest possible square error between the curves.

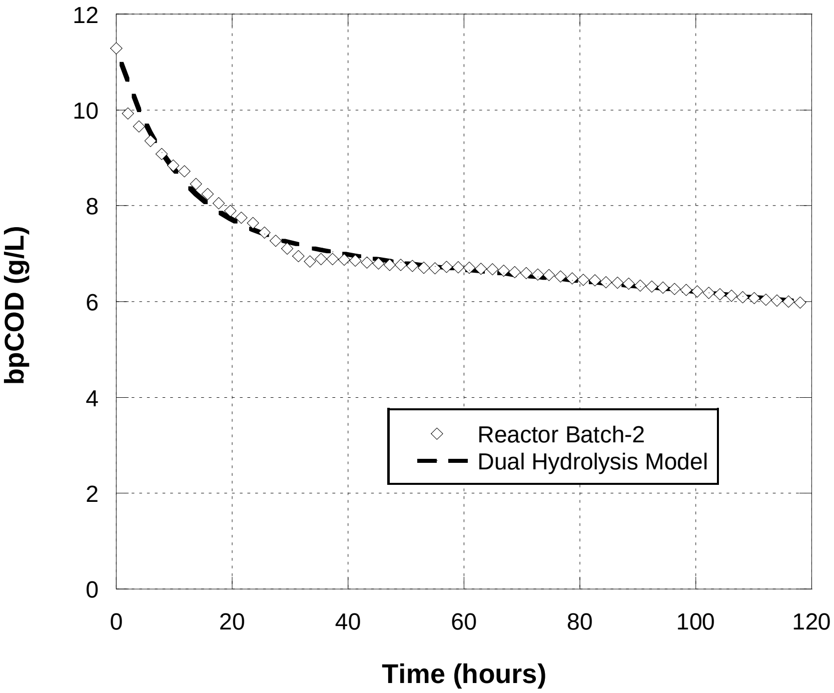


Figure 6. Dual hydrolysis model fitting of Batch-2 bpCOD concentration vs. time

The hydrolysis rates in a first order model are proportional to the concentration of bpCOD in the reactor. In this case, each of the rapid and slow rates is proportional to their respective bpCOD concentrations. Because the preexisting bpCOD in the reactor was not considered in the calculation of the initial concentration, an error was introduced in the determination of the hydrolysis rate coefficients. Any preexisting bpCOD in the reactor prior to feeding was likely slowly hydrolysable, as the rapid bpCOD had enough time to nearly completely hydrolyze between feedings. Therefore, the rapid hydrolysis rate coefficients determined from the dual hydrolysis model fitting will not contain this error (Table 14).

Table 14. Rapid hydrolysis rate coefficients and their given fraction of the bpCOD determined by least squares fitting of dual hydrolysis model to batch test data

Reactor	Rapid Fraction of bpCOD	Rapid Hydrolysis Rate Coefficient (d^{-1})
Batch-1	0.32	1.04
Batch-2	0.26	2.16
Batch-3	0.39	1.50
Batch-4	0.39	1.56
Duplicate of Batch-1	0.24	1.29

The long term reactors were used in the determination of the slow hydrolysis rate coefficients because they minimize the error introduced by unknown preexisting bpCOD concentrations. If the initial bpCOD concentration is assumed to be less than what is actually in the reactor, the hydrolysis rate will be under predicted for a single feeding event. Over many feeds the error will be mitigated by a buildup of bpCOD in the model due to the under predicted hydrolysis rate. This increase in bpCOD will cause the hydrolysis rate to increase until steady conditions are reached. Therefore, the predicted bpCOD concentration by the model will reach the reactor bpCOD concentration regardless of the initial bpCOD.

The long term reactor data was used to synthesize bpCOD concentration vs. time curves that spanned many feedings (Figure 7). Because these reactors were operated at long SRTs and allowed to reach steady operation, they did not demonstrate significant accumulation of hydrolysis products following feedings. The hydrolysis of bpCOD was therefore estimated by methane production only for the long term reactors. Like the batch reactors, the initial bpCOD concentration was determined by dividing the g bpCOD from the first feeding by the reactor volume. For subsequent feedings, the bpCOD concentration was increased by the g bpCOD fed divided by the reactor volume. The dual-hydrolysis model had to be modified so that it could be fit to the synthesized bpCOD curves with multiple feedings. The first feeding was done identically to the batch reactors. When new feedings occurred, and additional bpCOD was added, additional terms were added to account for the new bpCOD, each with a corresponding X_{c0}, f_{rh_xc}, and f_{sh_xc}. The new bpCOD terms were considered to be at time zero just as they were fed, while any remaining bpCOD from previous feeds continued to decay exponentially from their corresponding feeding time. Because the hydrolysis rate is proportional to the bpCOD in the reactor for a first order model, each new feeding can be considered separately and summed together to calculate the bpCOD concentration in the reactor.

The slow hydrolysis rate coefficients were determined by minimizing the square error between the synthesized bpCOD curves and the modified dual hydrolysis model curves. The average rapid hydrolysis rate coefficient (1.51 d^{-1}) and average rapid fraction of bpCOD (0.32) were taken from the batch reactor results, and only the slow hydrolysis rate coefficient was allowed to vary in Microsoft Excel's solver function in order to optimize the fit (Table 15).

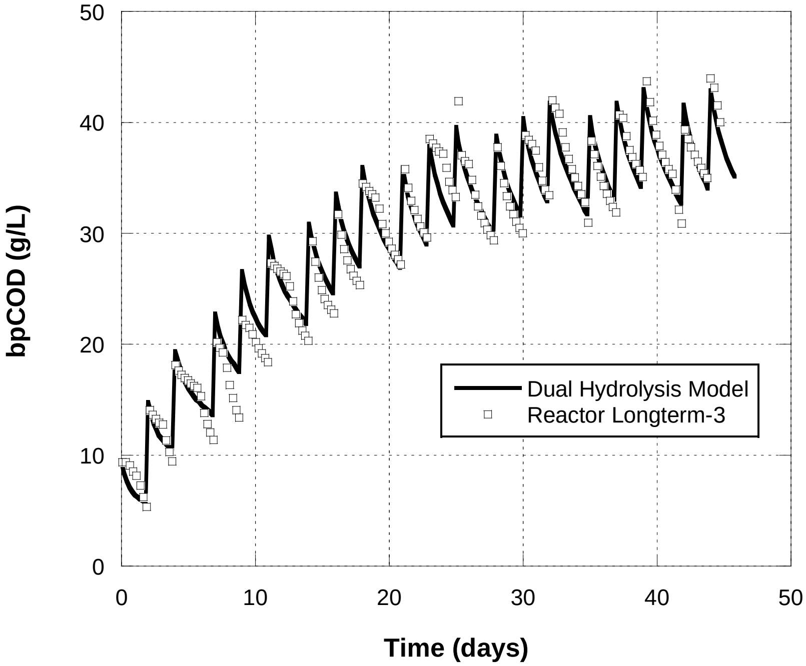


Figure 7. Least squares fit for dual hydrolysis model of the bpCOD concentration in reactor Longterm-3

Table 15. Slow hydrolysis rate coefficients determined from long term reactors. Average batch reactor results were used for rapid COD rate coefficient (1.51 d^{-1}) and rapid fraction of total COD (0.32).

Reactor	Slow Hydrolysis Rate Coefficient (d^{-1})	R^2	Slope
Longterm-1	0.32	0.72	0.74
Longterm-2	0.67	0.32	0.45
Longterm-3	0.07	0.91	0.88
Longterm-4	0.15	0.95	0.88
Longterm-5	0.12	0.92	1.01

Reactor Longterm-2 has a significantly higher rate coefficient than the other reactors. The fit is also by far the poorest and was therefore not considered in the final hydrolysis rate estimations used for simulations. Due to the nature of the synthesis of the bpCOD concentration vs. time curves, traditional fitting parameters like bivariate R^2 and slope don't necessarily provide a definitive representation of the goodness of fit. In a few cases, there was a small lag period between feeding and significant methane production. The model does not account for lag time, as most feedings saw immediate production of methane gas. Therefore, the reactors that had more feedings with lag periods may have poorer R^2 or sum of square error, even if the overall fit was visually better. A holistic approach combining R^2, slope, and visual confirmation was taken to describe goodness of fit (Table 15, Figure 7—Figure 11).

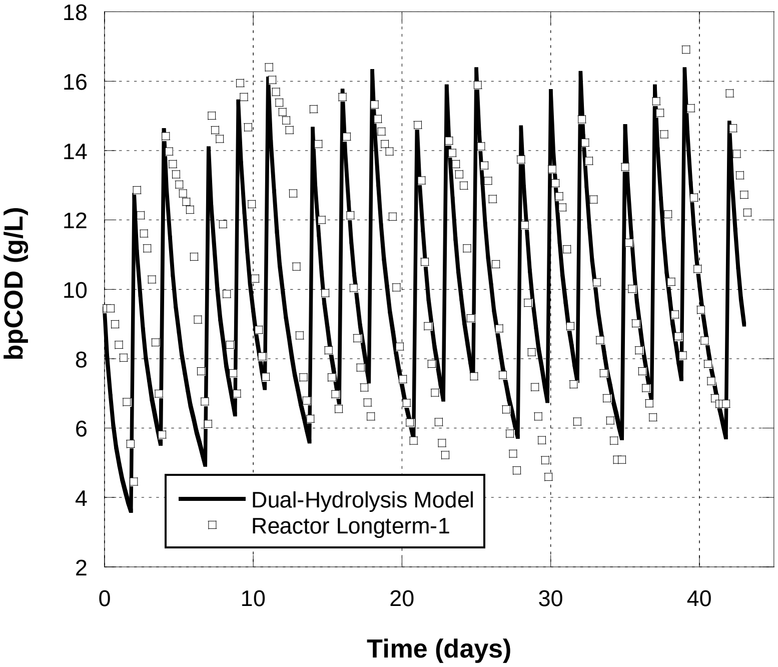


Figure 8. Least squares fit for dual hydrolysis model of the bpCOD concentration in reactor Longterm-1

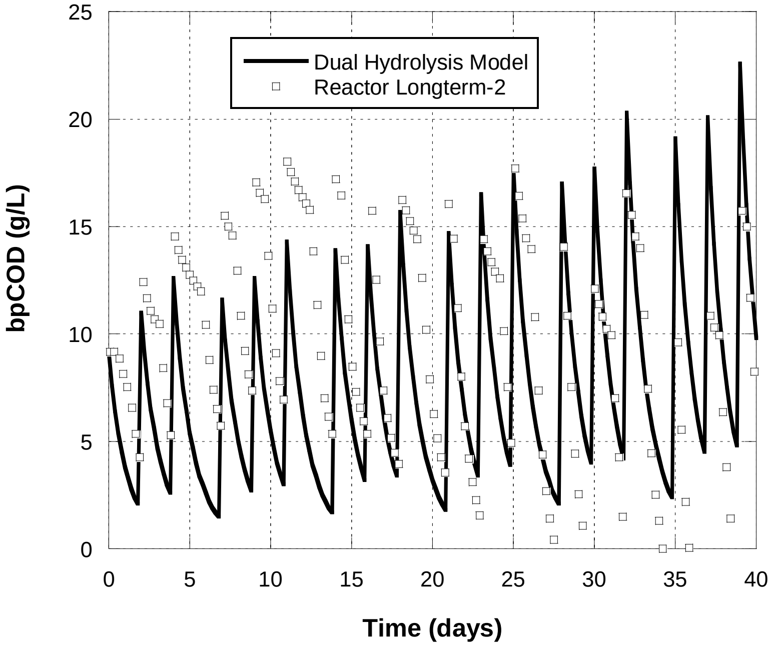


Figure 9. Least squares fit for dual hydrolysis model of the bpCOD concentration in reactor Longterm-2

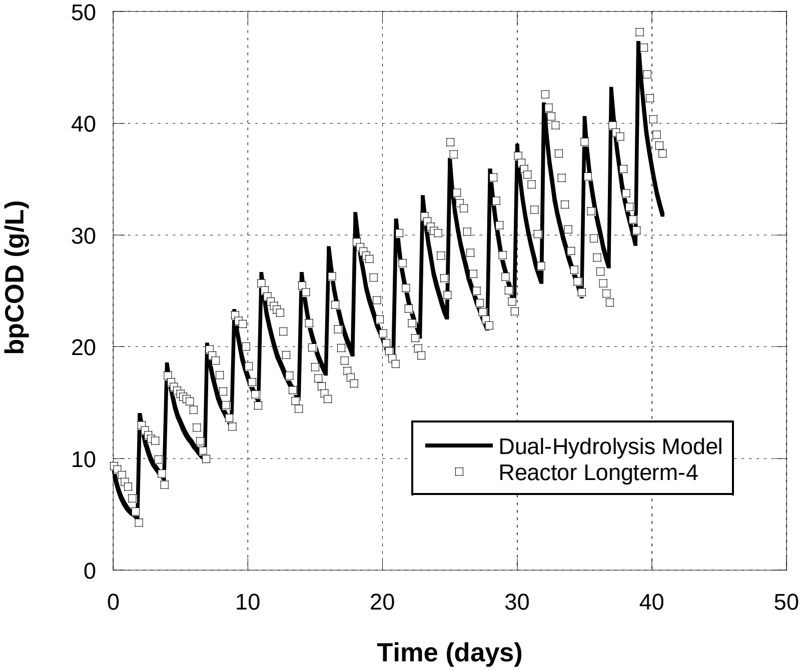


Figure 10. Least squares fit for dual hydrolysis model of the bpCOD concentration in reactor Longterm-4

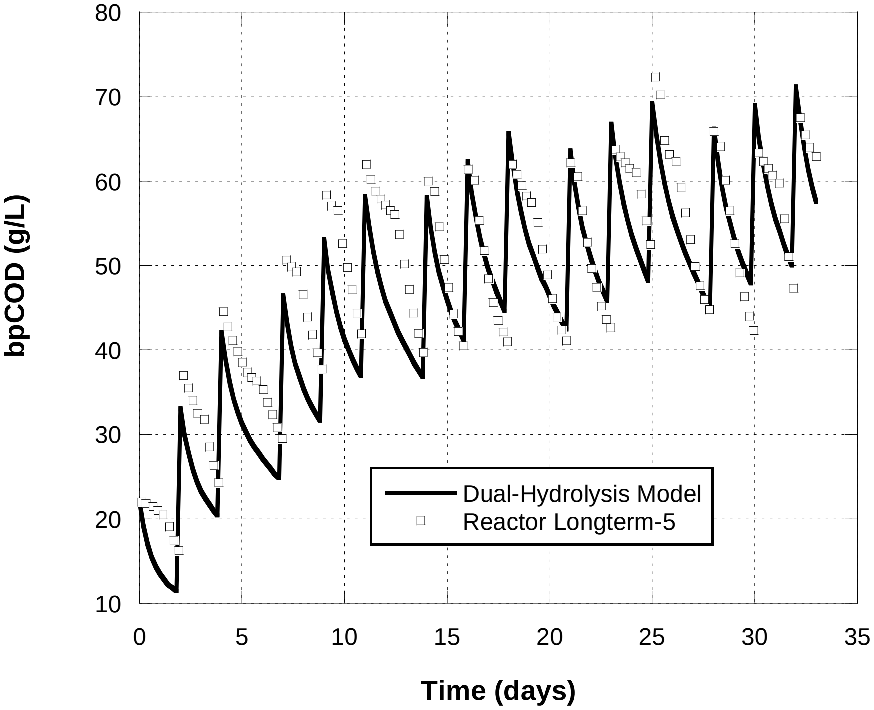


Figure 11. Least squares fit for dual hydrolysis model of the bpCOD concentration in reactor Longterm-5

As the R^2, slope, and visual fit suggest, Longterm-2 was unable to achieve a good fit using the dual-hydrolysis model. The other reactors had R^2 values and slopes from 0.72-0.95 and 0.74-1.01 respectively. These reactors had much better fits, which can be confirmed by Figure 7—Figure 11 . Longterm-1 had a slightly worse fit than 3, 4, or 5, according to R^2, slope, and visual appearance. The relative goodness of fit between reactors 3, 4, and 5 cannot be significantly distinguished by the fitting parameters used in this analysis.

The results from all long term reactors with the exception of Longterm-2 were averaged to estimate the slow hydrolysis rate coefficient. The value, 0.16 d^{-1}, is approximately an order of magnitude less than the 1.5 d^{-1} rapid rate coefficient. These values provided an initial estimate for the hydrolysis kinetics of food waste, which were used for simulations in the modified ADM1.

A secondary goal of the hydrolysis tests were to determine if the presence of FOG, variability in loading rate, or waste composition had an effect on the hydrolysis characteristics of food waste. No significant trends for the rapid or slow hydrolysis rate coefficients with respect to FOG addition, max loading rate, or ramping of the loading rate were found from these tests. These factors may have effects on the hydrolysis kinetics, but additional study, designed specifically to address any impacts, is needed.

CHAPTER V: MODEL SIMULATIONS

The calibrated ADM1 was used in model simulations to evaluate digester performance for planned operating conditions for pilot plant digesters to be installed at the USAFA to process food waste to energy. Two 600 gallon digesters will be filled initially with sludge obtained from an anaerobic digester at the USAFA domestic wastewater treatment facility. The following operational phases anticipated for the pilot plant study include: 1) start up and acclimation to the food waste feed, 2) steady state operation, 3) step-wise loading increases to a maximum level that maintains digester stability and 4) temporary reduced loading rates. Model simulations for various conditions were done to determine the effect of the above expected pilot plant test scenarios on digester performance and stability. The information gained from these simulations will be useful for determining expected performance for the operating conditions presently planned and may be used to guide decisions on pilot plant test conditions.

Table 16 summarizes the digester design liquid and head space volumes and operating temperature and the expected feed concentration for all of the simulations with regard to the pilot plant operation. The pilot plant digesters are expected to be batch fed over a 60 min period three times per week on Monday, Wednesday, and Friday. At the initial target loading of 7.0 gCOD/L-d, the HRT and SRT would be 18.5 days, based on the expected feed concentration of 129.5 gCOD/L. For higher loadings, the volumetric feed rate would be increased, and the SRT would be decreased as the feed concentration is expected to be relatively constant.

Table 16. Pilot plant digester specified design conditions

Parameter	Units	Value
Temperature	°C	36.7
Volume	m^3	1.893
Gas Volume	m^3	0.379
Feed Concentration	gCOD/L	129.5

The food waste composition was estimated by averaging the results from food proximate analyses of 15 USAFA food waste samples. Appendix E contains detailed data for each of the individual wastes. Table 17 summarizes the waste characteristics used in model simulations. The average protein, carbohydrate, lipid, and inert COD fractions are 0.29, 0.31, 0.34, and 0.06, respectively. The fractions of rapid and slowly hydrolysable COD and the hydrolysis characteristics are average values from the model calibrations as described previously.

Table 17. Average USAFA waste characteristics used for ADM1 simulations

Parameter	Units	Value
Protein COD	g/gCOD	0.29
Lipid COD	g/gCOD	0.34
Carbohydrate COD	g/gCOD	0.31
Rapid COD fraciton	g_{rapid}/gCOD	0.3
Slow COD fraction	g_{slow}/gCOD	0.64
Inert COD fraction	g_{inert}/gCOD	0.06
VS/TS	-	0.94

Because the digesters will be charged with anaerobic digester sludge from the USAFA digesters treating sludge from domestic wastewater, it was necessary to simulate that digester treatment first to characterize the pilot plant digester microbial population and undigested solids composition before feeding USAFA food waste. Three months of data from the USAFA wastewater treatment plant, including the daily flowrate, concentration of waste primary and secondary sludge, VS/TS ratio and digester TS were used to calculate the average VS destruction efficiency (Appendix F), which was used along with the digester volume and temperature in modified ADM1 simulations to establish the characteristics of the seed sludge to the digester. Using the conditions described by the USAFA domestic wastewater digester as the starting point, the model simulation plan listed in Table 18 was followed to evaluate the anticipated pilot plant operation.

Table 18. ADM1 simulations plan

Number	Simulation
1	Startup and acclimation
2	Steady state operation
3	Transition to higher loading rate
4	Temporary reduced loading rate
5	Effect of feeding strategy
6	Effect of hydrolysis kinetics coefficients
7	Effect of waste composition
8	Effect of endogenous decay rate

In addition to predicting digester food conversion efficiency and biomethane gas production rates, information on the potential for unstable operation and digester upset was an important aspect of the model simulations. Evaluation of the potential for digester instability required selecting appropriate digester performance or operating parameters that could be tracked and quantified in the model simulations to yield numerical values that would be expected for stable digester operation. Typical indicators of digester health include pH, alkalinity, VFA concentration, VFA/Alkalinity ratio, and relative biomethane and total gas production rates. Due to the highly degradable nature of the food wastes and their composition, the laboratory digesters often produced enough bicarbonate to sustain healthy alkalinity and pH values in spite of VFA concentrations increasing to inhibitory levels with a decline in biomethane production. In many laboratory digesters the pH and alkalinity were > 7.3 and > 9000 mg $CaCO_3$/L respectively, when the total VFA concentrations were up near 5000 mg/L as acetate. Biomethane production was inhibited in most of the laboratory digesters when the total VFA concentration exceeded 3000 mg/L as acetate. Thus, it would not be sufficient to base digester health and potential for upset on only typical parameters such as pH and alkalinity. Near day 32 of operation, the methane production in a laboratory digester loaded at 6gCOD/L-d declined when the total VFA concentration exceeded 2500 mg/L (Figure 12), while the pH was still above 7.6 (Figure 13). Appendix G shows additional laboratory reactors that exhibit similar behavior as Figure 12 and Figure 13.

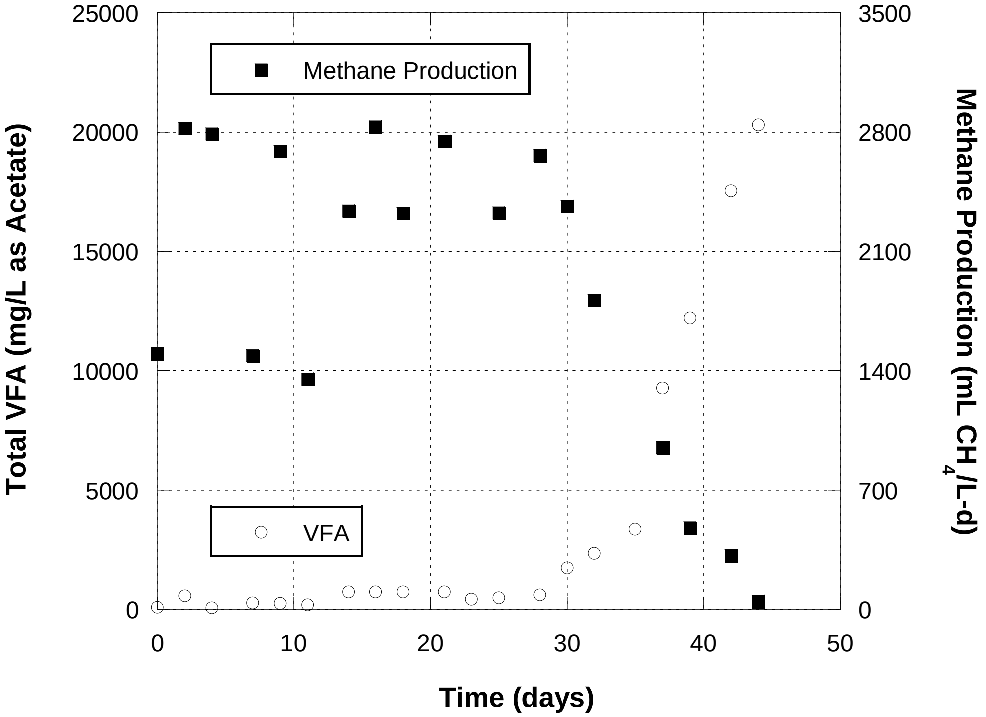


Figure 12. Total VFA concentration and methane production rate vs. time for a laboratory digester with a 6gCOD/L-d average loading rate

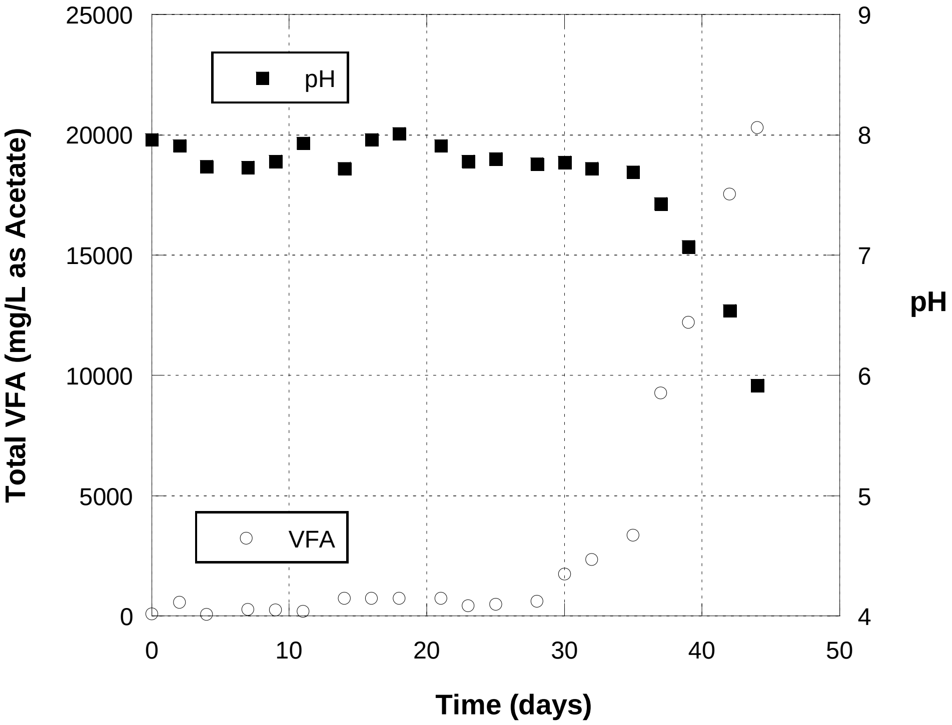


Figure 13. Total VFA concentration and pH vs. time for a laboratory digester with a 6 gCOD/L-d average loading rate

Unionized acetic acid has been shown to be inhibitory to methanogenesis at elevated levels (Fukuzaki et al. 1990, Kus and Wiesmann 1995, Ryhiner et al. 1992). Acetate concentration was used as the main indicator of digester health for the pilot scale food waste simulations because of the inhibitory effects seen in the lab-scale digesters. If the acetate gets fully utilized between feedings without significant accumulation and is not sustained at high concentration for prolonged periods, the digester will be considered under stable operation. In the evaluation of digester potential instability for the model simulations, a high potential for unstable operation was assumed if the acetate concentration exceeded 2500 mg/L. Propionate, another important VFA, typically ranged from 10 to 30% of the acetate concentration in simulations and steady lab digester operation.

During the startup period the digester microbial population and solids composition would change after the seed sludge from the USAFA digester starts receiving food waste. Laboratory digester studies with digester sludge from the King County Renton municipal WWTP showed immediate adaptation to food waste. The initial conditions for the pilot plant seed sludge was determined from simulations of the USAFA anaerobic digester using plant data on the digester temperature and SRT and feed solids concentrations and volatile fraction for waste primary and waste activated sludge.

Steady state operation

An initial loading of 7gCOD/L-d was used for the pilot plant study as laboratory studies showed this to be a safe loading for stable operation. This loading is an "average" daily loading over a 7-day or weekly period as the digesters are expected to be fed three times per week. The initial goal was defined as a “steady state” operation with the 7gCOD/L-d loading, but because the digester is not fed continuously, a true steady state condition in terms of constant gas production rates and constant digester parameter concentrations is not attainable. For the Monday, Wednesday, and Friday batch feeding strategy, a pseudo-steady state was defined by a week-long cycle. When the transient concentrations in the digester were replicated in successive weeks, the digester was considered to be operating at steady state. The steady state operation at the 7gCOD/L-d loading was then used as the initial condition for the remaining simulations in Table 18. Digester performance at 7gCOD/L-d is summarized after the determination of the optimized loading rate below.

Effect of transitioning to a higher loading rate

The digester loading rate was then increased in a stepwise manner to address the optimization and challenge phases of pilot plant operation. The first simulation increased the loading rate from 7gCOD/L-d to 15gCOD/L-d, corresponding to a decrease in SRT from 18.5 to 8.6 days. The acetoclastic biomass, X_{ac}, was compared for a thirty day transition vs. an immediate transition to the new loading rate. As the loading rate is increased incrementally, the amount of biomass that is withdrawn from the reactor for each feed also increases due to the higher flowrate, which causes the biomass concentration to be lowered at the beginning of each cycle after batch feeding (Figure 14). For example just before Day 40, when the 15gCOD/L-d loading is reached, the X_{ac} concentration is about 1.8 gCOD/L versus about 2.0 g COD/L at the start of the transient loading period. When the transition is made immediately from 7 to 15gCOD/L-d the population of X_{ac} is even lower at the same time (Figure 15).

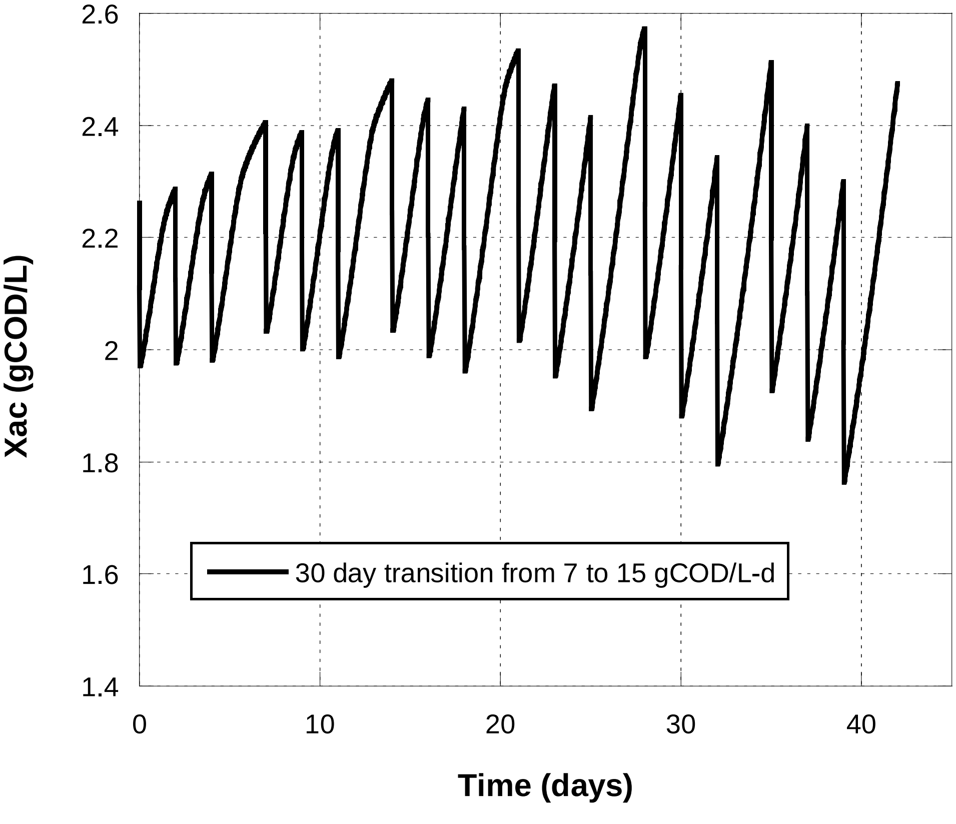


Figure 14. Simulated acetoclastic methanogen population vs. time for a 30 day transition from 7 to 15 gCOD/L-d by step wise increase in feed volume, equivalent to a decrease in SRT from 18.5 to 8.6 days

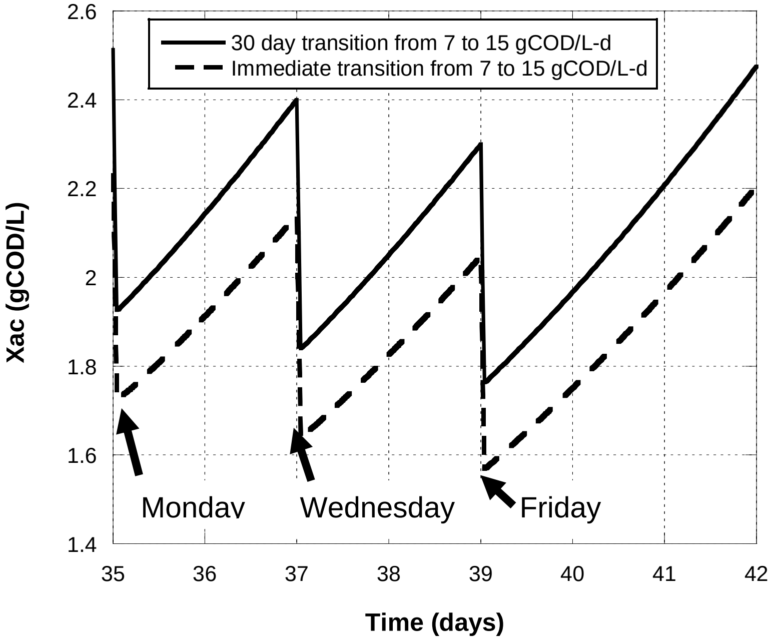


Figure 15. Simulated acetoclastic methanogen population vs. time for both immediate, and 30 day transitions from 7 to 15 gCOD/L-d by step wise increase in feed volume, equivalent to a decrease in SRT from 18.5 to 8.6 days. Day 35 corresponds to the first day of 15gCOD/L-d loading (Arrows indicate feed additions).

A digester that withdraws 11.5% of its volume each day of the week can be considered to have an SRT of 8.6 days. However, for three batch feed events (MWF) per week at the same average weekly SRT, 27% of the digester volume is withdrawn for each feeding. The withdrawal is much more dramatic for three feeds per week, which affects biomass wasting and growth potential in the digester. Biomass increases after each feeding event, and has three days to increase after Friday’s feed, as opposed to two days after Monday and Wednesday (Figure 15). The decline in the acetoclasts concentration with time due to the high fraction of digester volume withdrawn at 15gCOD/L-d loading causes the acetate concentration to increase with time to accumulate to unstable levels (Figure 16).

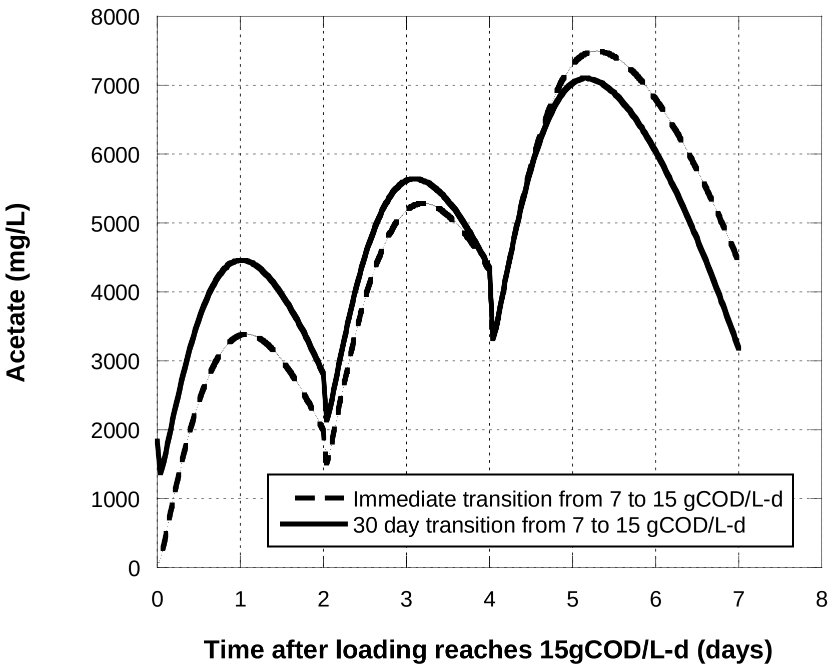


Figure 16. Simulated acetate concentration vs. time after the loading rate reaches 15gCOD/L-d for both immediate, and 30 day transitions from 7 to 15 gCOD/L-d by step wise increase in feed volume, equivalent to a decrease in SRT from 18.5 to 8.6 days.

The transient acetate peaks do not increase as rapidly after the loading reaches 15gCOD/L-d for the 30 day transition, leading to a lower peak acetate concentration by the third batch feed at 15gCOD/L-d. This is an effect of the increased X_{ac} population in the 30 day transition scenario.

Simulations for increasing the loading rate to 15gCOD/L-d when feeding three times a week proved to be unstable. A new target loading rate of 12gCOD/L-d (10.8 d SRT) was selected with the same operating conditions to see if stable operation could be reached. Acetate concentration and acetoclastic methanogen population were simulated for immediate transition; and 10, 20, and 30 day transitions from 7 to 12 gCOD/L-d (Figure 17 and Figure 18).

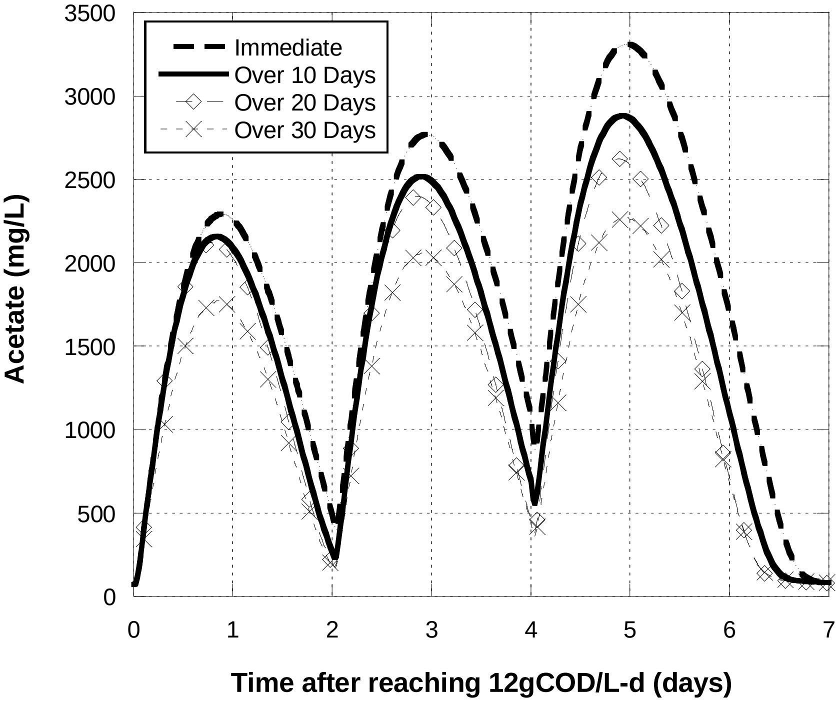


Figure 17. Simulated acetate concentration vs. time after reaching 12gCOD/L-d loading rate for immediate, 10 day, 20 day, and 30 day transitions from 7 to 12 gCOD/L-d by step wise increase in feed volume, equivalent to a decrease in SRT from 18.5 to 10.8 days.

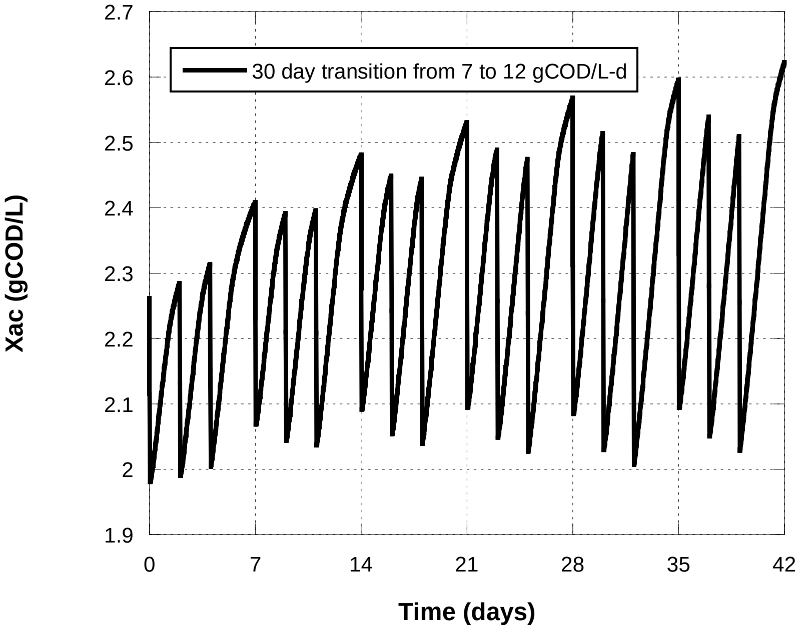


Figure 18. Simulated acetoclastic methanogen population vs. time for a 30 day transitions from 7 to 12 gCOD/L-d by step wise increase in feed volume, equivalent to a decrease in SRT from 18.5 to 10.8 days.

The effect of the length of the transition period for increasing the loading rate is much more apparent in the 12gCOD/L-d target loading simulations. The 12gCOD/L-d loading does not withdraw biomass at a rate that causes instability, as occurred for the 15gCOD/L-d scenarios. Figure 18 shows that for weekly intervals, the net acetoclastic methanogen population increases over the entire 30 day transitional period. The steady increase in biomass allows the digester to consume more acetate at higher loading rates than a digester that transitions immediately. Figure 17 demonstrates that the longer the transitional period, the smaller the transient acetate concentration will be when the target loading is reached. There is a limit to this effect. At a certain transitional length, the change in loading will be so small that biomass population will already be at the pseudo-steady state conditions described previously. The digester acetate concentration will be the same for any transitional period that approaches this limit. The 30 day transitional period is very close to this limit, as continued simulation at 12gCOD/L-d shows the pseudo-steady state conditions are met. Therefore, the peak acetate concentrations will never get significantly lower than those simulated for the 30 day transitional period in Figure 17.

When the loading was increased over a 30 day period, the transient acetate concentration remained under the acceptable limit of 2500 mg/L acetate. 12gCOD/L-d appeared to be approaching the maximum loading rate that keeps acetate under 2500 mg/L for three feeds per week operation. The digester performance of 7gCOD/L-d and 12gCOD/L-d loadings was summarized to compare the effects of operating at a higher loading rate (Table 19). The simulations were run until the pilot digester achieved pseudo-steady state operation at each loading rate. As expected, at the higher loading rate and lower SRT, the solids destruction efficiency is lower and the biomethane production rate per unit digester volume is higher.

Table 19. Simulated digester performance data for 7 and 12 gCOD/L-d average loadings operated at pseudo-steady state for three batch feeds (MWF) a week. SRTs are 18.5 and 10.8 days respectively. Methane production rates are at the 36.7 °C digester temperature.

Parameter	Units	7gCOD/L-d	12gCOD/L-d
Effective SRT	days	18.5	10.8
COD Conversion Efficiency	%	67	58
VS Destruction Efficiency	%	72	67
Methane Production Rate*	mL CH_4/L-d	1,860	2,780
Effluent VS concentration**	%	2.5	3.0
Effluent TS concentration**	%	3.1	3.6
Effluent Acetate concentration	mg/L	60	190
Effluent Alkalinity	mg/L as $CaCO_3$	11,620	10,480
Effluent pH	-	7.6	7.6
Effluent NH_4-N concentration	mg/L	3,250	2,983

*based on digester volume, ** based on sludge at specific gravity of 1.03

The final solids concentration in the digester is also an important factor which is related to the digester mixing requirements. As shown in Table 19, as the average loading was increased from 7.0 to 12.0 gCOD/L-d the model predicted that the digester volatile and total solids concentration would increase from 2.5 to 3.0% and 3.1 to 3.6%, respectively. At higher loadings the digester would have higher solids concentrations, which would impact the mixing requirements of the digester.

Effect of changing digester load by feed concentration or feed flow rate

With the limitation that the food waste feed concentration is constant, any the loading rate increases could only be done by increasing the volume fed to the digester. As seen in the simulations for transitioning to 15 gCOD/L-d, the instantaneous SRT was too low to allow for stable digester operation with the MWF batch feeds per week. To further demonstrate the impact of SRT during high loading rates the simulation for ramping from 7 to 15 gCOD/L-d was repeated, but instead the feed concentration was increased from 129.5 to 277.5 gCOD/L while keeping the SRT constant at 18.5 days. The fraction of acetoclastic methanogen population that is wasted during feeding periods is much less when the loading rate is increased by raising the feed concentration instead of the flowrate (Figure 19). For an SRT of 18.5 days only 12.6% of the biomass is wasted for each feeding, whereas an SRT of 8.6 days corresponds to 27% loss. As a result, the simulated acetoclast biomass is 38% higher for the feed concentration increase than for the flowrate increase after a week of feeding at 15gCOD/L-d. A greater population of biomass allows the digester to utilize acetate more rapidly. As expected from the increase in biomass, the model predicts lower acetate concentrations for higher loading by increasing the feed concentration instead of decreasing the SRT (Figure 20). The peak transient acetate concentrations during a week of feeding are less than 50% of those due to the same load increase associated with increased flowrate. The peak acetate concentrations are still over 2500 mg/L, meaning that a sudden increase to 15gCOD/L-d is still not advised under these operating conditions.

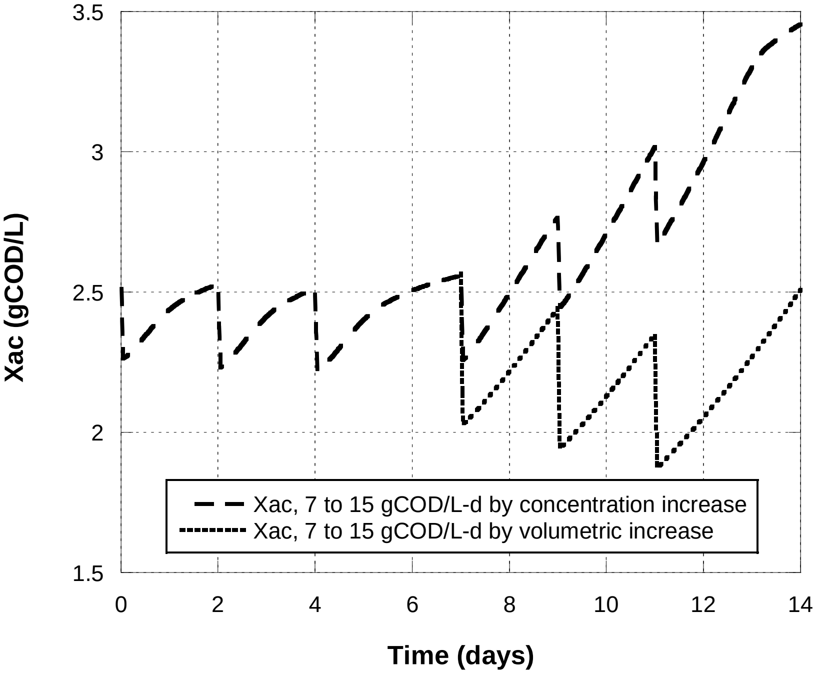


Figure 19. Comparison of simulated Xac concentration vs. time for increasing the loading rate from 7 to 15 gCOD/L-d by increasing the feed COD concentration (129.5 to 277.5 gCOD/L) versus increasing the feed volume. The loading rate is 7 gCOD/L-d for days 0-7 and 15gCOD/L-d for days 7-14.

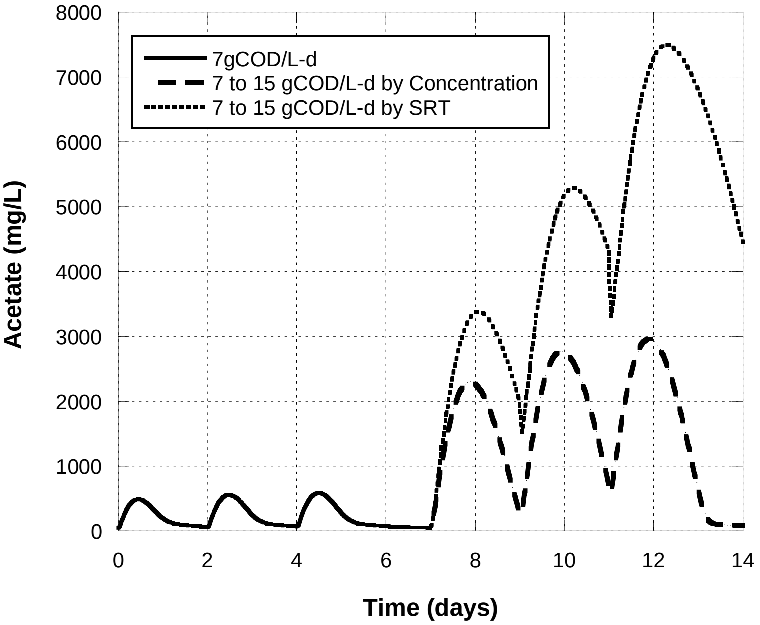


Figure 20. Comparison of simulated transient acetate concentration vs. time for increasing the loading rate from 7 to 15 gCOD/L-d by increasing the feed COD concentration (129.5 to 277.5 gCOD/L) versus increasing the feed volume. The loading rate is 7 gCOD/L-d for days 0-7 and 15gCOD/L-d for days 7-14.

These simulations show that for the same load increase in gCOD/L-d, the acetoclast population can increase faster and better respond to the loading change if the effluent flowrate is lower, which could occur if the loading rate is increased by raising the feed concentration instead of the flowrate. Thickening the feed to achieve a higher COD concentration may not be practical for digester operation, but there may be some control over the feed concentration. The model has demonstrated the effect of loading change due to increasing flow or concentration on acetate accumulation under transient conditions.

Effect of temporary reduced loading rate

We assume that with cadet activities changes at the USAFA, the resident population and amount of food waste available for digester feeding may change throughout the year. During the summer months not all the cadets are on campus. Model simulations were done by assuming the COD loading rate was decreased to 1/3 the typical load for a two month period during the summer. The population was then assumed to return to normal after these two months, and the digester response was evaluated when the loading rate was returned to normal. The original loading rate of 7gCOD/L-d (18.5 d SRT) was reduced threefold to 2.33gCOD/L-d (55.5 d SRT). The effect of the lower loading was seen through decreases in the digester VFA (Figure 21) and biomass concentrations (Figure 22) over the decreased loading period. Methane production rates decreased significantly during this period, producing an average of 50% less biomethane per feeding.

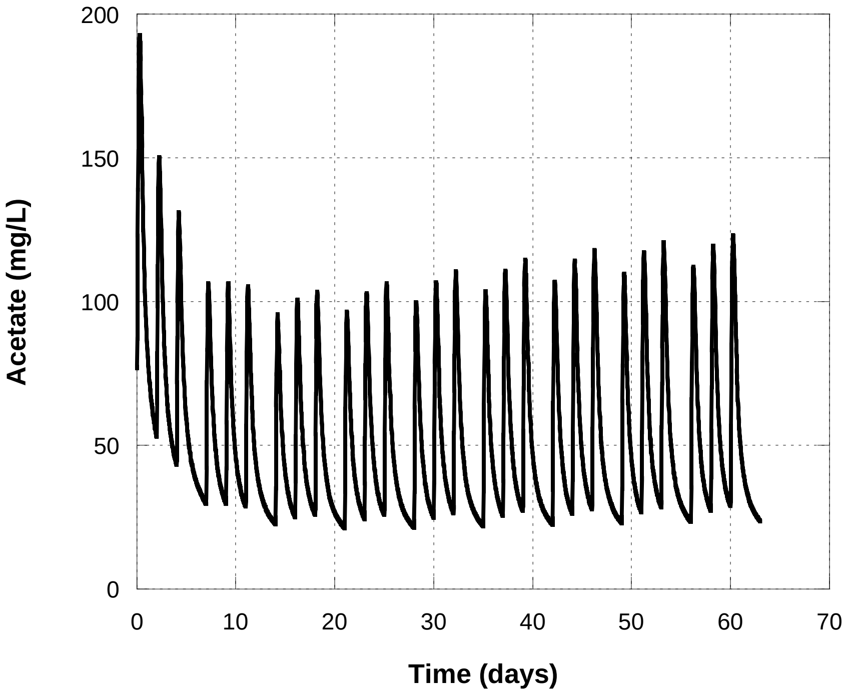


Figure 21. Simulated acetate concentration during a two month period with the load reduced to 2.33 gCOD/L-d (55.5 d SRT) from 7gCOD/L-d (18.5 d SRT)

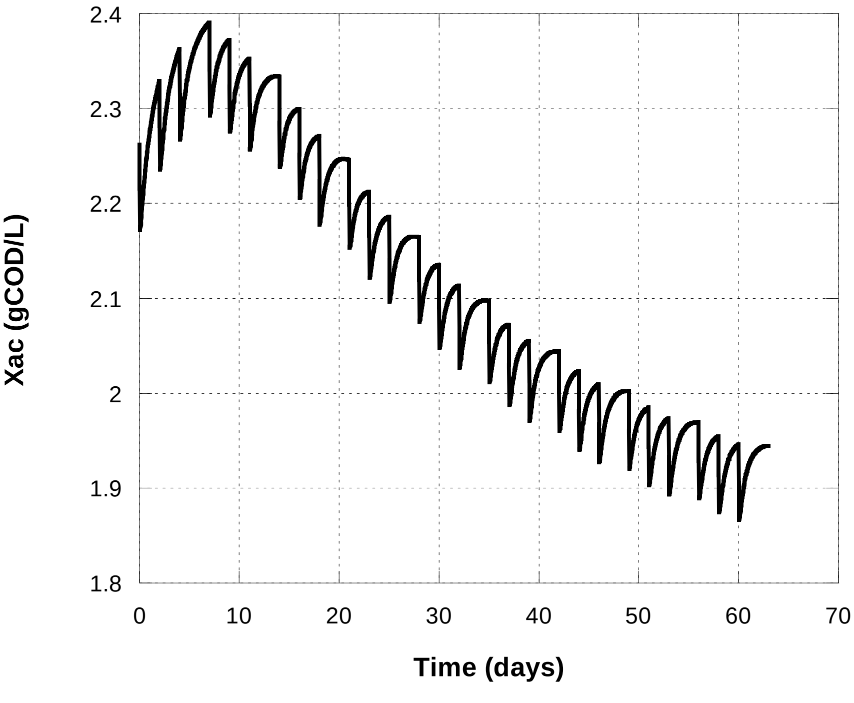


Figure 22. Simulated acetoclastic methanogen biomass with the load reduced to 2.33 gCOD/L-d (55.5 day SRT) from 7gCOD/L-d (18.5 d SRT)

The simulated increase in acetoclast concentration over the first week is a result of the sudden increase in SRT providing more time to consume residual bpCOD from the lower SRT operation. When the loading rate is reduced and the SRT increases to 55.5 days, a higher amount of the slowly hydrolysable bpCOD fed previously gets solubilized. The hydrolysis of the preexisting bpCOD causes the population to increase initially, but as it gets used up the population decreases due to the reduced loading rate.

An important issue for the pilot digester operation is whether stable digester operation is possible after returning to the previous 7gCOD/L-d loading. The biomass concentrations are lower following the reduced loading period, and thus the digester has lower substrate utilization rates. Model simulations showed that the digester could be returned to the 7gCOD/L-d loading without instability problems (Figure 23). When the digester resumes to a loading that still has a relatively long SRT, biomass loss in the effluent is low enough to allow the digester to accommodate the higher loading without instability. To demonstrate the potential instability effects of instead feeding at a higher loading rate, the simulation was also done with a 12gCOD/L-d loading (10.8 d SRT), which may also be used during pilot digester operation. In this case, acetate buildup and prolonged periods of high acetate concentration occurred (Figure 23).

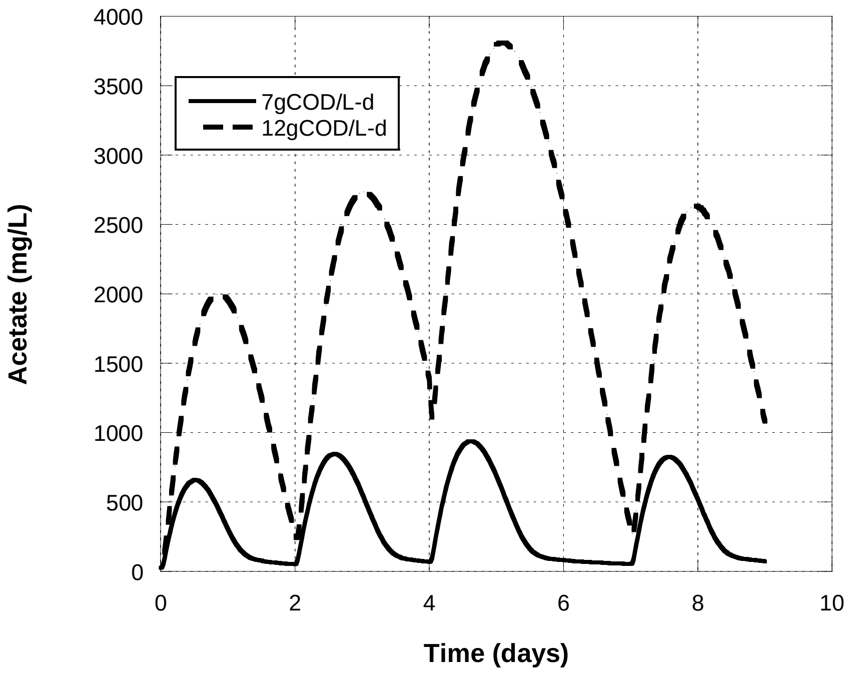


Figure 23. Simulated acetate concentration for resumption to 7gCOD/L-d (18.5 d SRT) or transition to 12gCOD/L-d (10.8 day SRT) following 2 months at 2.33 gCOD/L-d (55.5 d SRT)

Although the simulations for resumption at 7gCOD/L-d did not predict signs of instability, if the digester is operated at higher loading rates (lower SRTs) there may be more noticeable effects on digester stability. The decrease in digester biomass resulting from a reduced loading rate makes the digester more vulnerable to increases in loading rate.

Model Sensitivity Simulations

Model simulations were performed to examine the effect of various model parameters on predicted digester performance. The parameters that were hypothesized to have implications for the pilot plant study were feeding strategy, hydrolysis rate coefficients, food waste composition, and the acetoclast's endogenous decay rate.

Effect of feeding strategy

The digester feeding strategy has a major effect on the digester VFA concentration changes with time. The USAFA pilot digester is expected to be fed three times a week. Fewer feeding events per week result in larger instantaneous COD loadings to the digester. To demonstrate the effect of feeding frequency, digester acetate concentrations were observed in model simulations of daily and three feedings a week for the same average daily loading rate of 12gCOD/L-d (10.8 d SRT). The peak acetate concentration for daily feeding was approximately 850 mg/L, but was 1700-2200 mg/L for feeding at three times per week (Figure 24).

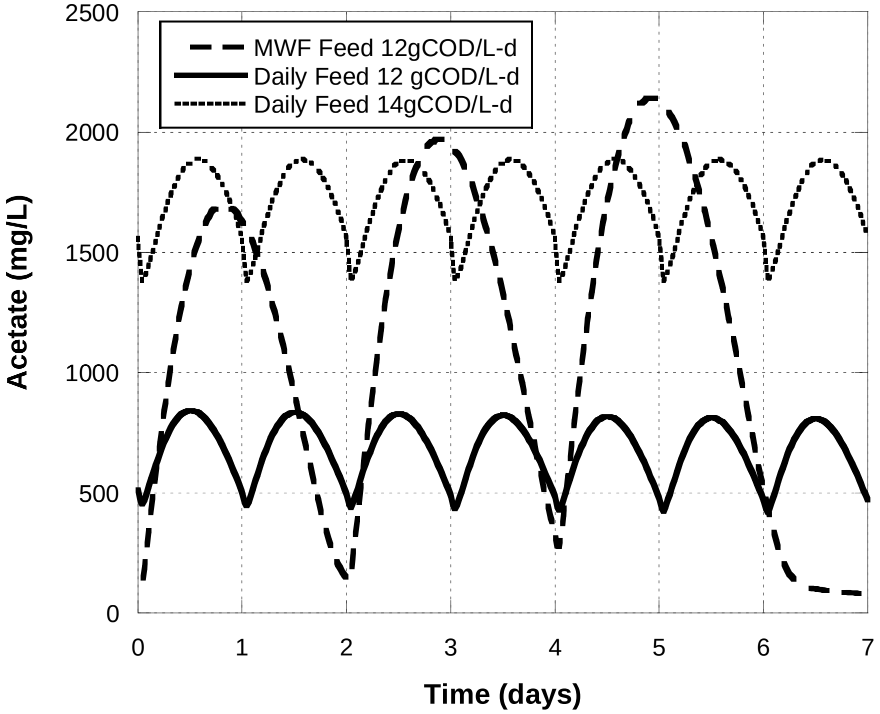


Figure 24. Simulated digester acetate concentration vs. time for daily and three batch feeds (MWF) per week at an average load of 12gCOD/L-d (10.8 d SRT) and daily batch feeds at an average load of 14gCOD/L-d (9.2 d SRT)

In addition to the 12gCOD/L-d loading rate feed frequency simulations, 14 and 15 gCOD/L-d average loading rates were simulated with daily batch feedings. For daily feeding with an average loading rate of 14gCOD/L-d, stable operation was simulated with acetate concentration under 2000 mg/L (Figure 24). Model simulations of daily batch feeds for a 15gCOD/L-d average loading rate resulted in extreme acetate concentration greater than 5000 mg/L at all times in the digester.

A number of advantages in operation and digester capacity result from more frequent feeding. Acetate concentration is lower at the same average loading rate resulting in more stable operation, as evidenced by Figure 24. A continuosly fed digester with a loading rate of

12gCOD/L-d (10.8 d SRT) has a simulated acetate concentration of 610 mg/L, demonstrating the trend of decreasing peak acetate concentration with increased feed frequency. Higher average loading rates are possible when the digester is operated with more frequent feeding, which increases biomethane production in the digester. Performance parameters such as volatile solids destruction and methane production are almost identical, all within 5%, for continuous, daily, or 3 feeds per week for the same average weekly loading. Reduced feeding frequency results in higher initial acetate concentrations and higher initial gas production rates, which raise concern about a greater potential for digester foaming.

Effect of hydrolysis rate

Solids hydrolysis rate is affected by the available surface area of the feed particles (Hobson 1987, Mshandete et al. 2006). The lab digesters were fed a milkshake-like slurry, while the pilot digesters are expected to be fed a more granular material. The dual hydrolysis model does not directly account for particle size and no particle size distribution tests were performed to compare the feeds. Thus simulations were done with reduced hydrolysis rate coefficient values from those determined from the laboratory digester studies to simulate the potential effect of increased particle size distribution in the USAFA pilot digester feed.

For the hydrolyis rate evaluation, consideration was given to the ease of applying the model and observing the results, such that the feed was assumed to be added at a constant rate and steady state conditions on digester performance could be observed and compared. Model simulations were done with the previously used rapid and slow hydrolysis rate coefficients reduced by 50%, from 1.51 and 0.16 d^{-1} to 0.76 and 0.08 d^{-1}, respectively. The loading rate and SRT for the comparison were 7gCOD/L-d and 20 days respectively with a feed concentration of 140 gCOD/L. The simulation showed that the reduced rate coeffiecents cause a decrease in volatile solids destruction efficiency, and ammonia production, which led to decreased methane and alkalinity production (Table 20). For an SRT of 20 days, a reduction of 50% to the hydrolysis rate coefficients resulted in a 13% reduction in volatile solids reduction. The effect of changes in hydrolysis rate coeffients will be more pronounced in shorter SRT systems.

Table 20. Effect of hydrolysis rate coefficients on digester performance through continuously fed steady state simulations at a 7gCOD/L-d loading and 20 day SRT. Composition of food waste is from average of food proximate analyses. Methane production rates are at the 36.7 °C digester temperature

Parameter	Units	Original Hydrolysis Rate Coefficients	50% of Original Rate Coefficients
VS Destruction Efficiency	%	69	60
Alkalinity concentration	mg/L as $CaCO_3$	11,880	10,300
Acetate concentration	mg/L	144	144
pH	-	7.7	7.6
Specific Methane Production Rate*	mL CH_4/L-d	1,900	1,660
%CH_4 in biogas	%	61	61
Effluent VS concentration**	%	3.0	3.9
NH_4-N concentration	mg /L	3,410	2,960

*based on digester volume ** based on sludge at specific gravity of 1.03

A dynamic simulation was also performed with the same reduced hydrolysis rate coefficients for the previous loading rate transition of 7 to 12 gCOD/L-d, corresponding to an SRT decrease from 18.5 to 10.8 days. The simulation results with the lower hydrolysis rate coefficients showed decreased transient acetate concentrations compared to that with the original hydrolysis coefficient values (Figure 25).

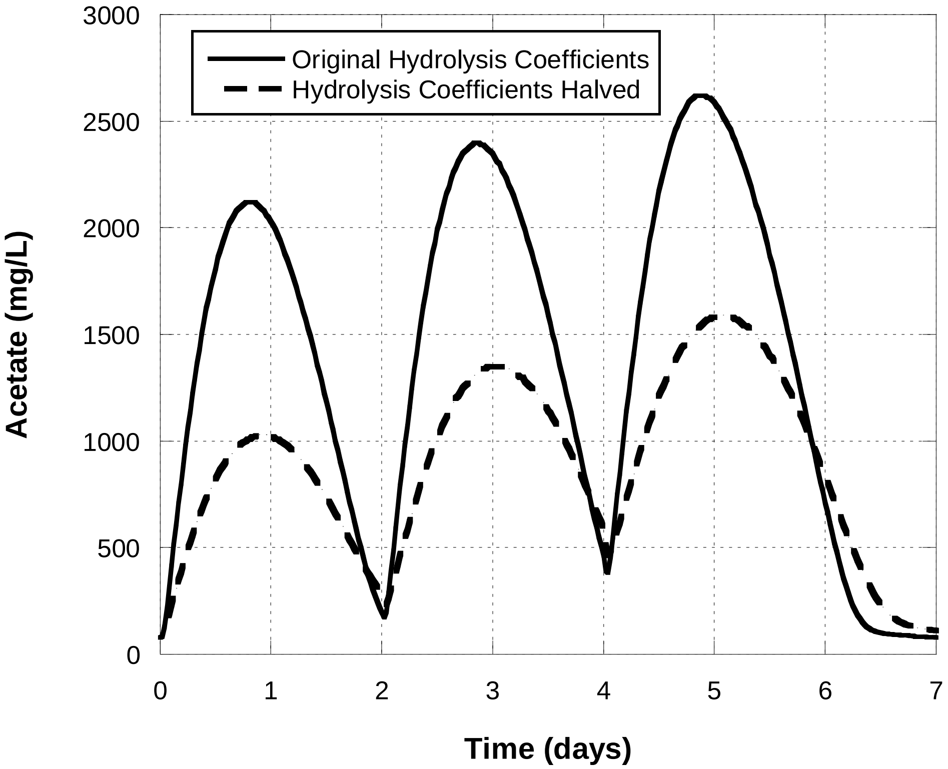


Figure 25. Simulated digester acetate concentration for ramping simulations from 7 to 12 gCOD/L-d at 5% increase/day for original hydrolysis rate coefficients (k_{rh} = 1.51 d^{-1} and k_{sh} = 0.16 d^{-1}) and halved hydrolysis rate coefficients (k_{rh} = 0.76 d^{-1} and k_{sh} = 0.08 d^{-1}).

The model predicts 82% as much biomethane will be produced over the week long interval with the lower hydrolysis coefficients. Overestimating the hydrolysis rate coefficients is a more conservative approach for evaluating digester stability because higher acetate concentrations will result from overestimated volatile solids reduction. The biomethane production will also be overestimated when the hydrolysis rate coefficients are assumed too high. For longer SRT designs, the overprediction of hydrolysis rate coefficents will have a smaller error on the volatile solids destruction and biomethane production values than for shorter SRT designs.

Effect of food waste composition

Food waste composition has a high degree of variability. The average values from food proximate analyses provided a balanced composition of protein, carbohydrate, and lipid for pilot scale simulations. To demonstrate the effect of food waste composition, continuously fed steady state simulations were developed with food wastes with a higher carbohydrate and higher lipid fraction than the average composition used in the pilot plant simulations (Table 21).

Table 21. Effect of food waste composition on digester performance for continuously fed steady state simulations at 7gCOD/L-d loading rate, 20 day SRT, and 140 gCOD/L feed concentration. Methane production rates are at the 36.7 °C digester temperature

Parameter	Units	Average of food proximate analyses (balanced)	FW-011 (lipid rich)	FW-004 (carb rich)
Protein COD Content	%	29	24	17
Carbohydrate COD Content	%	31	17	51
Lipid COD Content	%	34	53	26
Inert COD Content	%	6	6	6
VS Destruction Efficiency	%	69	67	70
Alkalinity	mg/L as $CaCO_3$	11,880	8,660	4,460
Acetate	mg/L	144	144	144
pH	-	7.7	7.6	7.2
Methane Production Rate	mL CH_4/L-d	1,900	1,910	1,890
%CH_4 in biogas	%	61	64	56
Ammonia	mg NH_4-N/L	3,410	2,510	1,330

The most noticeable differences in digester parameters are alkalinity, pH, and ammonia concentration. These are all a direct result of the protein fraction of the feed. The balanced composition has 29% protein content, whereas FW-004 and FW-011 have 17% and 24% respectively. For the reduced protein content, model simulations predicted decreased ammonia production, leading to a lower digester alkalinity concentration and pH (7.2 versus 7.6). The other significant effect that can be seen is the %CH_4 in the biogas. The lipid rich food wastes produced a higher fraction of CH_4, resulting in an increased methane production rate.

For a food waste digester receiving a variety of wastes during operation, it would be unlikely to see the effect of extremes in protein, lipid, and carb fractions as shown by these continuously fed simulations. It is still important to know the effect of waste composition for less frequent occasions of prolonged exposure to an extreme composition. The protein content in particular is critical for maintaining sufficient digester alkalinity, so extended periods of protein deficient feed could be cause for concern.

Effect of endogenous decay rate

The default ADM1 provides a first order decay rate constant to be applied to all biomass terms as an initial estimate. Batstone et al. (2002) acknowledge that in many cases the decay rate, particularly for acetoclastic methanogens, may be as much as double this default value. Starvation simulations were performed to examine the effect of decay rate on digester response to a period of no feeding, followed by a return to regular feeding.

A two week long period of starvation was simulated at the original decay rate for acetoclastic methanogens (0.02 d^{-1}), and twice the decay rate (0.04 d^{-1}). These were followed by a return to the three times per week feeding at 12gCOD/L-d (10.8 d SRT). The concentration of acetoclastic methanogens was approximately 22% lower after the two week starvation period when the decay rate was doubled (Figure 26). The rate at which the digester could utilize acetate was therefore reduced, and when the loading rate was returned to 12gCOD/L-d (10.8 d SRT) the digester acetate concentration reached much higher transient concentrations at levels of concern for stable operation (Figure 27).

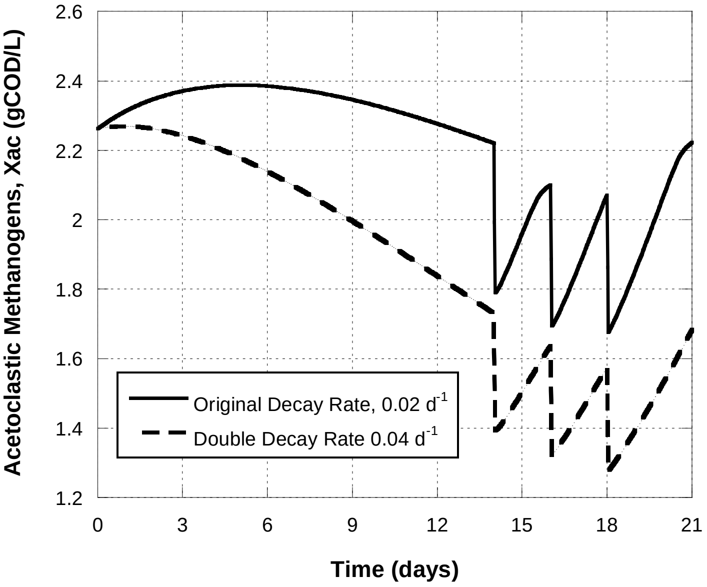


Figure 26. Simulated digester acetoclastic methanogen population vs. time with default and doubled first order decay rates for Xac over a two week starvation period and one week of 12gCOD/L-d (10.8 d SRT) at three feed events per week.

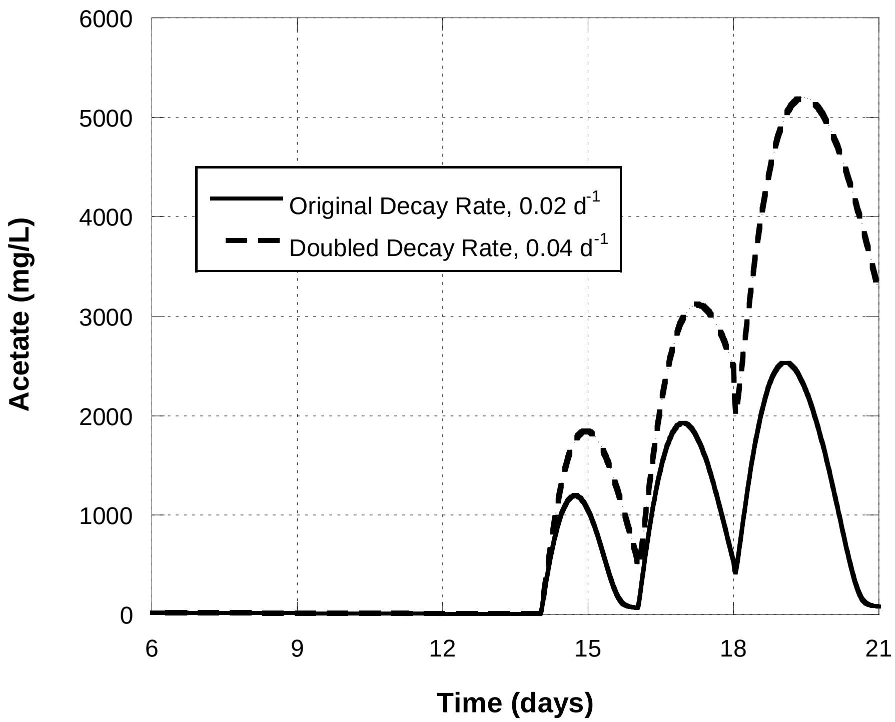


Figure 27. Simulated digester acetate concentration vs. time with default and doubled first order decay rates for Xac over a two week starvation period and one week of 12gCOD/L-d (10.8 d SRT) at three feed events per week.

The original decay rate of 0.02 d^{-1} fit the methane production data from lab-scale digesters, so there is no apparent reason to assume a higher decay rate. It is possible though that the fitting could be achieved with a greater decay rate in conjunction with a greater substrate utilization rate. Conklin et al. (2006) found a k_d of 0.006 ± 0.003 d^{-1} for a *Methanosaeta* enriched reactor, suggesting the decay rate is not likely higher than the default value of 0.02 d^{-1}. Therefore, the model results with the default ADM1 decay rates were assumed to adequately predict the effects of lower loadings or starvation. The effect of decay rate is clearly significant when recovering from periods of starvation. Additional data from starvation testing on the pilot digester will help to discern the decay rate of the acetoclastic methanogen population.

Comparison of Model Predictions for Food Waste Digestion to Municipal Sludge Digestion

Lastly, simulations were performed to compare anaerobic digestion performance for food waste and municipal wastewater sludge treatment. A digester SRT of 20 days and a daily loading rate of 7gCOD/L-d were used. The assumed TS and COD concentrations of the food waste and municipal sludge for these simulations are 9 % and 140 gCOD/L and 6.4% and 80.4 gCOD/L, respectively. The average loading rate for the municipal digester was 4 gCOD/L-d. The dual hydrolysis model has been previously incorporated into the ADM1 by Straub (2008) for municipal sludge digestion. The sludge composition and hydrolysis rate coefficients from Straub were used to simulate a continuously fed municipal digester (Table 22).

Table 22. ADM1 composition and kinetic parameters used to simulate municipal sludge digestion from Straub (2008)

Parameter	Value	Units
$f_{sI,xc}$	0.01	gS_I/gX_c
$f_{xI,xc}$	0.23	gX_I/gX_c
$f_{ch,xc}$	0.20	gX_{ch}/gX_c
$f_{pr,xc}$	0.40	gX_{pr}/gX_c
$f_{li,xc}$	0.16	gX_{li}/gX_c
$f_{rh,xc}$	0.33	gX_{rh}/gX_c
$f_{sh,xc}$	0.43	gX_{sh}/gX_c
$k_{hyd,rh}$	2.2	d^{-1}
$k_{hyd,sh}$	0.25	d^{-1}

The hydrolysis rate coefficients for rapid and slowly hydrolysable municipal waste found by Straub are approximately 30% greater than the food waste hydrolysis coefficients. However, the inert fraction is higher for municipal sludge compared to food waste. For a continuously fed simulation, volatile solids destruction, methane production rate and % CH_4 are all higher for food waste than municipal sludge at the same SRT (Table 23).

Table 23. Comparison of food waste digestion to municipal sludge digestion by continuously fed steady state simulation at 7gCOD/L-d and a 20 day SRT. Composition of food waste is from average of food proximate analyses. Methane production rates are at the 36.7 °C digester temperature

Parameter	Units	Food Waste Digester	Municipal Sludge Digester
VS Destruction Efficiency	%	69	60
Alkalinity	mg/L as $CaCO_3$	11,880	7,600
Acetate	mg/L	144	144
pH	-	7.7	7.4
Methane Production Rate*	mL CH_4/L-d	1,900	940
Digester VS concentration**	%	3.0	2.1
Digester TS concentration**	%	3.7	3.0
%CH_4 in biogas	%	61	59
Ammonia	mg NH_4-N/L	3,410	2,210

*based on digester volume ** based on sludge at specific gravity of 1.03

The low inert fraction of the food wastes results in higher volatile solids destruction efficiency for the same SRT, and therefore greater biomethane production per unit of COD fed. Differences in digester alkalinity, pH, and ammonia are derived from the difference in composition.

A higher volatile solids destruction efficiency was also found for food waste vs. municipal sludge in a study done at the East Bay Utility District (USEPA 2008). Results for mesophilic digestion of food waste at a 15 day SRT were compared to mesophilic municipal wastewater solids digestion with a 15 day SRT. For the 15 day SRT, 74% volatile solids destruction efficiency was found for food waste vs. 57% for municipal sludge (Table 24).

Table 24. Comparison of mesophilic food waste digestion and municipal wastewater solids digestion data at a 15 day SRT from USEPA (2008).

Parameter	Units	Food Waste Digestion	Municipal Sludge Digestion
SRT	days	15	15
VS Destruction Efficiency	%	74	57
COD Loading, Feed	gCOD/L-d	6.7	3.1
%CH_4 in biogas	%	64	63
Methane Production Rate*	mL CH_4/L-d	2,300	940

*based on digester volume

Summary of findings from calibrated ADM1 simulations

The pilot plant simulations performed using the calibrated ADM1 have been used to evaluate numerous operating conditions and model parameters. The model has shown that the pilot digester can operate under stable conditions when fed three times per week at 7 and 12 gCOD/L-d average loading rates. Model simulations to investigate loading transition scenarios indicated that for a constant feed concentration, the time it took to reach the new load and the magnitude of the new load were important. The effect of feeding frequency was found to be a very important parameter effecting digester loading capacity and stability. Comparison on simulations with daily vs. three batch feedings per week showed that more frequent feeding increases digester stability for the same average daily loading rate, which may allow for stable operation at higher average daily loading rates. Though not a topic within the capability of the modeling, the less frequent feeding with higher instantaneous COD loadings could have a greater potential for digester foaming than with more frequent feeding. The modified ADM1 model could account for the effect of hydrolysis rate coefficients and food waste composition on digester performance when these parameters were varied.

The results from the model simulations have created a basis for guiding pilot plant operation during the optimization and challenge phases. When being fed three times per week, the pilot digesters should not be fed higher than 12gCOD/L-d (10.8 d SRT). If the feeding strategy is changed to daily feeding, or the concentration of the feed is increased, a higher loading rate can be achieved during the optimization phase. When attempting to determine the maximum loading rate during the optimization phase it is recommended that daily feeding is employed. This will allow stable operation at higher loading rates than feeding three times per week, and will therefore maximize biomethane gas production. Model simulations show that the pilot plant can withstand a two month reduced loading period, and the ability to do so is favored more for operation at longer SRTs.

During the early portion of the pilot plant study the model will require further calibration. The main variables that will need to be investigated are the hydrolysis rate coefficients, as the feed particle size will be different for the pilot plant than for the lab digesters used for the original calibration. Some data collection is expected during the pilot study to account for the feed composition, which can be used for additional calibration.

SUMMARY and CONCLUSIONS

ADM1 was modified and applied for simulating anaerobic digestion performance when treating food waste from a military installation. The model was incorporated for use in Mathcad15, a commonly available and user friendly software package. Model changes specific to the food waste application were the incorporation of a dual hydrolysis kinetic model and the adjustment of the carbon and nitrogen content of the amino acid component from protein hydrolysis. Additional changes to the default ADM 1, which provided stable model runs under transient conditions were the incorporation of a continuous pH inhibition model and the use of ammonia production from amino acid degradation to predict the bicarbonate alkalinity concentration for use in the pH calculation. Successful model calibration to food waste anaerobic degradation was achieved using long term laboratory digesters and batch bottle tests. Hydrolysis kinetic rate coefficients were determine for readily and slowly biodegradable particulate COD in the food waste.

Model simulations with the calibrated ADM1 were used to indicate operating conditions that can lead to digester instability and evaluate digester performance. The model can be used to evaluate a wide range of transient feeding conditions to provide information on changes in digester VFA concentrations, pH, biomethane production rates, and COD conversion rates to biomethane energy. The calibrated model has been shown to have value as a predictive tool for evaluating pilot plant operational conditions. The following conclusions were drawn from the calibrated ADM1 simulations that have implications for the pilot plant study:

1. Stable operation is possible at average loading rates of 7 and 12 gCOD/L-d for three batch feeds (MWF) per week.
2. Daily batch feeding is more stable than three batch feeds per week, and a higher average COD loading rate can be used.
3. Transition of loading from 7 to 12 gCOD/L-d required a 30 day time period for stable operation with daily incremental increases.
4. The hydrolysis rate is a critical parameter for evaluating digester volatile solids reduction, total methane production, and transient loading VFA concentrations. Assuming higher hydrolysis rates provides a more conservative approach to evaluating digester stability.

5. The relative quantities of lipids and proteins in the food waste composition have a noticeable effect on digester performance and stability with regard to methane production and alkalinity and ammonia production, respectively.
6. At the same SRT, the volatile solids reduction efficiency for food waste digestion is higher than that for municipal waste sludge digestion.

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APPENDIX A: PETERSEN MATRICES FOR DEFAULT ADM1

The following two tables are presented on the next pages:

Table A-1. Petersen matrix for the soluble variables in the default ADM1

Table A-2. Petersen matrix for the particulate variables in the default ADM1

Component →	i	1	2	3	4	5	6	7	8	9	10	11	12	**Rate (ρ_j, g COD L^{-1} d^{-1})**
j	**Process ↓**	S_{su}	S_{aa}	S_{fa}	S_{va}	S_{bu}	S_{pro}	S_{ac}	S_{h2}	S_{ch4}	S_{IC}	S_{IN}	S_I	
1	Disintegration												$f_{sI,xc}$	$k_{dis}X_c$
2	Hydrolysis Carbohydrates	1												$k_{hyd,ch}X_{ch}$
3	Hydrolysis of Proteins		1											$k_{hyd,pr}X_{pr}$
4	Hydrolysis of Lipids	$1-f_{fa,li}$		$f_{fa,li}$										$k_{hyd,li}X_{li}$
5	Uptake of Sugars	-1				$(1-Y_{su})\ f_{bu,su}$	$(1-Y_{su})\ f_{pro,su}$	$(1-Y_{su})\ f_{ac,su}$	$(1-Y_{su})\ f_{h2,su}$		$-\sum_{i=1-9,11-24} C_i\, v_{i,5}$	$-(Y_{su})\ N_{bac}$		$k_{m,su}\frac{S_{su}}{K_S+S_{su}}X_{su}I_1$
6	Uptake of Amino Acids		-1		$(1-Y_{aa})\ f_{va,aa}$	$(1-Y_{aa})\ f_{bu,aa}$	$(1-Y_{aa})\ f_{pro,aa}$	$(1-Y_{aa})\ f_{ac,aa}$	$(1-Y_{aa})\ f_{h2,aa}$		$-\sum_{i=1-9,11-24} C_i\, v_{i,6}$	$N_{aa}-(Y_{aa})\ N_{bac}$		$k_{m,aa}\frac{S_{aa}}{K_S+S_{aa}}X_{aa}I_1$
7	Uptake of LCFA			-1				$(1-Y_{fa})\ 0.7$	$(1-Y_{fa})\ 0.3$			$-(Y_{fa})\ N_{bac}$		$k_{m,fa}\frac{S_{fa}}{K_S+S_{fa}}X_{fa}I_2$
8	Uptake of Valerate				-1		$(1-Y_{c4})\ 0.54$	$(1-Y_{c4})\ 0.31$	$(1-Y_{c4})\ 0.15$			$-(Y_{c4})\ N_{bac}$		$k_{m,c4}\frac{S_{va}}{K_S+S_{va}}X_{c4}\frac{1}{1+S_{bu}/S_{va}}I_2$
9	Uptake of Butyrate					-1		$(1-Y_{c4})\ 0.8$	$(1-Y_{c4})\ 0.2$			$-(Y_{c4})\ N_{bac}$		$k_{m,c4}\frac{S_{bu}}{K_S+S_{bu}}X_{c4}\frac{1}{1+S_{va}/S_{bu}}I_2$
10	Uptake of Propionate						-1	$(1-Y_{pro})\ 0.57$	$(1-Y_{pro})\ 0.43$		$-\sum_{i=1-9,11-24} C_i\, v_{i,10}$	$-(Y_{pro})\ N_{bac}$		$k_{m,pro}\frac{S_{pro}}{K_S+S_{pro}}X_{pro}I_2$
11	Uptake of Acetate							-1		$(1-Y_{ac})$	$-\sum_{i=1-9,11-24} C_i\, v_{i,11}$	$-(Y_{ac})\ N_{bac}$		$k_{m,ac}\frac{S_{ac}}{K_S+S_{ac}}X_{ac}I_3$
12	Uptake of Hydrogen								-1	$(1-Y_{h2})$	$-\sum_{i=1-9,11-24} C_i\, v_{i,12}$	$-(Y_{h2})\ N_{bac}$		$k_{m,h2}\frac{S_{h2}}{K_S+S_{h2}}X_{h2}I_1$
13	Decay of X_{su}													$k_{dec,xsu}X_{su}$
14	Decay of X_{aa}													$k_{dec,xaa}X_{aa}$
15	Decay of X_{fa}													$k_{dec,xfa}X_{fa}$
16	Decay of X_{c4}													$k_{dec,xc4}X_{c4}$
17	Decay of X_{pro}													$k_{dec,xpro}X_{pro}$
18	Decay of X_{ac}													$k_{dec,xac}X_{ac}$
19	Decay of X_{h2}													$k_{dec,xh2}X_{h2}$
		Monosaccharides (g COD L^{-1})	Amino Acids (g COD L^{-1})	Long Chain Fatty Acids (g COD L^{-1})	Total Valerate (g COD L^{-1})	Total Butyrate (g COD L^{-1})	Total Propionate (g COD L^{-1})	Total Acetate (g COD L^{-1})	Hydrogen Gas (g COD L^{-1})	Methane Gas (g COD L^{-1})	Inorganic Carbon (mol L^{-1})	Inorganic Nitrogen (mol L^{-1})	Soluble Inerts (g COD L^{-1})	Inhibition Factors: $I_1 = I_{pH}I_{IN,lim}$ $I_2 = I_{pH}I_{IN,lim}I_{h2}$ $I_3 = I_{pH}I_{IN,lim}I_{NH3,Xac}$

Component →	i	13	14	15	16	17	18	19	20	21	22	23	24	Rate (ρ_j, g COD L^{-1} d^{-1})
j	**Process ↓**	X_c	X_{ch}	X_{pr}	X_{li}	X_{su}	X_{aa}	X_{fa}	X_{c4}	X_{pro}	X_{ac}	X_{h2}	X_I	
1	Disintegration	-1	$f_{ch,xc}$	$f_{pr,xc}$	$f_{li,xc}$								$f_{xi,xc}$	$k_{dis}X_c$
2	Hydrolysis Carbohydrates		-1											$k_{hyd,ch}X_{ch}$
3	Hydrolysis of Proteins			-1										$k_{hyd,pr}X_{pr}$
4	Hydrolysis of Lipids				-1									$k_{hyd,li}X_{li}$
5	Uptake of Sugars					Y_{su}								$k_{m,su}\frac{S_{su}}{K_S+S_{su}}X_{su}I_1$
6	Uptake of Amino Acids						Y_{aa}							$k_{m,aa}\frac{S_{aa}}{K_S+S_{aa}}X_{aa}I_1$
7	Uptake of LCFA							Y_{fa}						$k_{m,fa}\frac{S_{fa}}{K_S+S_{fa}}X_{fa}I_2$
8	Uptake of Valerate								Y_{c4}					$k_{m,c4}\frac{S_{va}}{K_S+S_{va}}X_{c4}\frac{1}{1+S_{bu}/S_{va}}I_2$
9	Uptake of Butyrate								Y_{c4}					$k_{m,c4}\frac{S_{bu}}{K_S+S_{bu}}X_{c4}\frac{1}{1+S_{va}/S_{bu}}I_2$
10	Uptake of Propionate									Y_{pro}				$k_{m,pro}\frac{S_{pro}}{K_S+S_{pro}}X_{pro}I_2$
11	Uptake of Acetate										Y_{ac}			$k_{m,ac}\frac{S_{ac}}{K_S+S_{ac}}X_{ac}I_3$
12	Uptake of Hydrogen											Y_{h2}		$k_{m,h2}\frac{S_{h2}}{K_S+S_{h2}}X_{h2}I_1$
13	Decay of X_{su}	1				-1								$k_{dec,xsu}X_{su}$
14	Decay of X_{aa}	1					-1							$k_{dec,xaa}X_{aa}$
15	Decay of X_{fa}	1						-1						$k_{dec,xfa}X_{fa}$
16	Decay of X_{c4}	1							-1					$k_{dec,xc4}X_{c4}$
17	Decay of X_{pro}	1								-1				$k_{dec,xpro}X_{pro}$
18	Decay of X_{ac}	1									-1			$k_{dec,xac}X_{ac}$
19	Decay of X_{h2}	1										-1		$k_{dec,xh2}X_{h2}$
		Composites (g COD L^{-1})	Carbohydrates (g COD L^{-1})	Proteins (g COD L^{-1})	Lipids (g COD L^{-1})	Sugar Degraders (g COD L^{-1})	Amino Acid Degraders (g COD L^{-1})	LCFA Degraders (g COD L^{-1})	Valerate and Butyrate Degraders (g COD L^{-1})	Propionate Degraders (g COD L^{-1})	Acetate Degraders (g COD L^{-1})	Hydrogen Degraders (g COD L^{-1})	Particulate Inerts (g COD L^{-1})	Inhibition Factors: $I_1 = I_{pH}I_{IN,lim}$ $I_2 = I_{pH}I_{IN,lim}I_{h2}$ $I_3 = I_{pH}I_{IN,lim}I_{NH3,Xac}$

APPENDIX B: ADM1 SUGGESTED MODEL PARAMETERS

Table B-1. ADM1 suggested kinetic parameter values

Kinetic Parameter	Value at 35°C	Units
k_{dec_all}	0.02	d^{-1}
k_{m_su}	30	d^{-1}
K_{S_su}	0.5	gCOD/L
Y_{su}	0.1	gCOD$_X$/gCOD$_S$
k_{m_aa}	50	d^{-1}
K_{S_aa}	0.3	gCOD/L
Y_{aa}	0.08	gCOD$_X$/gCOD$_S$
k_{m_fa}	6	d^{-1}
K_{S_fa}	0.4	gCOD/L
Y_{fa}	0.06	gCOD$_X$/gCOD$_S$
k_{m_c4}	20	d^{-1}
K_{S_c4}	0.2	gCOD/L
Y_{c4}	0.06	gCOD$_X$/gCOD$_S$
k_{m_pro}	13	d^{-1}
K_{S_pro}	0.1	gCOD/L
Y_{pro}	0.04	gCOD$_X$/gCOD$_S$
k_{m_ac}	8	d^{-1}
K_{S_ac}	0.15	gCOD/L
Y_{ac}	0.05	gCOD$_X$/gCOD$_S$
k_{m_h2}	35	d^{-1}
K_{S_h2}	7.00E-06	gCOD/L
Y_{h2}	0.06	gCOD$_X$/gCOD$_S$

Table B-2. ADM1 suggested values for carbon and nitrogen content of model variables

C_i or N_i	C or N Content (mole C or N/gCOD$_i$)
C_{ch}	0.0313
C_{li}	0.022
C_{su}	0.0313
C_{fa}	0.0217
C_{va}	0.024
C_{bu}	0.025
C_{pro}	0.0268
C_{ac}	0.0313
C_{h2}	0
C_{ch4}	0.0156
C_{IC}	1
C_{IN}	0
C_{biom}	0.0313
N_{bac}	0.00625
N_{aa}	0.007

Table B-3. ADM1 suggested stoichiometric parameters

Variable	Fraction i from j
f_{fa_li}	0.95
f_{h2_su}	0.19
f_{bu_su}	0.13
f_{pro_su}	0.27
f_{ac_su}	0.41
f_{h2_aa}	0.06
f_{va_aa}	0.23
f_{bu_aa}	0.26
f_{pro_aa}	0.05
f_{ac_aa}	0.4

APPENDIX C: ADM1 LIQUID/GAS EQUATIONS

Gas transfer rate equations:

$$\rho_{T,H_2} = k_L a\left(S_{liq,H_2} - 16K_{H,H_2} p_{gas,H_2}\right) \tag{32}$$

$$\rho_{T,CH_4} = k_L a\left(S_{liq,CH_4} - 64K_{H,CH_4} p_{gas,CH_4}\right) \tag{33}$$

$$\rho_{T,CO_2} = k_L a\left(S_{liq,CO_2} - K_{H,CO_2} p_{gas,CO_2}\right) \tag{34}$$

where:

$\rho_{T,i}$ = transfer rate of gas I (g COD L^{-1} d^{-1} for H_2 and CH_4 and mol L^{-1} d^{-1} for CO_2)

k_La = overall mass transfer coefficient (d^{-1})

$S_{liq,i}$ = the liquid concentration of i (gCOD L^{-1} for H_2 and CH_4 and mol L^{-1} for CO_2)

$K_{H,i}$ = Henry's constant for gas i (M_{liq} bar_{gas}^{-1})

$p_{gas,i}$ = partial pressure of gas i (bar)

$$p_{gas,H_2} = S_{gas,H_2}\ RT/16 \tag{35}$$

$$p_{gas,CH_4} = S_{gas,CH_4}\ RT/64 \tag{36}$$

$$p_{gas,CO_2} = S_{gas,CO_2} RT \tag{37}$$

where:

$S_{gas,i}$ = gas i concentration (g COD L^{-1} for H_2 and CH_4 and M for CO_2)

R = universal gas constant (L bar mol^{-1} K^{-1})

T = temperature (K)

$$\frac{dS_{gas,i}}{dt} = -\frac{S_{gas,i} q_{gas}}{V_{gas}} + \rho_{T,i}\frac{V_{liq}}{V_{gas}} \tag{38}$$

where:

q_{gas} = the gas flow rate, L_{gas}/d, and is defined by the following equation:

$$q_{gas} = \frac{RT}{\sum_i p_{gas,i}} V_{liq}\left(\frac{\rho_{T,H_2}}{16} + \frac{\rho_{T,CH_4}}{64} + \rho_{T,CO_2}\right) \tag{39}$$

APPENDIX D: PETERSEN MATRICES FOR MODIFIED ADM1

The following two tables are presented on the next pages:

Table D-1. Petersen matrix for the soluble variables in the modified ADM1*

Table D-2. Petersen matrix for the particulate variables in the modified ADM1*

*Differences between modified and default ADM1 Petersen Matrices are highlighted in gray.

Component →	i	1	2	3	4	5	6	7	8	9	10	11	12	Rate (ρ_j, g COD L^{-1} d^{-1})
j	**Process ↓**	S_{su}	S_{aa}	S_{fa}	S_{va}	S_{bu}	S_{pro}	S_{ac}	S_{h2}	S_{ch4}	S_{IC}	S_{IN}	S_I	
1	Partitioning of Composite												$f_{sI,xc}$	k_{inst}
2	Preexisitng Rapid Hydrolysis	$f_{ch,rh0}$	$f_{pr,rh0}$	$f_{li,rh0}$										$k_{hyd,rh0}X_{rh0}$
3	Preexisitng Slow Hydrolysis	$f_{ch,sh0}$	$f_{pr,sh0}$	$f_{li,sh0}$										$k_{hyd,sh0}X_{sh0}$
4	Rapid Hydrolysis	$f_{ch,rh}$	$f_{pr,rh}$	$f_{li,rh}$										$k_{hyd,rh}X_{rh}$
5	Slow Hydrolysis	$f_{ch,sh}$	$f_{pr,sh}$	$f_{li,sh}$										$k_{hyd,sh}X_{sh}$
6	Recycling Biomass Decay	$f_{ch,ed}$	$f_{pr,ed}$	$f_{pr,ed}$										$k_{inst}X_{ed}$
7	Uptake of Sugars	-1				$(1-Y_{su})\ f_{bu,su}$	$(1-Y_{su})\ f_{pro,su}$	$(1-Y_{su})\ f_{ac,su}$	$(1-Y_{su})\ f_{h2,su}$		$-\sum_{i=1-9,11-26} C_i v_{i,5}$	$-(Y_{su})\ N_{bac}$		$k_{m,su} \frac{S_{su}}{K_S+S_{su}} X_{su}$
8	Uptake of Amino Acids		-1		$(1-Y_{aa})\ f_{va,aa}$	$(1-Y_{aa})\ f_{bu,aa}$	$(1-Y_{aa})\ f_{pro,aa}$	$(1-Y_{aa})\ f_{ac,aa}$	$(1-Y_{aa})\ f_{h2,aa}$		$-\sum_{i=1-9,11-26} C_i v_{i,6}$	$N_{aa} -(Y_{aa})\ N_{bac}$		$k_{m,aa} \frac{S_{aa}}{K_S+S_{aa}} X_{aa}$
9	Uptake of LCFA			-1				$(1-Y_{fa})\ 0.7$	$(1-Y_{fa})\ 0.3$			$-(Y_{fa})\ N_{bac}$		$k_{m,fa} \frac{S_{fa}}{K_S+S_{fa}} X_{fa}$
10	Uptake of Valerate				-1		$(1-Y_{c4})\ 0.54$	$(1-Y_{c4})\ 0.31$	$(1-Y_{c4})\ 0.15$			$-(Y_{c4})\ N_{bac}$		$k_{m,c4} \frac{S_{va}}{K_S+S_{va}} X_{c4} \frac{1}{1+S_{bu}/S_{va}}$
11	Uptake of Butyrate					-1		$(1-Y_{c4})\ 0.8$	$(1-Y_{c4})\ 0.2$			$-(Y_{c4})\ N_{bac}$		$k_{m,c4} \frac{S_{bu}}{K_S+S_{bu}} X_{c4} \frac{1}{1+S_{va}/S_{bu}}$
12	Uptake of Propionate						-1	$(1-Y_{pro})\ 0.57$	$(1-Y_{pro})\ 0.43$		$-\sum_{i=1-9,11-26} C_i v_{i,10}$	$-(Y_{pro})\ N_{bac}$		$k_{m,pro} \frac{S_{pro}}{K_S+S_{pro}} X_{pro}$
13	Uptake of Acetate							-1		$(1-Y_{ac})$	$-\sum_{i=1-9,11-26} C_i v_{i,11}$	$-(Y_{ac})\ N_{bac}$		$k_{m,ac} \frac{S_{ac}}{K_S+S_{ac}} X_{ac} I_{pH}$
14	Uptake of Hydrogen								-1	$(1-Y_{h2})$	$-\sum_{i=1-9,11-26} C_i v_{i,12}$	$-(Y_{h2})\ N_{bac}$		$k_{m,h2} \frac{S_{h2}}{K_S+S_{h2}} X_{h2}$
15	Decay of X_{su}													$k_{dec,xsu}X_{su}$
16	Decay of X_{aa}													$k_{dec,xaa}X_{aa}$
17	Decay of X_{fa}													$k_{dec,xfa}X_{fa}$
18	Decay of X_{c4}													$k_{dec,xc4}X_{c4}$
19	Decay of X_{pro}													$k_{dec,xpro}X_{pro}$
20	Decay of X_{ac}													$k_{dec,xac}X_{ac}$
21	Decay of X_{h2}													$k_{dec,xh2}X_{h2}$
		Monosaccharides (g COD L^{-1})	Amino Acids (g COD L^{-1})	Long Chain Fatty Acids (g COD L^{-1})	Total Valerate (g COD L^{-1})	Total Butyrate (g COD L^{-1})	Total Propionate (g COD L^{-1})	Total Acetate (g COD L^{-1})	Hydrogen Gas (g COD L^{-1})	Methane Gas (g COD L^{-1})	Inorganic Carbon (mol L^{-1})	Inorganic Nitrogen (mol L^{-1})	Soluble Inerts (g COD L^{-1})	Inhibition Factors: I_{pH}: For acetoclastic methanogens only

Component →		i	13	14	15	16	17	17	19	20	21	22	23	24	25	26	
j	Process ↓		X_c	X_{ed}	X_{rh0}	X_{sh0}	X_{rh}	X_{sh}	X_{su}	X_{aa}	X_{fa}	X_{c4}	X_{pro}	X_{ac}	X_{h2}	X_I	Rate (ρ_j, g COD L^{-1} d^{-1})
1	Partitioning of Composite		-1				$f_{rh,xc}$	$f_{sh,xc}$								$f_{xI,xc}$	k_{inst}
2	Preexisitng Rapid Hydrolysis				-1												$k_{hyd,rh0}X_{rh0}$
3	Preexisitng Slow Hydrolysis					-1											$k_{hyd,sh0}X_{sh0}$
4	Rapid Hydrolysis						-1										$k_{hyd,rh}X_{rh}$
5	Slow Hydrolysis							-1									$k_{hyd,sh}X_{sh}$
6	Recycling Biomass Decay			-1												$f_{xI,ed}$	$k_{inst}X_{ed}$
7	Uptake of Sugars								Y_{su}								$k_{m,su}\frac{S_{su}}{K_S+S_{su}}X_{su}$
8	Uptake of Amino Acids									Y_{aa}							$k_{m,aa}\frac{S_{aa}}{K_S+S_{aa}}X_{aa}$
9	Uptake of LCFA										Y_{fa}						$k_{m,fa}\frac{S_{fa}}{K_S+S_{fa}}X_{fa}$
10	Uptake of Valerate											Y_{c4}					$k_{m,c4}\frac{S_{va}}{K_S+S_{va}}X_{c4}\frac{1}{1+S_{bu}/S_{va}}$
11	Uptake of Butyrate											Y_{c4}					$k_{m,c4}\frac{S_{bu}}{K_S+S_{bu}}X_{c4}\frac{1}{1+S_{va}/S_{bu}}$
12	Uptake of Propionate												Y_{pro}				$k_{m,pro}\frac{S_{pro}}{K_S+S_{pro}}X_{pro}$
13	Uptake of Acetate													Y_{ac}			$k_{m,ac}\frac{S_{ac}}{K_S+S_{ac}}X_{ac}I_{pH}$
14	Uptake of Hydrogen														Y_{h2}		$k_{m,h2}\frac{S_{h2}}{K_S+S_{h2}}X_{h2}$
15	Decay of X_{su}			1					-1								$k_{dec,xsu}X_{su}$
16	Decay of X_{aa}			1						-1							$k_{dec,xaa}X_{aa}$
17	Decay of X_{fa}			1							-1						$k_{dec,xfa}X_{fa}$
18	Decay of X_{c4}			1								-1					$k_{dec,xc4}X_{c4}$
19	Decay of X_{pro}			1									-1				$k_{dec,xpro}X_{pro}$
20	Decay of X_{ac}			1										-1			$k_{dec,xac}X_{ac}$
21	Decay of X_{h2}			1											-1		$k_{dec,xh2}X_{h2}$
			Composites (g COD L^{-1})	Endogenous Decay (g COD L^{-1})	Preexisting Rapidly Hydrolyzable Composite (g COD L^{-1})	Preexisting Slowly Hydrolyzable Composite (g COD L^{-1})	Rapidly Hydrolyzable Composite (g COD L^{-1})	Slowly Hydrolyzable Composite (g COD L^{-1})	Sugar Degraders (g COD L^{-1})	Amino Acid Degraders (g COD L^{-1})	LCFA Degraders (g COD L^{-1})	Valerate and Butyrate Degraders (g COD L^{-1})	Propionate Degraders (g COD L^{-1})	Acetate Degraders (g COD L^{-1})	Hydrogen Degraders (g COD L^{-1})	Particulate Inerts (g COD L^{-1})	Inhibition Factors: I_{pH}: For acetoclastic methanogens only

APPENDIX E: FOOD PROXIMATE ANALYSES FOR USAFA FOOD WASTES

The following two tables are presented on the next pages:

Table E-1. Raw food proximate analyses for USAFA food wastes

Table E-2. USAFA food waste description on dry weight and COD basis

Sample #	Meal	Description	Calories (per 100g)	VS (%)	TS (%)	VS/TS	TP (mg/100g)	TKN (% of wet weight)	Moisture (%)	Protein (% of wet weight)	Fat (% of wet weight)	Ash (% of wet weight)	Carbs (% of wet weight)
FW-001	Breakfast	Vegetable matter (greens and orange), possibly eggs, starches	111	22.6	24	0.94	256	1.67	76.00	10.40	4.1	1.4	8.1
FW-002	Lunch	Cheese, bits of paper, black peels from beans or grapes, yellow clumps, meat	117	23.9	25.7	0.93	80.3	0.95	74.30	5.90	3.6	1	15.2
FW-003	Dinner	Rice, meat, vegetable matter	106	30.2	30.7	0.98	58.8	0.85	69.30	5.30	1.9	0.7	17
FW-004	Breakfast	Vegetable matter, meat, dairy and possibly eggs, strings of plastic	90	18.8	19.9	0.94	31.5	0.50	80.10	3.10	2.5	0.6	13.7
FW-005	Lunch	Yellow and white matter (appears to be starch or dairy) with pieces of meat, low moisture content	312	34.1	62.3	0.55	188	2.32	37.70	14.50	13.4	1.1	33.3
FW-006	Dinner	High moisture content, vegetable matter (green, orange and red), small pieces of meat	96	14.2	22.5	0.63	40	0.55	77.50	3.40	1.5	0.5	17.1
FW-007	Breakfast	Mostly meat, low moisture content, strips of plastic, orange peel, eggs or starches	286	32	59.7	0.54	108	3.26	40.30	20.40	10	0.7	28.6
FW-008	Lunch	Mostly yellow starchy material (low moisture) with bits of meat, yellow and black vegetable matter	277	30.3	55.7	0.54	130	2.40	44.30	15.00	11.6	1	28.1
FW-009	Dinner	Meat, vegetable matter (yellow, orange green and black), citrus peel, strips of plastic	158	30.8	31.3	0.98	62.7	1.25	68.70	7.80	7.1	0.7	15.7
FW-010	Breakfast	Mostly meat, medium moisture content, vegetable matter (red, green, yellow and white), strips of plastic	65	15.6	16.1	0.97	30	0.35	83.90	2.20	0.6	0.6	12.7
FW-011	Lunch	Yellow starch or dairy, medium moisture content, vegetable matter (green, red, orange and black), bits of paper, possible grape peel material	137	23.2	24.7	0.94	80	1.15	75.3	7.2	8.6	1.1	7.8
FW-012	Dinner	Mostly white meat, low moisture content, Vegetal matter (green, yellow, orange and white)	122	23	23.4	0.98	76.5	2	76.6	12.7	6.1	0.6	4
FW-013	Breakfast	Wet brown material with pieces of pink meat, Vegetable matter (red, green and white), possible grape peel material, some of the material has a blue-green discoloration	159	30.1	31.9	0.94	87.4	2.96	68.1	18.5	7.8	2	3.6
FW-014	Lunch	High moisture content, pink meat, nuts, peel material, vegetable matter (red, yellow, white, green and black)	125	26.4	26.8	0.99	97.5	2.52	73.2	15.8	4.6	1.2	5.2
FW-015	Dinner	Dark meat, grains (rice or barley), high moisture content, vegetable matter (green, orange yellow and white)	164	33	40.1	0.82	106	1.69	59.9	10.6	7.6	1.2	13.2
FG-051410-B	Cooking Oil	Solid at room temperature, some water, small bits of food	576	66.5	67.6	0.98	30	0.04	32.4	0.2	61.3	0.2	5.9
FW-016 (FW-011 Duplicate)	Lunch	Yellow starch or dairy, medium moisture content, vegetable matter (green, red, orange and black), bits of paper, possible grape peel material	145	25.6	27.1	0.94	79.5	1.28	72.9	8	8.4	1.3	9.4

Sample #	Moisture (%)	Protein (% of wet weight)	Fat (% of wet weight)	Ash (% of wet weight)	Carbs (% of wet weight)	Dry weight Protein (g/gVS)	Dry weight Lipids (g/gVS)	Dry weight Carb (g/gVS)	Protein COD (g/g COD)	Lipid COD (g/g COD)	Carb COD (g/g COD)
FW-001	76.00	10.40	4.1	1.4	8.1	0.46	0.18	0.36	0.43	0.33	0.24
FW-002	74.30	5.90	3.6	1	15.2	0.24	0.15	0.62	0.25	0.29	0.46
FW-003	69.30	5.30	1.9	0.7	17	0.22	0.08	0.70	0.25	0.17	0.58
FW-004	80.10	3.10	2.5	0.6	13.7	0.16	0.13	0.71	0.17	0.27	0.55
FW-005	37.70	14.50	13.4	1.1	33.3	0.24	0.22	0.54	0.22	0.40	0.37
FW-006	77.50	3.40	1.5	0.5	17.1	0.15	0.07	0.78	0.18	0.16	0.66
FW-007	40.30	20.40	10	0.7	28.6	0.35	0.17	0.48	0.34	0.32	0.34
FW-008	44.30	15.00	11.6	1	28.1	0.27	0.21	0.51	0.26	0.39	0.35
FW-009	68.70	7.80	7.1	0.7	15.7	0.25	0.23	0.51	0.24	0.42	0.34
FW-010	83.90	2.20	0.6	0.6	12.7	0.14	0.04	0.82	0.17	0.09	0.73
FW-011	75.3	7.2	8.6	1.1	7.8	0.31	0.36	0.33	0.24	0.57	0.19
FW-012	76.6	12.7	6.1	0.6	4	0.56	0.27	0.18	0.46	0.43	0.11
FW-013	68.1	18.5	7.8	2	3.6	0.62	0.26	0.12	0.51	0.42	0.07
FW-014	73.2	15.8	4.6	1.2	5.2	0.62	0.18	0.20	0.55	0.32	0.13
FW-015	59.9	10.6	7.6	1.2	13.2	0.34	0.24	0.42	0.30	0.42	0.27
FG-051410-B	32.4	0.2	61.3	0.2	5.9	0.003	0.91	0.09	0.00	0.96	0.03
FW-016 (FW-011 Duplicate)	72.9	8	8.4	1.3	9.4	0.31	0.33	0.36	0.26	0.53	0.22

APPENDIX F: USAFA ANAEROBIC DIGESTER VOLATILE SOLIDS DESTRUCTION EFFICIENCY

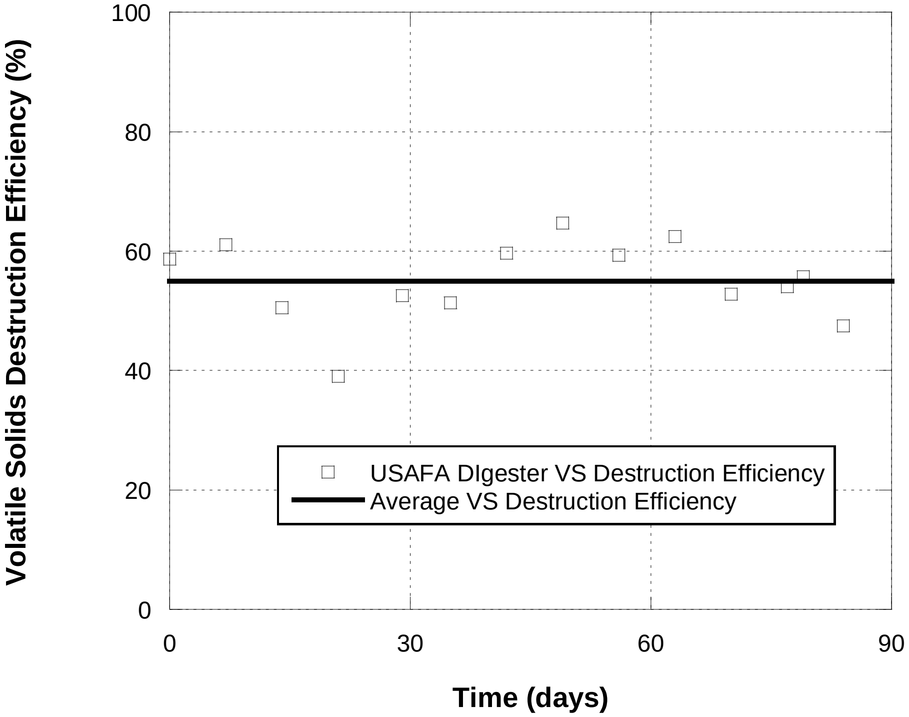

Figure F-1. USAFA wastewater treatment plant anaerobic digester volatile solids destruction efficiency vs. time for a relatively steady three month period. Average VS Destruction Efficiency is 55.0%.

APPENDIX G: EFFECT OF VFA CONCENTRATION ON METHANE PRODUCTION

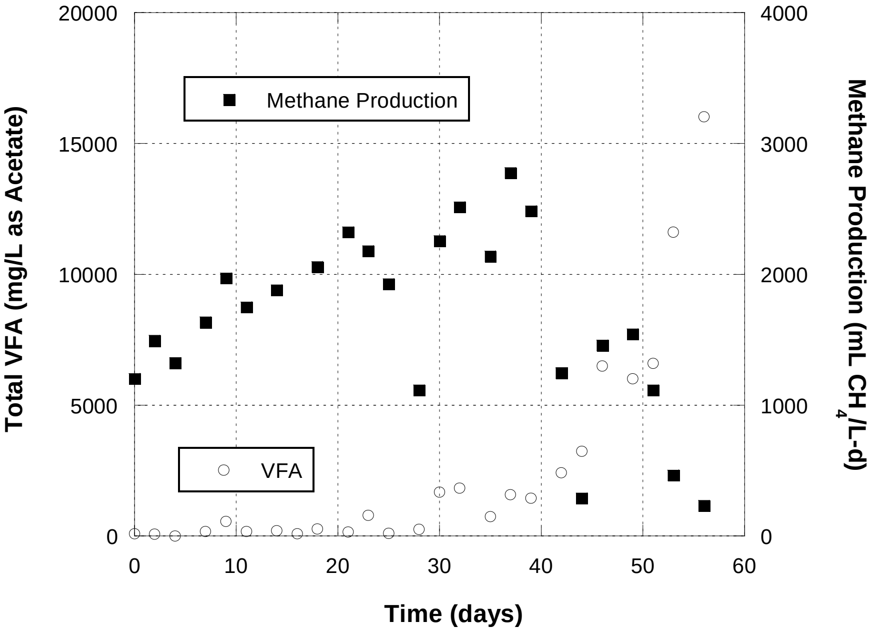

Figure G-1. Total VFA concentration and methane production rate vs. time for a laboratory digester with loading rate transitioned from 5 to 10 gCOD/L-d over 50 days

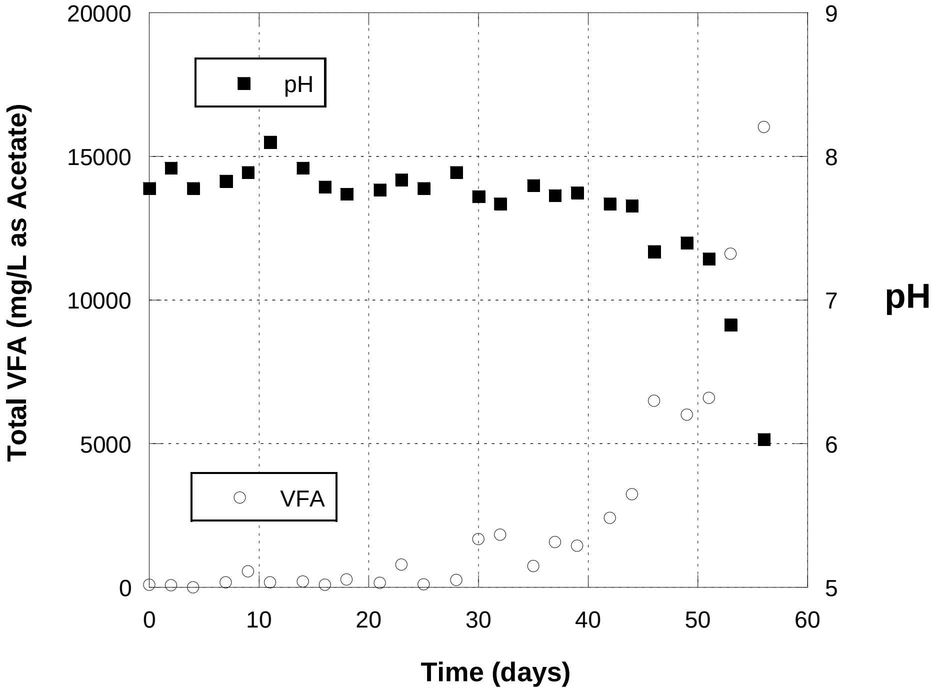

Figure G-2. Total VFA concentration and pH vs. time for a laboratory digester with loading rate transitioned from 5 to 10 gCOD/L-d over 50 days

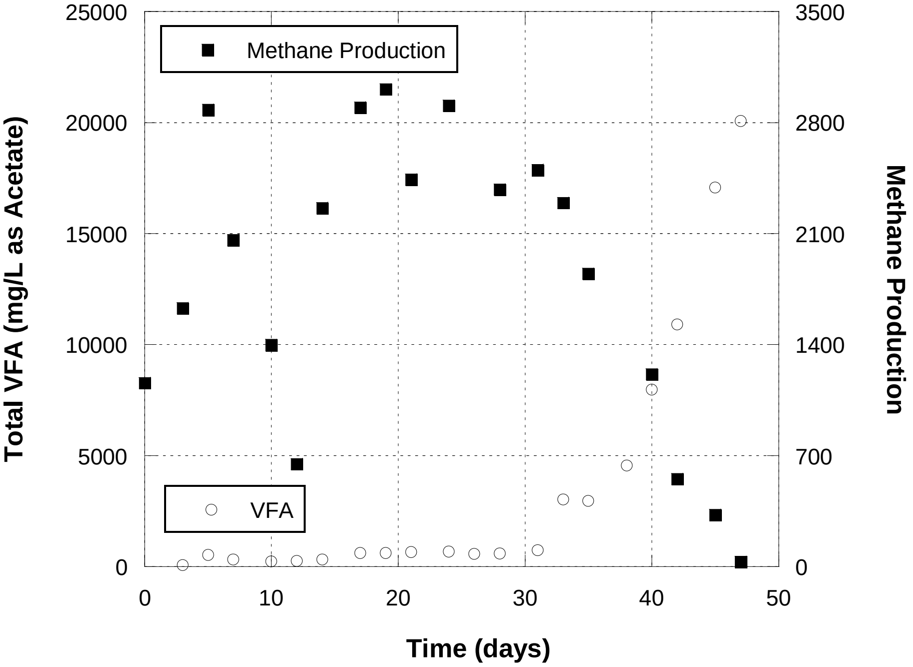

Figure G-3. Total VFA concentration and methane production rate vs. time for another laboratory digester with a 6gCOD/L-d average loading rate

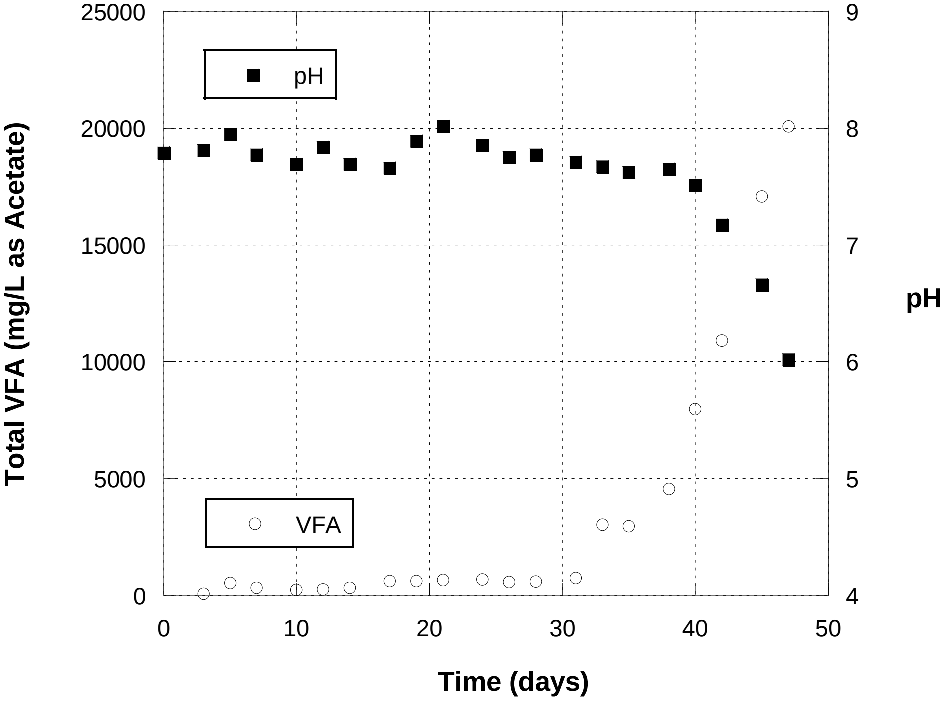

Figure G-4. Total VFA concentration and pH vs. time for another laboratory digester with a 6 gCOD/L-d average loading rate

Appendix F: TDA Biogas Purification Report

FINAL REPORT

Pilot-scale Biogas CO_2/Humidity Removal System and Desulfurization Sorbent

ESTCP Project Number ER 200933

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December 2015

OVERVIEW

A low cost two-stage complete biogas purification system has been developed that removes a wide variety of contaminants from the gases produced by an anaerobic digester. The contaminants removed include inorganic sulfur, organic sulfur, siloxanes, and bulk gases such as CO_2, and moisture, producing a product that is greater than 95% bio-methane. The first stage is based on a low-cost, high-capacity and expendable sorbent called SulfaTrap^{TM} that simultaneously removed sulfur and siloxane down to ppb levels. The second stage is a vacuum swing adsorption system based on a regenerable mesoporous carbon media modified with surface functional groups that reduces the CO_2 and H_2O concentration in the biogas to pipeline specifications.

The purification system was demonstrated in conjunction with a food waste anaerobic digester run at the U.S. Air Force Academy (USAFA) in Colorado Springs, CO. In this project the pilot scale biogas purification system was installed and tested with biogas generated via anaerobic digestion of a variety of food wastes, including pre- and post-consumer food waste, waste cooking oil, and grease trap waste to produce pipeline quality bio-methane. The sulfur in the raw biogas was typically around 1,000 – 1,500 ppm H_2S with trace amounts of organic sulfur compounds. The SulfaTrap^{TM}-R7 desulfurization sorbent removed the sulfur compounds to less than 0.25 ppmv.

We initially carried out breakthrough tests with the CO_2 sorbent beds in the field. We used desulfurized food waste derived biogas to measure the capacity of the saturated VSA adsorbent beds, which was above 4.4% wt. CO_2. We then optimized the VSA cycles in the field, and the optimized VSA cycle scheme was used to produce high purity bio-methane with a methane recovery greater than 90%. VSA cycle schemes with both feed end and product end pressurizations provided sorbent CO_2 working capacities of 2.8% wt., and the CO_2 concentration in the bio-methane product was reduced to less than 0.5% by vol. The dew point of the biogas was reduced from 10-15°C to less than -40°C, providing essentially a dry bio-methane product. The methane purity of the bio-methane produced was confirmed by a CO_2 probe and an IR based methane analyzer. We operated the biogas purification system for a total of 54 hours, purifying more than 3,620 SCF of biogas to produce bio-methane with greater than 90% methane recovery.

We also demonstrated the CO_2 sorbent's performance in a bench-scale two-bed vacuum swing system, demonstrating the life of our sorbent for over 2,900 cycles. We carried out a design for a VSA unit that is sized to process 2,000 m^3/day of biogas with a composition of 60% CH_4, 40% CO_2 (on dry basis) that is saturated with water at 24°C. We estimated the vacuum power requirement to be 14.6 kW_e, the sorbent bed size to be 600 L/bed, the operating power cost was \$0.04 per m^3 CH_4 produced and the total operating cost including the sorbent replacement cost was \$0.07 per m^3 CH_4 produced with a methane purity and recovery of 99.5% and 80.3%, respectively. The methane recovery can be further increased to 90% or above by relaxing the methane purity to 96%+% and increasing operating power cost to \$0.05 per m^3 CH_4 produced, which results in a total operating cost (including sorbent replacement) of \$0.08 per m^3 CH_4 produced for CO_2 and H_2O removal and the total cost of sulfur removal is \$41.3 per kg sulfur.

1.0 INTRODUCTION

Food is the largest component (21 percent) of municipal solid waste. Hence, innovative processes are needed that divert food waste from landfills and recover valuable resources. Anaerobic digestion is an effective process where food wastes including pre- and post-consumer food waste, waste cooking oil, and grease trap waste are converted to biogas, which can be further purified and converted to bio-methane, which contains more than 95% methane. Bio-methane can then be used for transportation purposes or to generate combined heat and electricity using fuel cells. A major challenge is the cost-effective purification of biogas while simultaneously minimizing energy requirements.

Biogas is often produced by anaerobic digestion in municipal wastewater treatment facilities (WWTFs) and wastewater treatment plants for the food and beverage industry. Biogas is the result of decomposition of organic wastes, but the methane is diluted with large amounts of CO_2 (greater than 30%) and it therefore possesses less energy per unit volume than pipeline methane (natural gas). In addition to CO_2 and CH_4, the biogas generated in the digesters and fermentation units also contain moisture at saturation and various trace contaminants such as sulfur compounds (e.g., hydrogen sulfide) and siloxanes. Table 1 shows the typical biogas composition generated from anaerobic digestion. These contaminants must be removed and CO_2 and the other inerts reduced to produce a higher quality fuel that contains more than 90% methane (bio-methane).

Table 1. Typical ADG biogas composition after bulk sulfur removal.

Gas Pressure	5-20 in. water column, positive
Gas Temperature	110°F
Gas Composition, by volume	60% CH_4, 35% CO_2, and 5% N_2
Moisture Content	Saturated
Siloxanes	
Total	4.5 ppmv
D4	0.4 ppmv
D5	4.1 ppmv
Halogens	1 ppmv
Sulfur	
Hydrogen sulfide	200 ppmv
Carbonyl sulfide	5 ppmv
Carbon disulfide	1 ppmv
Dimethyl sulfide	5 ppmv
Dimethyl disulfide	5 ppmv
Other disulfides	2 ppmv
Methyl mercaptan	5 ppmv
Ethyl mercaptan	1 ppmv
BTX	less than 1 ppmv

Although various adsorbents or solvent systems are available to remove hydrogen sulfide (H_2S), the most common form of sulfur in the biogas, the biogas also contains a wide range of organic sulfur compounds ranging from mercaptans to higher molecular weight disulfides.

Unfortunately, the conventional desulfurization systems do very little to remove the organic sulfur compounds, particularly the disulfides. The conventional sorption systems such as iron sponge and SulfaTreat^{TM} also have disadvantages with respect to safety and material handling. Another class of compounds present in biogas are the siloxanes. Siloxanes are generated during anaerobic digestion of waste activated sludge that concentrates silicone-based personal hygiene, health-care and industrial products. Siloxanes must be removed from biogas prior to its use as an energy source.

1.1 BACKGROUND

Food waste based anaerobic digester units capable of producing pipeline quality methane could be instrumental in eliminating the difficulties associated with its disposal and be a source of heating and electricity and significantly reduce disposal costs and operating expenses. If consumed properly, use of food waste derived fuels can also protect against environmental problems such as groundwater leaching and greenhouse gas emissions (methane emissions) associated with land filling of the food wastes. In today's scenario of growing energy demands worldwide any methane emitted into the atmosphere is an untapped resource of energy that has a global warming potential (GWP) of 25 (over 100 years). TDA's CO_2 removal system could also be used for capturing CO_2 from other industrial gases, such as off-gases from refineries, cement plants etc.

Biogas to pipeline or transportation methane technology can be part of new digestion system installations or an add-on to current systems. According to the U.S. Environmental Protection Agency (EPA), biogas recovery systems are technically feasible at more than 8,000 U.S. dairy and swine operations in the U.S. and biogas recovery is also feasible at some poultry operations (AgSTAR Oct 2010). As of July 2010 there were 157 large-farm located anaerobic digesters operating in the U.S. (Key 2011), and it is estimated that an average of 15 new digesters are coming online each year (AgSTAR 2011). This corresponds to a total addressable market in the dairy farm area of $348 million.

Even though the anaerobic digester system includes a desulfurization system, existing systems will remove only H_2S and will leave behind other organic sulfur species such as higher sulfides and mercaptans. Depending on the biomass feedstock and digester design, the concentration of these higher sulfide species ranges from 0.1 ppmv to as high as 30 ppmv. The main source of the VSCs in biosolids is protein degradation, especially degradation of the amino acid methionine (Higgins et al., 2004). Similarly, H_2S can be formed from the degradation of the sulfur containing amino acid cysteine. Once H_2S and MeSH are formed, they can be methylated to form Me_2S and can be oxidized to form Me_2Se_2 and other higher sulfides. In short,

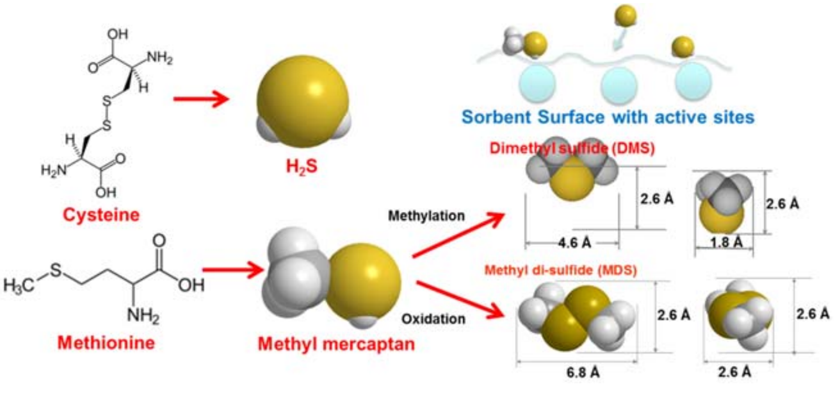


Figure 1. Some of the disulfide molecules present in the biogas.

sulfur is always present at significant levels in animal wastes. In the digester, hydrolysis of sulfur containing proteins (e.g., cysteine, cystine, methionine) and organic sulfur compounds produces H_2S, mercaptans and organic sulfides and disulfides.

The sulfur concentration of the biogas could be as high as 1.5% vol. Even conventional CHPs require some level of sulfur removal to prevent corrosion of the metal components, acidifying the engine oil and emissions of SO_2. A sulfur limit of 100 ppmv is often recommended for trouble-free operation of conventional CHPs. These limits can easily be achieved using off-the-shelf desulfurization technology. However, the sulfur limits must be reduced by an additional two orders of magnitude (to 4 ppmv or lower) if the biogas is to be further purified to pipeline or transportation methane levels. This sulfur limit needs to reduced to by an additional order of magnitude (to 0.1 ppmv or lower) for it to be used as fuel cell feedstock. In several studies (Matsuzaki 2001) the poisoning effects of H_2S on the Ni-YSZ (yttria stabilized zirconia) cermet electrolytes have been documented. One study shows 30% decline in cell performance as the sulfur concentration in the fuel gas exceeds 0.4 ppmv (Israelson, 2003). Therefore, long-term stable electrochemical performance requires the feed sulfur level be reduced to ultra low (ppb) levels.

Conventional Desulfurization Technology

Biogas can be desulfurized by various physical, biological and chemical processes. Because it is difficult to reduce the sulfur content from the percent range to ppb range, usually a two-step cleaning process is followed (e.g., a rough gas cleaning a step followed by adsorption for sulfur polishing). Below we describe the currently available bulk desulfurization process. All of these are designed for H_2S removal, remove little, if any of the organic sulfur compounds (particularly the disulfides), and reduce the sulfur from the percent levels to tens of ppm (but not ppbs).

Biological Desulfurization: In this process, H_2S is adsorbed in water and then degraded biologically with microorganisms of the species *Thiobacillus* and *Sulfolobus*. These bacteria require oxygen in the immobilization bioreactors. This approach works well for plants of less than 200kW capacity. Trickling filters and other bio-scrubbers are used with caustic soda reduce the H_2S content to 75-100 ppmv range.

Sulfide Precipitation: For the fixation of sulfur, a mixture of Fe^{2+} (e.g., $FeCl_2$) and Fe^{3+} ($FeCl_3$) are contacted in a mixing tank to precipitate a stable iron (II) sulfide and sulfur. A fresh supply of iron salt must be continuously provided. The process can reduce the sulfur level to less than 30 ppmv, but is relatively expensive due to the high cost of the iron salt.

Absorption in Ferric Chelate Solution: This is known as the LO CAT process. In a ferric chelate solution Fe^{3+} ions are reduced to Fe^{2+}, while H_2S is oxidized to elementary sulfur. A chelating agent is needed to ensure the Fe^{2+} ions do not react spontaneously to iron sulfide and/or iron hydroxide and can be continuously used. The chelate is regenerated by converting Fe^{2+} to Fe^{3+} in a separate reactor. The sulfur concentrate is collected at the reactor bottom and periodically removed. This process removes most of the H_2S (e.g., 99.9% removal efficiency) and is viable for biogas with high levels of sulfur (up to 15,000 ppmv). However, the LO CAT® process cannot remove mercaptans, COS and higher sulfides.

Solid Scavengers: Iron sponge and bog iron ores can be used to effectively remove H_2S with high capacity. There are several products that use iron oxides to remove a bulk of the sulfur. Iron oxides remove sulfur by forming insoluble iron sulfides. The most well known iron oxide product is called "iron sponge." Iron-oxide media such as SulfaTreat®, Sulfur-Rite®, and Media-G2® have been offered as improved alternatives to iron sponge (Zicari, 2003). Among various varieties, SulfaTreat® supplies a natural ore comprised of iron hydroxide [$Fe(OH)_3$] and iron oxide (Fe_2O_3) mixture to remove H_2S. These sorbent is placed in a tower reactor, and is periodically removed when it is saturated with sulfur. The biogas and the sorbent are contacted at 50°C; the gas has to be humidified to prevent water carryover from the sorbent. The H_2S concentration can be reduced to less than 4 ppmv, however, the so-called "H_2S scavengers" can only remove H_2S, and cannot remove COS, mercaptans and other sulfur species.

Chemical Sorbents: The H_2S content of the biogas could also be reduced to the 2-3 ppm using a chemical absorbent such as zinc oxide (ZnO) and its derivatives. Because sulfur is removed via a chemical reaction these systems operate at relatively high temperatures (300-400°C), these sorbents are not compatible with some downstream uses of the methane, for example a molten carbonate fuel cell (MCFC), which needs a cold feed stream for heat management reasons.

Physical Adsorbents: The technologies listed above have been applied effectively to the bulk H_2S removal from the biogas, however, they do not reduce the sulfur content to the ppb levels. Adsorptive removal of sulfur is an attractive option to achieve ultra low sulfur concentrations. Activated carbons are somewhat effective at removing H_2S, if the biogas is free of oxygen. However, the sulfur capacity and removal efficiency of the carbon beds are poor unless they are chemically modified. One approach is to impregnate the activated carbon with potassium iodide (KI) at a concentration of 1-5% by weight. In the presence of oxygen and water, H_2S dissolves in the water layer on the carbon surface and reacts with the oxygen at 50-70°C. Potassium carbonate (K_2CO_3) at 10-20% weight concentration works in a similar manner. H_2S concentrations in the gas can be reduced to less than 1 ppmv with these adsorbents. Unfortunately, neither the carbon sorbents nor their competitors based on silica, alumina, or zeolite can remove the larger and more complex mercaptans, sulfides and disulfides (which are also present at the 1-30 ppm level.)

Unfortunately, the conventional desulfurization systems do very little to remove the organic sulfur compounds, particularly the disulfides. The conventional sorption systems such as iron sponge and SulfaTreat™ also have disadvantages with respect to safety and material handling.

Conventional CO_2 Removal Technology

There are commercial systems available that produce pipeline methane from biogas. However, these systems are more energy intensive and require a separate dehydration system to meet pipeline specification. TDA's VSA system provides process intensification by removing moisture and CO_2 simultaneously. Also, the sorbent used in commercial systems are not tolerant to sulfur compounds present in the biogas while TDA's system maintains its CO_2 capacity in the presence of sulfur compounds.

The commercial technologies already available for biogas upgrading are: pressurized water system (PWS), pressure swing adsorption system (PSA) and membrane system, and below we describe their strengths and weaknesses.

Pressure Swing Adsorption (PSA): Pressure swing adsorption (PSA) is a process in which CO_2 and other trace gases are removed from biogas according to the species' molecular characteristics and affinity for the adsorbent material. An adsorptive material such as activated carbon or a molecular sieve (zeolite) is used to adsorb the CO_2 at high pressure (4-7 atm). The process then swings to low pressure to desorb the CO_2 from the adsorbent material. This allows the gas to be separated into the two separate streams: the CO_2 and methane. Prior to the PSA process, sulfur and water vapor must be removed from the raw biogas since these substances can damage the sorbent (activated carbon or zeolites) material used (Munz 2011). Commercial PSA systems include BGX Solutions unit that operates on a fast-cycle PSA technology are available from Xebec Corporation. This technology is based on the company's hydrogen product platform but that is modified to remove CO_2 from low quality methane streams. HADETEC BV offers a vacuum PSA (VPSA) process for CO_2 removal from biogas using a 3-4 bed PSA process. The CO_2 is adsorbed on a molecular sieve and the methane goes through up to the NG quality and the gas needs to be pretreated and pressurized while also usingvacuum to achieve higher methane recovery (The Rootselaar Group, 2011).

Pressurized Water Scrubbing (PWS): In pressurized water scrubbing (PWS) system carbon dioxide is absorbed in water while the methane passes through since CO_2 is more soluble in water than methane. The separation typically occurs at high pressure since the solubility of CO_2 increases with increased pressure. The absorption process occurs in a counter-current flow absorber column where the biogas is pressurized and fed at the bottom of the column and the water is fed in the top. A small amount of methane absorbs into the water since it is partially soluble in water. The water stream exits the column and is depressurized to release the CO_2. The gas stream is typically run through the PWS system multiple times. This process can also remove hydrogen sulfide and ammonia present in raw biogas (Nozic, 2006). Several companies offer this technology. However, high methane purities are not possible and the PWS process is highly energy intensive with an operating cost of \$0.12/m^3 methane produced.

Amine System: Monoethanolamine (MEA) or diethanolamine (DEA) can be used as a solvent to remove CO_2 from biogas. In MEA washing, the biogas flows into an absorber and contacts an aqueous solution of MEA flowing counter-currently to the flue gas stream. The CO_2 in the biogas and MEA react exothermically to form a water soluble salt. The MEA-rich stream exits the absorber at the bottom and is heated in a heat exchanger by the MEA-lean stream leaving the stripper. The MEA-rich stream enters the stripper where the reaction is reversed and the CO_2 is removed through the top of the stripper. The MEA-lean stream leaves through the bottom and goes into the heat exchanger. The MEA-lean stream is recycled back into the absorber (D.Singh, 2003). Before the MEA capturing process, H_2S must be removed from the flue gas stream since the MEA is degraded by sulfur species (Yeh, 2005). Also, the regeneration energy requirement for amines are more than thrice of the TDA's sorbent.

Membrane System: Membrane systems to separate CO_2 from the methane in biogas work according to the principle of selective permeation through the membrane. The biogas must be cleaned of H_2S and pressurized before entering the membrane system. The membranes made of acetate-cellulose separate small polar molecules such as carbon dioxide, moisture and the remaining H_2S from the methane. In tradition membrane systems, a purity of 96% methane can be achieved (IEA Bioenergy, 2011). However, they have a bigger methane loss and the operating cost is about $0.07/m^3 methane produced.

1.2 OBJECTIVE OF THE DEMONSTRATION

CDM Federal Programs Corp. (CDM Smith) led a $1.9 million research project (Project # ER-200933) funded by the Department of Defense (DoD) Environmental Security Technology Certification Program (ESTCP) to demonstrate “Renewable Energy Production from DoD Installation Solid Wastes by Anaerobic Digestion”. This project set out to demonstrate and validate the ability to digest wastes common to DoD installations, including pre- and post-consumer food waste, waste cooking oil, and grease trap waste to produce pipeline quality methane by removing non-methane portions of the biogas such as CO_2, H_2O, H_2S etc. In this ESTCP project CDM Smith installed an anaerobic digestion system at the U.S. Air Force Academy (USAFA) in Colorado Springs, CO, and provided the technical support services and equipment for the CO_2, H_2O and sulfur removal needed to upgrade the bio-methane produced to pipeline quality.

TDA developed a CO_2 and humidity removal system for biogas to produce pipeline quality methane under funding from EPA (EPD-12-037) and has also been supplying sulfur removal sorbents for to a variety of government and commercial demonstrations run with biogas. In this project, TDA designed and built a stand-alone test skid for upgrading biogas to pipeline grade methane (CO_2 & moisture removal) and also supplied 70 L of desulfurization sorbent (1 year supply) for the demonstration at the U.S. Air Force Academy (USAFA). The objective of this combined demonstration of CDM Smith’s food waste digestion and TDA’s gas clean-up technologies is to validate the use of food waste from DoD installations to generate transportation methane (a renewable fuel) and thereby reduce their carbon foot print.

1.3 REGULATORY DRIVERS

Renewable fuels include liquid and gaseous fuels and electricity derived from renewable biomass energy sources, as opposed to fossil fuels. Many renewable fuels achieve significant lifecycle greenhouse gas emissions reductions relative to fossil fuels. Increased use of renewable fuels in the United States can reduce dependence on foreign sources of crude oil and foster development of domestic energy sources, while at the same time providing important reductions in greenhouse gas emissions that contribute to climate change.

To accelerate use of fuels derived from renewable sources, Congress established standards under the Energy Policy Act of 2005 designed to encourage the blending of renewable fuels into our nation's motor vehicle fuel supply. Congress strengthened the renewable fuels program under the Energy Independence and Security Act of 2007 to include specific annual volume standards for total renewable fuel and also for the specific renewable fuel categories of cellulosic biofuel, biomass-based diesel, and advanced biofuel. The revised statutory requirements also include new criteria for both renewable fuels and for the feedstocks used to produce them, including lifecycle greenhouse gas emission thresholds. Under the new regulations the transportation methane generated from biogas qualifies under the cellulosic biofuels and is being widely sought out by municipalities, DoD establishments and power producers to meet their specific annual quota under renewable fuel standard program.

2.0 TECHNOLOGY

TDA has developed a two-stage complete biogas purification system that removes the various contaminants such as inorganic sulfur, organic sulfur, siloxanes, CO_2, and moisture to produce greater than 95% bio-methane. The first stage is based on a low-cost, high-capacity and expendable sorbent called SulfaTrap^{TM} that simultaneously removed sulfur and siloxane down to ppb levels. The second stage is a vacuum swing adsorption system based on a regenerable mesoporous carbon media modified with surface functional groups to reduce the CO_2 and H_2O concentration in the biogas to pipeline specifications. Figure 2 shows the two stage biogas purification process to bio-methane.

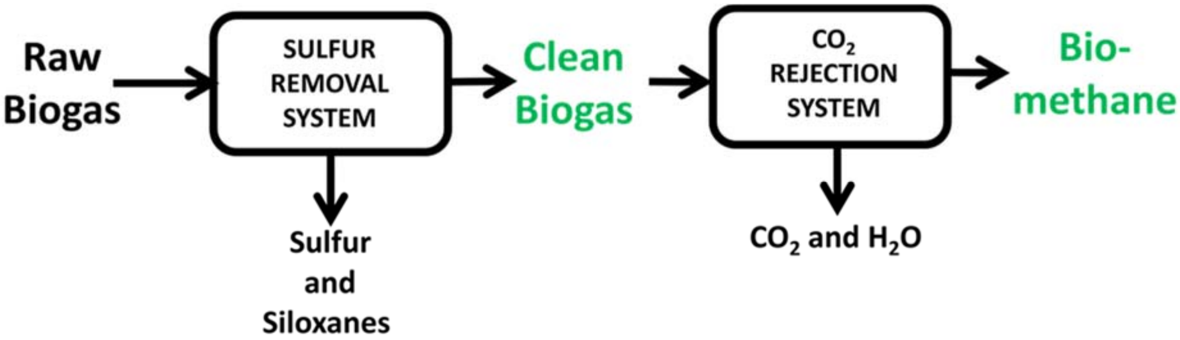


Figure 2. Two stage biogas purification process to bio-methane.

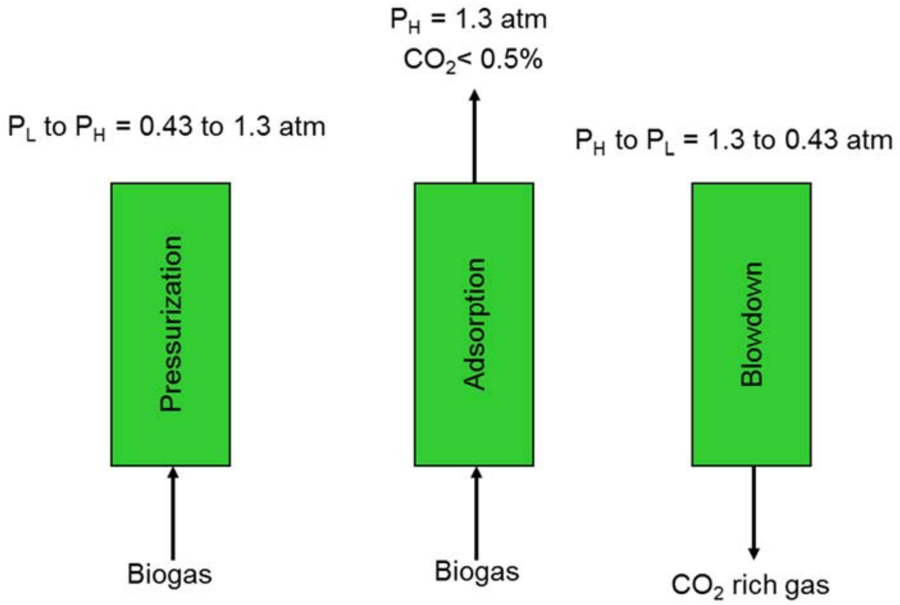
2.1 TECHNOLOGY DESCRIPTION

Sulfur Removal System

TDA Research Inc. (TDA) has developed a low-cost, high-capacity expendable sorbent SulfaTrap^{TM}-R7 that can remove both H_2S and organic sulfur species in biogas to the ppb levels. Another class of compounds present in biogas is siloxanes. Siloxanes are generated during anaerobic digestion of waste activated sludge that concentrates silicone-based personal hygiene, health-care and industrial products. Siloxanes must be removed from biogas prior to use as an energy source. SulfaTrap^{TM}-R7 contains TDA proprietary mixed metal oxide phase that removes both the sulfur and siloxane compounds in the biogas.

CO_2 Rejection System

The vacuum swing adsorption system uses TDA Research, Inc's proprietary CO_2 adsorbent to reduce the CO_2 and other inerts in the biogas to less than 5%. The approach is similar to the PSA and VSA systems that have been successfully used for years in small to medium scale air separation processes to produce very high purity oxygen. A simple vacuum swing cycle consists of three steps as shown in Figure 4. The adsorption of CO_2 from the biogas stream is carried out at the biogas delivery pressure (about 1.3 atm), while the sorbent is regenerated and CO_2 recovered under vacuum (at about 0.2 atm). The bed is subsequently pressurized with the feed (biogas) gas. The methane loss from the system is reduced by using intermediate pressure equalization steps between the main adsorption and regeneration portions of the cycle. The methane loss with the full vacuum swing cycle is minimal (i.e., less than 10%).



P_H = 1.3 atm
CO_2< 0.5%
P_L to P_H = 0.43 to 1.3 atm
P_H to P_L = 1.3 to 0.43 atm
Pressurization
Adsorption
Blowdown
Biogas
Biogas
CO_2 rich gas

Figure 3. Schematic of a simplified 3-bed vacuum swing adsorption cycle for CO_2 removal from methane biogas.

TDA's CO_2 sorbent is a proprietary mesoporous carbon that contains surface functional groups that are selective for CO_2 removal. The carbon support is previously developed for ultra-capacitors, and has large pores to achieve liquid transport. TDA's proprietary preparation process enables TDA to introduce stable surface functional groups and control the pore size distribution, For example, Figure 4 shows three different mesoporous carbon formulations having a much wider pore size distributions in the 10-100 Å range while Figure 5 shows TDA's mesoporous carbons having a narrow pore size distribution 15-20 Å.

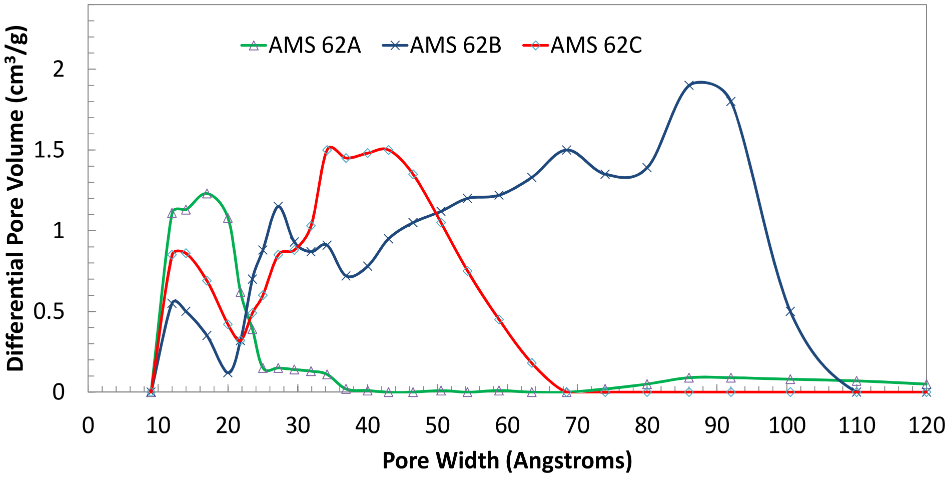


Figure 4. TDA's mesoporous carbons with a wide pore size distribution (10-100 Å).

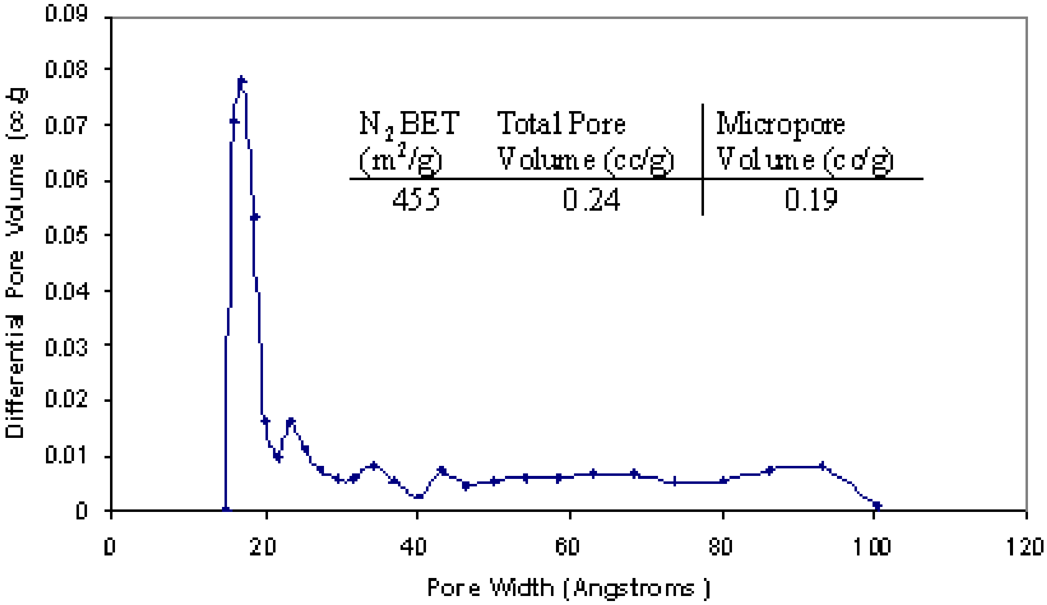


Figure 5. TDA's mesoporous carbons with a narrow pore size distribution (15-20 Å).

2.2 TECHNOLOGY DEVELOPMENT

Sulfur Sorbent

CDM Smith provided a wide range of operating conditions for the sulfur removal sorbent i.e., 40 to 60°F for pilot scale operation and 98°F for full scale operation and humidity levels up to 100% RH at operating temperature. Hence, we prepared and tested two batches of desulfurization sorbents in bench-scale apparatus at TDA using simulated biogas:

- SulfaTrap^{TM}-R7B –wet gas
- SulfaTrap^{TM}-R7E – wet & dry gas

Both sorbents are now available in commercial quantities from SulfaTrap LLC, the licensor of TDA Research's sulfur sorbents. In these bench scale evaluations we included a commercial biogas desulfurization sorbent SulfaTreat Select Premium along with the two SulfaTrap^{TM} samples. SulfaTreat Select premium works only in the presence of high levels of moisture. Figure 6 shows the comparison of the three sorbents under high temperature (50°C) and high moisture (sat. H_2O at 22°C) and the two SulfaTrap^{TM}-R7 samples achieved slightly higher capacity ~27% wt. sulfur compared to 25.2% wt. sulfur for the SulfaTreat Select Premium. Figure 7 shows the comparison under low temperature (22°C) and high moisture (sat. H_2O at 22°C). Hence, the SulfaTrap^{TM}-R7E sample retained its capacity at low temperature i.e., achieved a high loading of 26.2% wt. sulfur while the capacity of the SulfaTrap^{TM}-R7B and SulfaTreat Select Premium samples decreased to less than 20%. It is to be noted that SulfaTrap samples have higher bulk density compared to SulfaTreat Select Premium, which results in a significantly higher breakthrough time (volumetric loading) for SulfaTrap^{TM}-R7B compared to SulfaTreat Select premium.

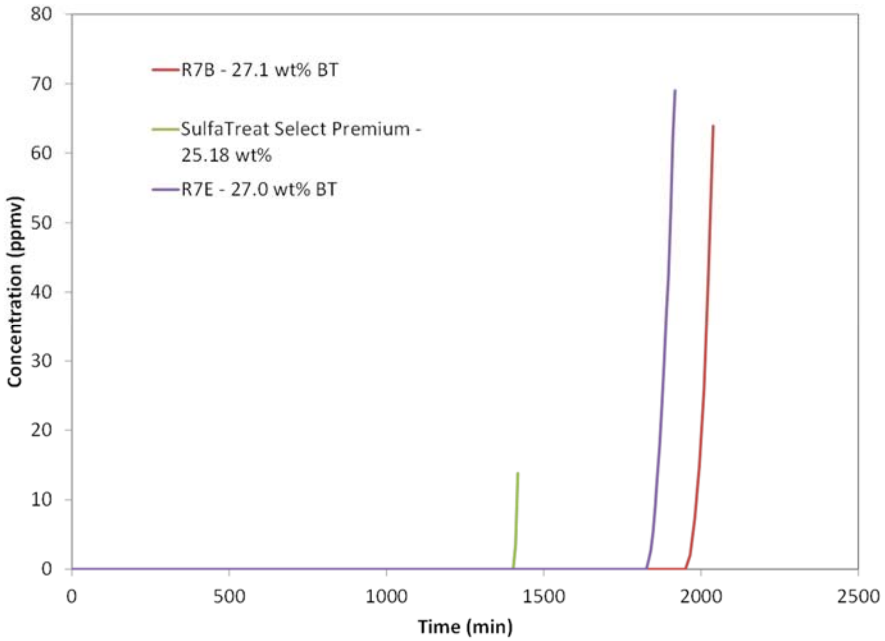


Figure 6. H_2S removal from simulated biogas in bench-scale with various biogas desulfurization sorbents at high temperature and high moisture. T= 50°C, 2000 ppmv H_2S, 40% CO_2, 60% CH_4, 22°C sat. (2.7%) H_2O, GHSV=4,000 h^{-1}.

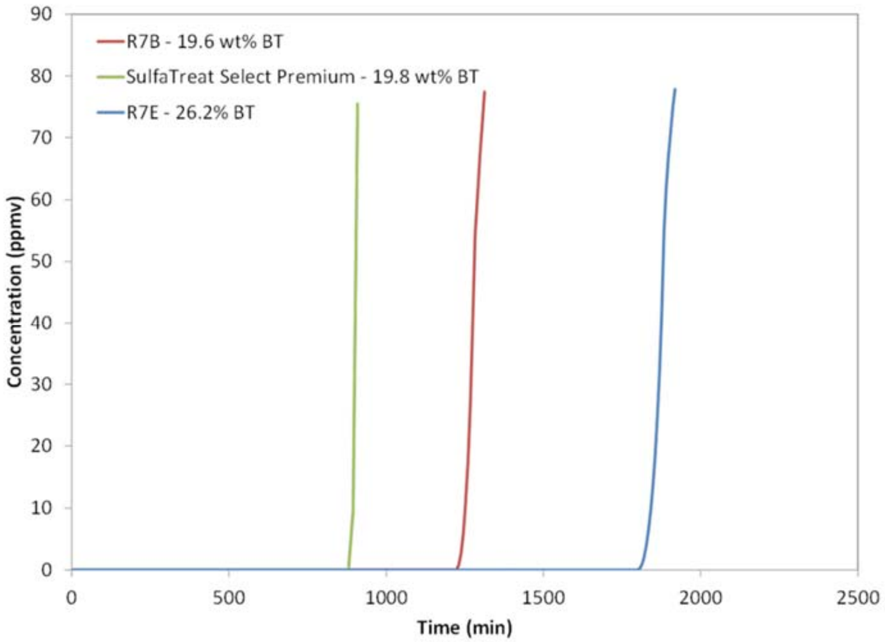


Figure 7. H_2S removal from simulated biogas in bench-scale with various biogas desulfurization sorbents at low temperature and high moisture. T= 22°C, 2000 ppmv H_2S, 40% CO_2, 60% CH_4, 22°C sat. (2.7%) H_2O, GHSV=4,000 h^{-1}.

We then down selected to the two SulfaTrap^{TM}-R7 samples due to their high capacity at low operating temperatures and tested the two samples under low temperature (22°C) and low moisture (4,000 ppmv H2O, 20°F dew point). We found that under low moisture condition SulfaTrap^{TM}-R7E achieved a high capacity of 17.9% wt. sulfur while SulfaTrap^{TM}-R7B achieved a low capacity of 2.4% wt. sulfur at breakthrough (Figure 8). These bench-scale tests showed that SulfaTrap^{TM}-R7E is the sorbent of choice, since it can work under a wide variety of operating conditions including the extremes of low temperature and low moisture expected during winter and the high temperature and high moisture conditions expected during summer.

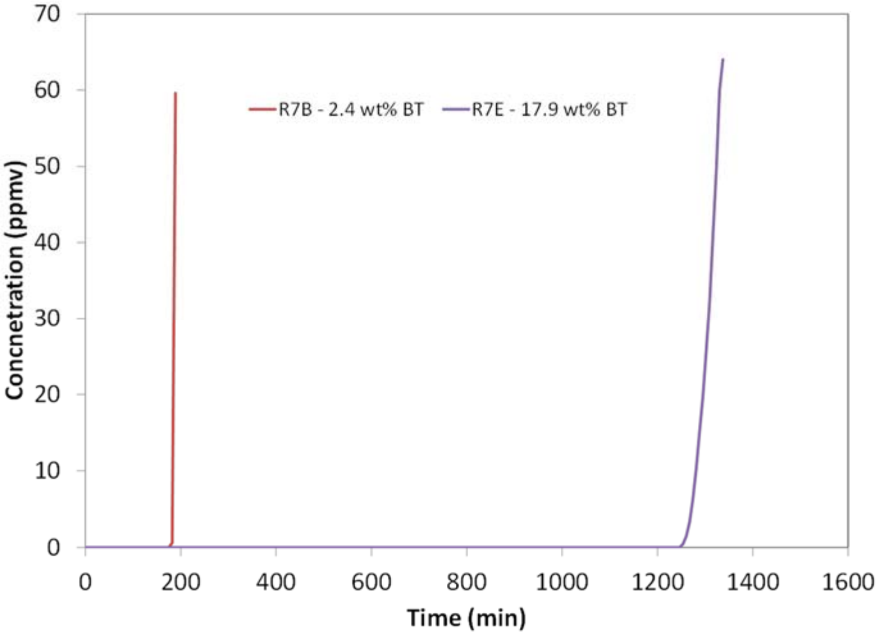


Figure 8. H_2S removal from simulated biogas in bench-scale with various SulfaTrap^{TM}-R7 sorbents at low temperature and low moisture. T= 22°C, 2000 ppmv H_2S, 40% CO_2, 60% CH_4, 20°F sat. (4,000 ppmv) H_2O, GHSV=4,000 h^{-1}.

Next, we carried out detailed bench-scale evaluations with the SulfaTrap^{TM}-R7E (sulfur sorbent of choice). SulfaTrap^{TM}-R7E achieved a high sulfur capacity under different levels of moisture (Figure 9). The sulfur capacity was above 25% wt. sulfur down to 40°F dew point. It had a slight decrease in capacity, achieving a breakthrough capacity of 17.9% wt. sulfur, when the moisture was reduced to 20°F dew point. We then varied the operating temperature while keeping moisture level in the simulated biogas at 72°F dew point (Figure 10). SulfaTrap^{TM}-R7E retained a high capacity of 26+% wt. sulfur at operating temperatures between 72 to 122°F (22 to 50°C).

Finally, we tested SulfaTrap^{TM}-R7E using simulated biogas containing 400 ppmv H_2S and compared the sorbent performance against simulated biogas containing 2,000 ppmv H_2S. The sulfur breakthrough results are summarized in Figure 11. SulfaTrap^{TM}-R7E retained its high sulfur capacity at 400 ppmv H_2S achieving a sulfur loading of 25.4% wt. sulfur.

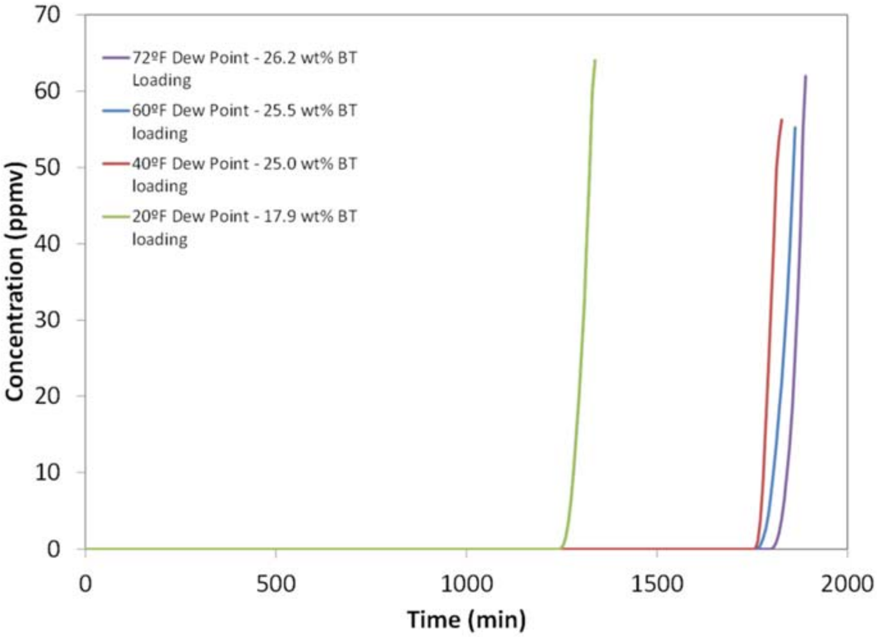


Figure 9. H_2S **removal from simulated biogas in bench-scale at low temperature and different moisture levels. T= 22°C, 2000 ppmv** H_2S**, 40%** CO_2**, 60%** CH_4**, varying** H_2O**, GHSV=4,000** h^{-1}**.**

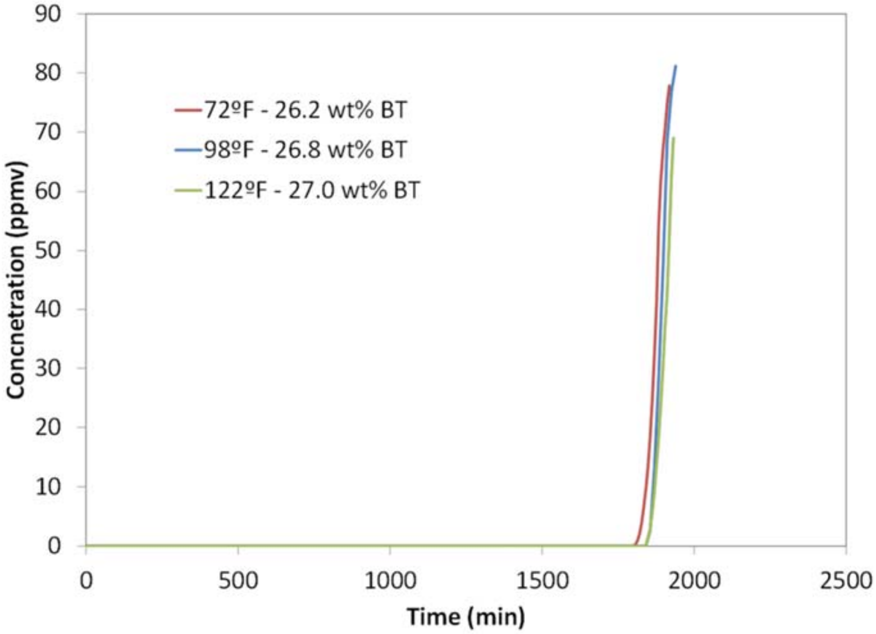


Figure 10. H_2S **removal from simulated biogas in bench-scale at different temperature and high moisture level. T= varying, 2000 ppmv** H_2S**, 40%** CO_2**, 60%** CH_4**, 72°F sat. (2.7%)** H_2O**, GHSV=4,000** h^{-1}**.**

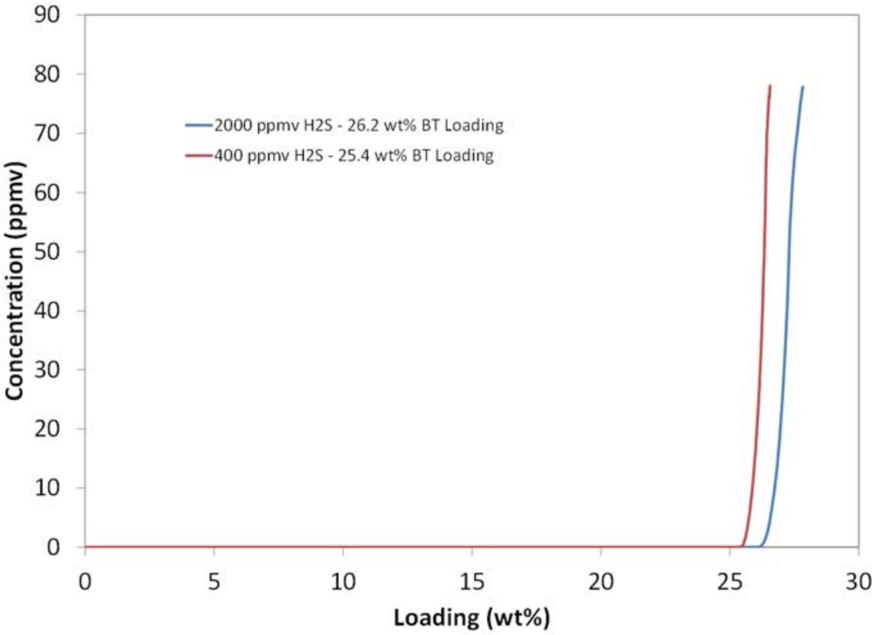


Figure 11. H_2S removal from simulated biogas in bench-scale at low temperature and high moisture level. T= 22°C, varying H_2S, 40% CO_2, 60% CH_4, 72°F sat. (2.7%) H_2O, GHSV=4,000 h^{-1}.

CO_2 Rejection System

TDA has previously demonstrated the CO_2 sorbent's performance in a bench-scale two-bed vacuum swing system (Figure 12) under the EPA sponsored SBIR project (EP-D-11-051). This system is capable of counter-current adsorption and desorption operation simulating the VSA operation expected in the full-scale system. In this system, the desired gas mixtures (CH_4 and CO_2) are directed into a bench-scale reactor that contains the sorbent. All gas flows are controlled with electronic mass flow controllers. An in-line sparger is used to introduce moisture at 100% relative humidity in the biogas. After mixing in a manifold, the feed gas mixture is then directed into the reactor. A valve system allows the gases to bypass the reactor and flow directly to the analytical system for accurate measurement of the feed gas composition as needed. The sorbent reactor consists of a 1.5 inch outside-diameter spring loaded stainless reactor. One hundred g of sorbent particles in the 8-20 mesh size are loaded in to the reactor for testing. The reactor is spring loaded and has a length/diameter (L/D) ratio of 8 with a bed volume of 100 mL. The reactor has three thermocouple ports to monitor the sorbent bed temperature. A back pressure regulator is used to control the adsorption pressure. After exiting the reactor, the CO_2, and CH_4 content of the stream are monitored by an on-line NOVA Multi-gas Analyzer and Vaisala CO_2 and humidity probes. Continuous analysis of CO_2 allows us to monitor breakthrough gas concentrations and to measure a total CO_2 adsorption capacity. The desorption line is equipped with a BOC Edwards scroll (oil-free) vacuum pump. The pump can easily reach vacuums of less than 1 psia. The apparatus is fully automated using a control system from Opto 22 Corporation and can run without an operator for long periods of time, including overnight. The control system controls the test conditions, logs the analytical data, and also safely shut down the apparatus in case of a malfunction. We used a simulated biogas composition of 60% CH4 and 40% CO_2 on a dry basis for the bench-scale evaluations (the water content was 3% by vol.).

We used the this previously built system in the EPA SBIR project to run bench-scale tests in which we demonstrated the performance of our sorbent for over 2,900 cycles without any loss in performance. In these tests the sorbent beds produced high purity methane above 99%. Figure 13 shows the results from these bench-scale tests.

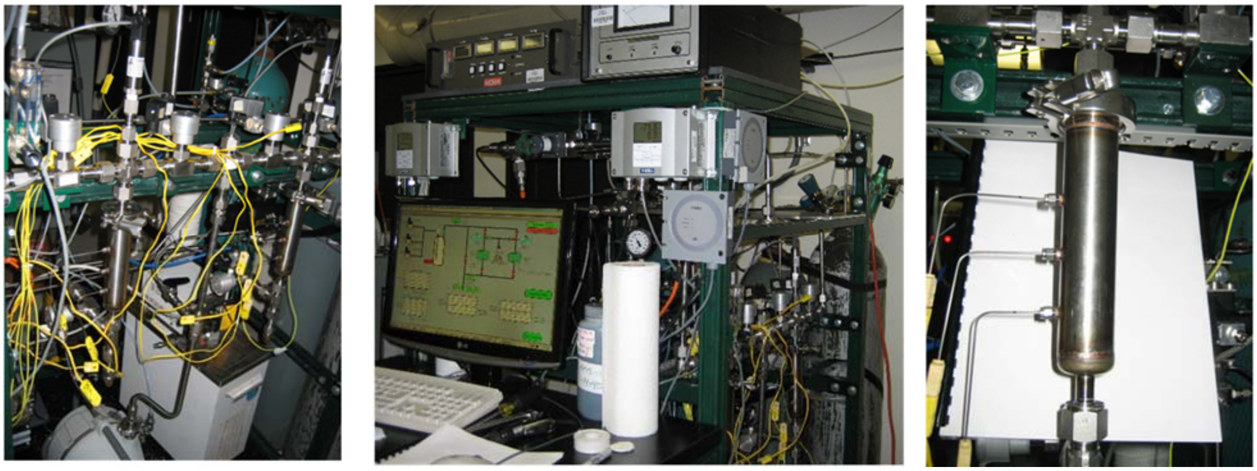


Figure 12.Picture of the bench-scale 2-bed VSA system.

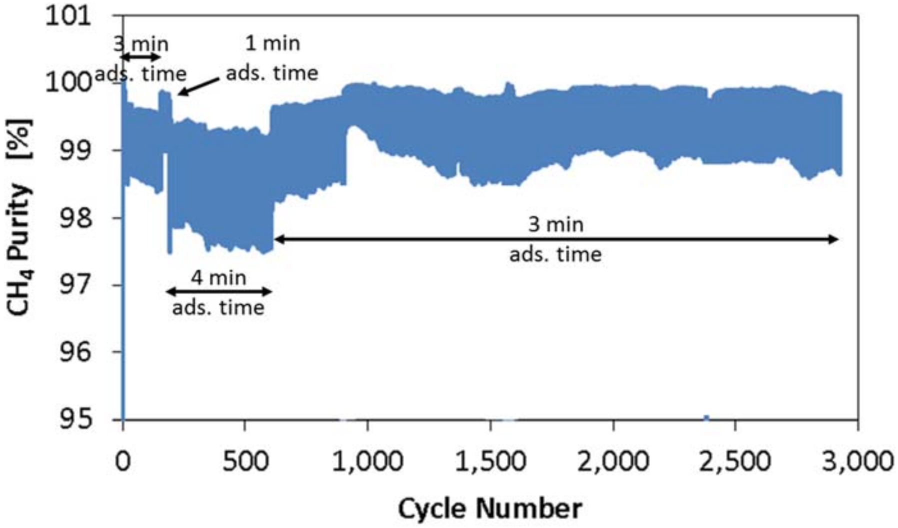


Figure 13. Bench-scale tests in a two-bed vacuum swing cycling system. CH_4 = 60%, CO_2 = 40%, (dry basis), H_2O = sat. at 22°C, space velocity = 125 h^{-1}; T = ambient, P_{ads} = 19.0 psia, P_{des} = 0.2 psia, L/D = 8.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

We compared TDA's VSA system against other competing technologies for biogas purification, such as the high pressure (HP) water system and a membrane system. Of these the HP water system is the only system that currently has full scale commercial systems in place. However, the HP water system cannot achieve greater than 97% methane purity and is the most energy and capital intensive process. Membrane systems are under development and are prone to leaks from pin holes and damage from impurities such as sulfur compounds. TDA's vacuum swing sorbent system is tolerant to all the contaminants present in the biogas. Our process is the least energy intensive among the options available, it has a slightly higher methane loss than the membrane system. Table 2 shows the comparison of these technologies based on their power cost per m^3 of CH_4 produced. TDA's Case 1 and 2 have the lowest power cost at \$0.04 and \$0.05 per m^3 CH_4 produced followed by the membrane system at \$0.06 and finally the HP water system at \$0.12.

Table 2. Comparison of different technologies based on per m^3 methane produced.

	HP water system	Membrane System	TDA VSA System Case 1	TDA VSA System Case 2
Fermentation gas flow (m^3/day)	2000	2000	2000	2000
Methane in the feed (m^3/day)	1200	1200	1200	1200
Methane Purity	97%	99.5%	99.5%	99.5%
Methane Recovery	97%	90%	80.0%	90.0%
Methane produced	1164	1080	960	1080
Power required (kW$_e$)	57.0	25.0	14.6	21.8
Power cost (\$/m^3 CH_4) @ \$0.1/kWh	\$0.12	\$0.06	\$0.04	\$0.05
Sorbent Amount (lbs/year)			1376	1376
Sorbent Cost (@ \$10/lb) \$/m^3 CH_4			\$0.03	\$0.03
Total Operating Cost including sorbent replacement (\$/m^3 CH_4)			\$0.07	\$0.08

3.0 PERFORMANCE OBJECTIVES

The performance objective for TDA supplied biogas purification system is to produce bio-methane (treated biogas) that meets the natural gas specifications. The success criteria were set based on the natural gas specifications, which include:

< 4 ppmv Sulfur
$\geq 95\%$ Methane (CH_4) purity in the product gas
$< 3\%$ Nitrogen (N_2) and Carbon Dioxide (CO_2) in the product gas
$< 0.2\%$ Oxygen (O_2) in the product gas
< 7 lbs/MMscf Moisture

Table 3. Performance Objectives.

Performance Objective	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives			
Gas purification	Methane recovery	$\geq 80\%$ methane recovery	$\geq 90\%$ methane recovery
	Natural gas specifications	$\geq 95\%$ CH_4 in treated biogas	$\geq 96\%$ CH_4 in treated biogas
		< 4 ppm H_2S in treated biogas	< 0.25 ppm H_2S in treated biogas
		$< 3\%$ N_2 and CO_2 in treated biogas	$< 2.7\%$ N_2 and CO_2 in treated biogas
		$< 0.2\%$ O_2 in treated biogas	$< 0.5\%$ O_2 in treated biogas
		< 7 lbs/MMscf Moisture	< 7 lbs/MMscf Moisture
Qualitative Performance Objectives			
Ease of use	Feedback from field technician on usability of technology and time required	A single field technician able to effectively operate the system remotely with minimal on-site help	System was operated remotely from TDA facilities in Wheat Ridge, CO with minimal to none on-site help

Also we set a qualitative performance objective that the system should be easy to operate remotely with minimal on-site help and a quantitative objective that methane recovery should be greater than 80%.

Methane Recovery is defined as the amount of CH_4 present in the biogas that is recovered as bio-methane (treated biogas).

$$Methane\ recovery\ (\%) = \frac{CH_4\ present\ in\ bio-methane\ product}{CH_4\ present\ in\ biogas}\ x\ 100$$

In order to calculate methane recovery, the volumetric flow rates of the raw biogas feed to TDA's biogas purification system and the bio-methane product (treated biogas) produced are measured using flowmeters upstream (FM-101 Flow Technology's FT series turbine meter) and downstream (FM-401 Brooks Instrument's thermal flowmeter) of the 3-bed VSA system, respectively. We also had in-line CO_2 and humidity probes (from CO_2 meters.com and Kahn Instruments) to quantify the amount of CO_2 and H_2O present in the raw and treated biogas. We also confirmed the methane purity of the raw biogas feed and the treated biogas (bio-methane) using Infrared analyzer in the CDM Smith test Skid to confirm that the bio-methane has greater than 95% methane in it.

CDM Smith also took gas samples of the raw biogas feed before and after both the sulfur sorbent bed and the VSA system and sent them to outside laboratory (ALS Environmental, Simi Valley, CA) for analysis. The samples were received intact under chain of custody by the Laboratory and were stored in accordance with the analytical method requirements till their analysis. The analysis was performed as soon as possible after receipt by the laboratory.

Fixed Gases Analysis: The samples were analyzed for fixed gases (oxygen/argon, nitrogen, methane and carbon dioxide) according to modified EPA Method 3C (single injection) using a gas chromatograph equipped with a thermal conductivity detector (TCD).

Sulfur Analysis: The samples were also analyzed for twenty sulfur compounds per ASTM D 5504-12 using a gas chromatograph equipped with a sulfur chemiluminescence detector (SCD). All compounds with the exception of hydrogen sulfide and carbonyl sulfide are quantitated against the initial calibration curve for methyl mercaptan.

4.0 SITE DESCRIPTION

CDM Smith selected U.S. Air Force Academy (USAFA) located in Colorado Springs, CO as the field test site. A site selection white paper was submitted by CDM Smith to ESTCP on March 3, 2011, which was approved by ESTCP on April 27, 2011. Final approval from USAFA for use of the site for this ESTCP demonstration project was secured on April 12, 2013.

USAFA has many attributes making it an excellent site for the ESTCP demonstration. These characteristics include:

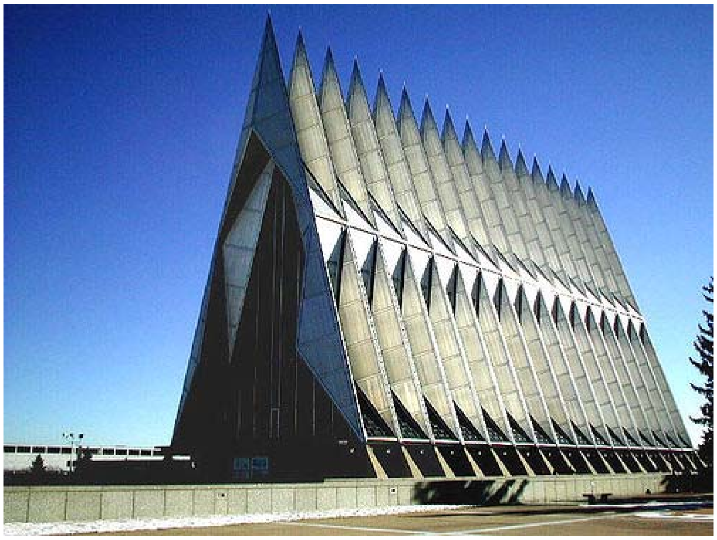


Figure 14. USAFA (Colorado Springs, CO).

- Plentiful supply of food waste and grease trap waste
  USAFA educates 4,500 cadets who eat 3 meals per day/7 days per week at Mitchell Hall. Thus a readily available source of food waste exists. A large grease trap also exists on site and is a ready source of fats, oils, and grease for the CDM Smith demonstration of food waste anaerobic digestion.

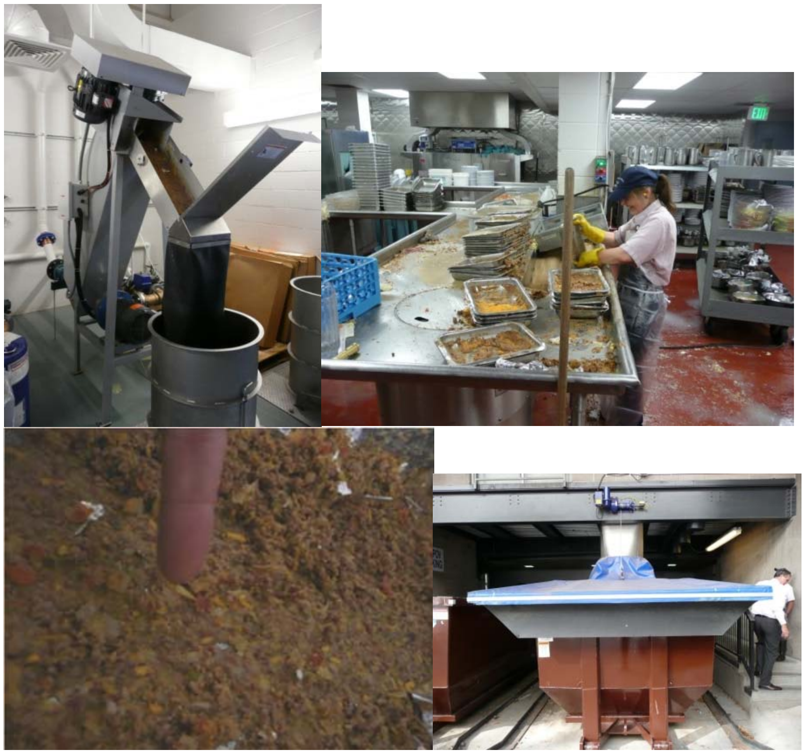


Figure 15. Existing food waste processing at USAFA.

- Existing food waste processing capability
  Food waste is sluiced off of plates and containers, ground, and dewatered prior to being bagged and dropped into roll off containers for landfilling. This pretreatment makes transport and handling of the digester feed stock efficient.

- Operational wastewater treatment plant on-base
  There is an existing anaerobic digester in the wastewater treatment plant and provides an excellent location for the demonstration and provides utilities including electricity,

natural gas, and non-potable/potable water. Demonstration digested sludge can be discharged into full-scale digester 3 according to USAFA staff. Demonstration bio-methane produced by TDA skid (adsorption step product) and the residual/waste biogas (desorption product) can be routed to an existing flare that is currently used to burn full-scale digester biogas.

The scope of the field tests include the anaerobic digestion of the food wastes generated in the USAFA canteens to generate biogas, which is further purified and upgraded to bio-methane (natural gas specification). TDA's responsibility included just the supply of the sulfur sorbent (SulfaTrap^{TM}-R7E) and the VSA system for upgrading biogas to bio-methane, while CDM Smith was responsible for the generation of the biogas from food wastes.

4.1 SITE LOCATION AND INSTALLATION

The pilot plant was installed at the USAFA wastewater treatment plant located approximately ten miles north of downtown Colorado Springs off Stadium Boulevard and Community Center Drive. The unit was installed on the north end of the plant's anaerobic digesters as this space is easily accessible for construction, it had nearby utilities which were tapped for connections, the existing digesters and biogas flare were used to manage the digested waste and excess biogas, and the site was reasonably close to Mitchell Hall, the source of the food waste feedstock. The aerial and ground photographs of the installation site before installation are provided in Figure 16. The bottom right picture in the Figure 16 shows the CDM Smith food waste digestion pilot plant installed along with the biogas storage sphere. The biogas storage sphere was used to store the desulfurized biogas produced from food wastes. Once the biogas sphere is full, the gas was sent to TDA's VSA system to upgrade it to bio-methane.

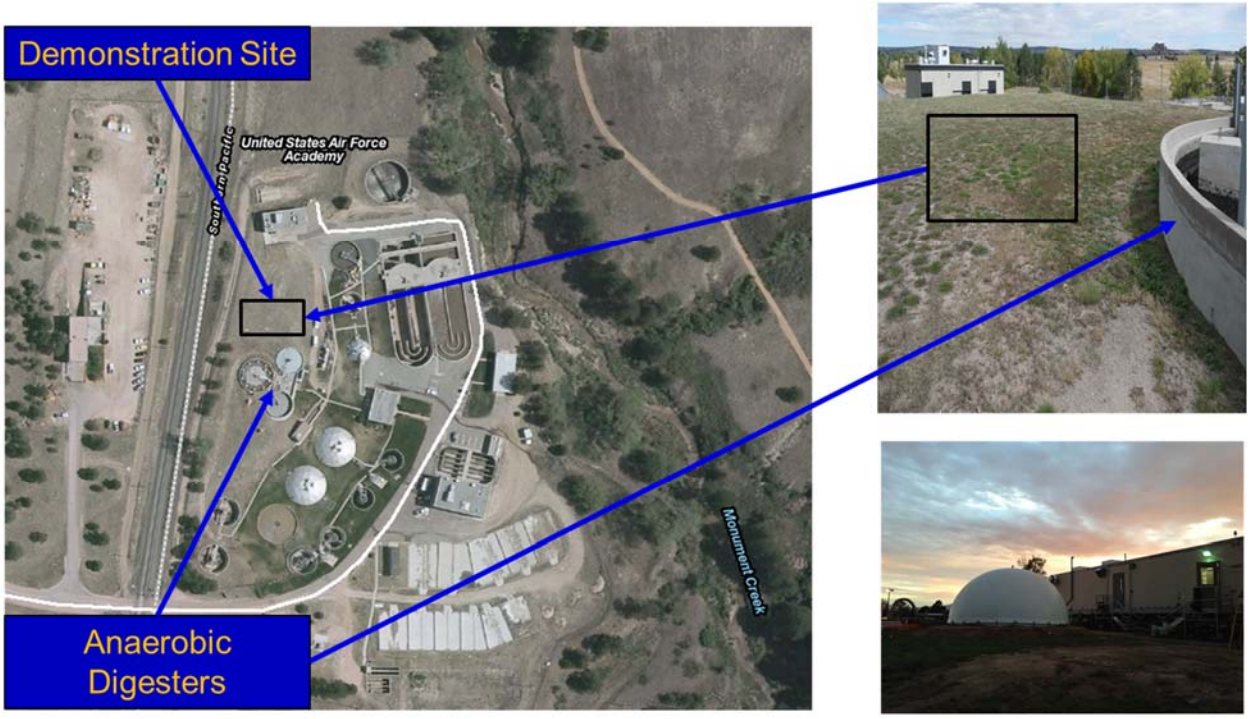


Figure 16. USAFA field test site.

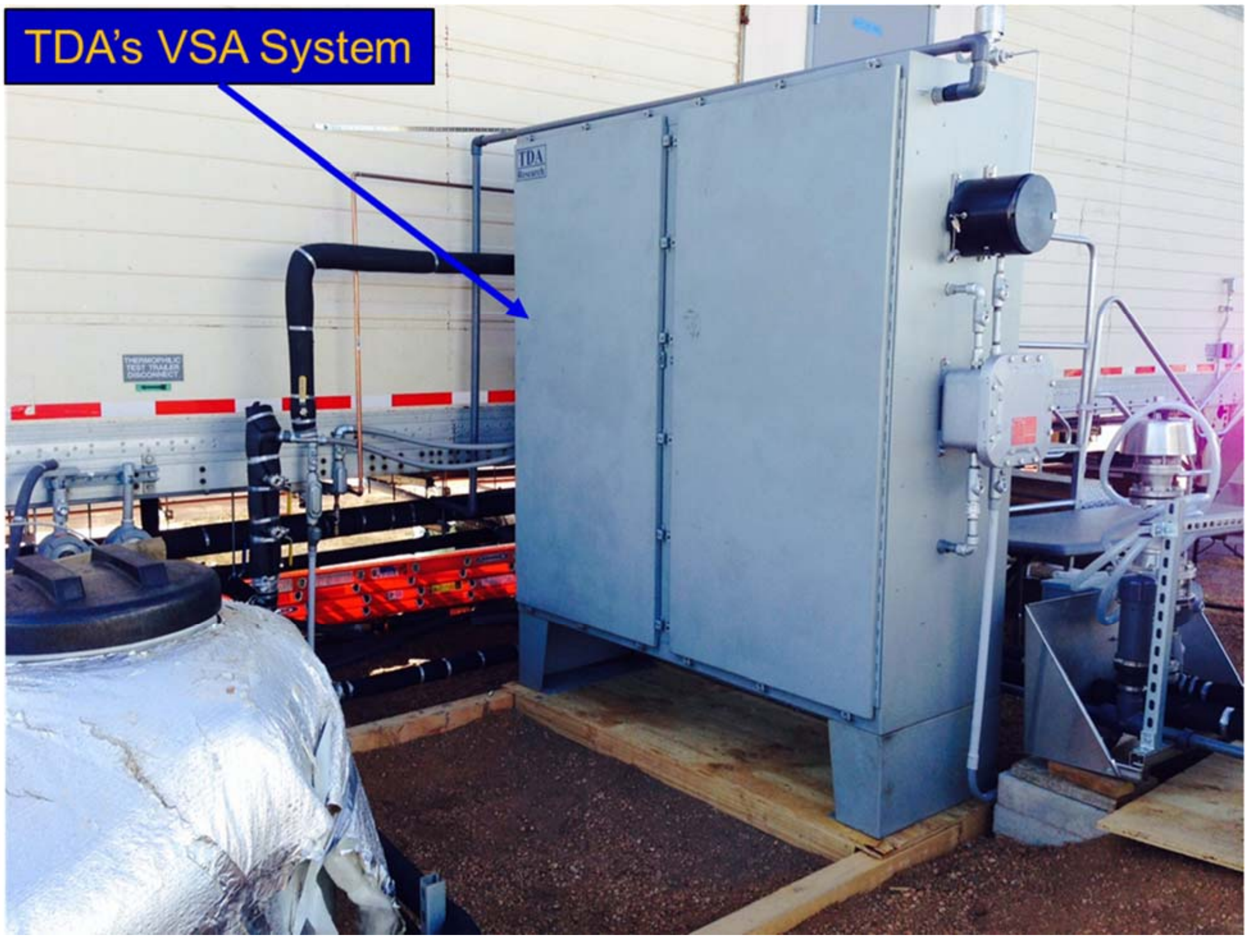


Figure 17. TDA's VSA system installed at USAFA (Colorado Springs, CO).

Figure 17 shows the TDA's VSA system installed at USAFA (Colorado Springs, CO). As seen in the picture TDA's unit was located next to the trailer containing the CDM Smith food waste digestion pilot plant and the biogas sphere.

5.0 TEST DESIGN

This section provides the detailed description of the system design and testing conducted during the field test (demonstration) with TDA's biogas purification sub-systems i.e., the SulfaTrap^{TM} sorbents and the VSA system.

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

TDA's biogas purification system has two stages: Stage 1 removes the sulfur and siloxanes, and Stage 2 removes the CO_2, and moisture to produce bio-methane that contains greater than 95% methane. The first stage is based on a low-cost, high-capacity and expendable sorbent called SulfaTrap^{TM} that simultaneously removed sulfur and siloxane down to ppb levels. The second stage is a vacuum swing adsorption system based on a regenerable mesoporous carbon media modified with surface functional groups to reduce the CO_2 and H_2O concentration in the biogas to pipeline specifications. A schematic of the two-stage system is shown in Figure 2.

A detailed description of the SulfaTrap^{TM} sorbent selection for the first stage and the VSA technology were provided in Section 2.1.

VSA System Description

TDA completed a detailed design and fabricated a fully automated carbon dioxide and moisture removal VSA based demonstration system, as part of the joint effort of the CDM Smith subcontract under the ESTCP project (ER 200933) and the EPA sponsored SBIR Project (EP-D-12-037). The demonstration system was installed at the USAFA waste water treatment plant for field testing with the CDM Smith provided biogas derived from food waste. This system was installed downstream of the food waste digester, desulfurization system, and a storage sphere with 2,000 ft^3 volume. The desulfurization system was used to reduce the sulfur and siloxanes in the biogas to below their detectable limit. The storage sphere was used to store biogas and feed TDA's carbon dioxide and moisture removal VSA system. The VSA system was run in a batch mode and is also capable continuous operation achieving the following performance targets:

> 95% Methane (CH_4) purity in the product gas
> 80% Methane Recovery
< 3% Combined Nitrogen (N_2) and Carbon Dioxide (CO_2) in the product gas
< 0.2% Oxygen (O_2) in the product gas
< 7 lbs/MMscf Moisture

The carbon dioxide and moisture removal system was designed and fabricated with the following characteristics:

- Rated for a Class 1 Division 1 environment. Electronics such the control laptop were de-rated since they are kept a minimum of 10 feet from the biogas lines
- Be fully automated
- Use a regenerable (non-consumptive) media for carbon dioxide adsorption
- Be skid mounted

- Have process control and data logging capability
- Carbon steel piping, vessels and appurtenances are permissible
- Equipped for installation in an outdoor environment

The objective of the field demonstration is to validate anaerobic digestion of food wastes and digester gas treatment technologies in the field through pilot-scale operation, while testing different operational configurations and inputs to determine the most cost effective and stable means of operation. The technical objectives of this demonstration/validation project include: demonstrate anaerobic digestion of commonly available, high-organic waste streams at DoD installations to produce methane-rich biogas; determine suitable waste mixtures and feeding strategies for biogas production and associated engineering design parameters that can guide technology implementation at DoD installations (CDM Smith Scope); validate the ability to produce a valuable end product (bio-methane) from a waste stream for application within the DoD; and document cost and performance of the purification technology (TDA Scope). Prior to transferring the demonstration system to the USAFA we powered-up the VSA system at TDA facilities where we carried out shake-down tests and validated the control sequence. In these tests at TDA we used simulated biogas mixtures containing CO_2 and N_2 mixtures as feed gas.

VSA System Design and Review

The Biogas CO_2 and Moisture Separation System (BioCAMSS a.k.a VSA system) is designed to treat biogas generated from anaerobic digestion of solid wastes from the USAFA by removing the non-methane portions of the biogas (CO_2 and moisture) and producing pipeline quality methane. VSA system will treat biogas with the following inlet conditions:

Temperature: 20-110°F (ambient temperature in Colorado Springs, CO)
CH_4 Content: 50-75% (68% avg)
CO_2 Content: 25-50% (32% avg)
Moisture: Saturated
Pressure: 0-14"W.C.
Flowrate: 0.14-1.4 L/s (8.4-84 SLPM, 28 SLPM average)

The system uses a 3-bed vacuum swing adsorption design with an inlet booster diaphragm pump, vacuum desorption pump (scroll-type), a recycle diaphragm pump, and all of the necessary valves and tubing to control flow through the system. It is an automated self-contained system using an OPTO22 controller but was connected to a laptop for remote viewing and adjustment of operating variables. The entire system is built within a NEMA 4/12 electrical enclosure. The enclosure utilizes a Type-X purge system. Type X purging reduces the classification within the protected enclosure from Division 1 to nonhazardous. Failure to maintain pressure within the protected enclosure and/or adequate exhaust flow from the enclosure vent is detected by an alarm/ indicator. The dilution purge time is an automatically controlled operation and once the enclosure has been purged of ignitable or flammable concentrations, only positive pressure and adequate exhaust flow from enclosure vent are required to be maintained within the protected enclosure. If the alarm is actuated, the power to the entire enclosure is turned off. Heat tracing is provided on the condensate drain lines to prevent freezing. These are simple heat tapes with integral thermostats.

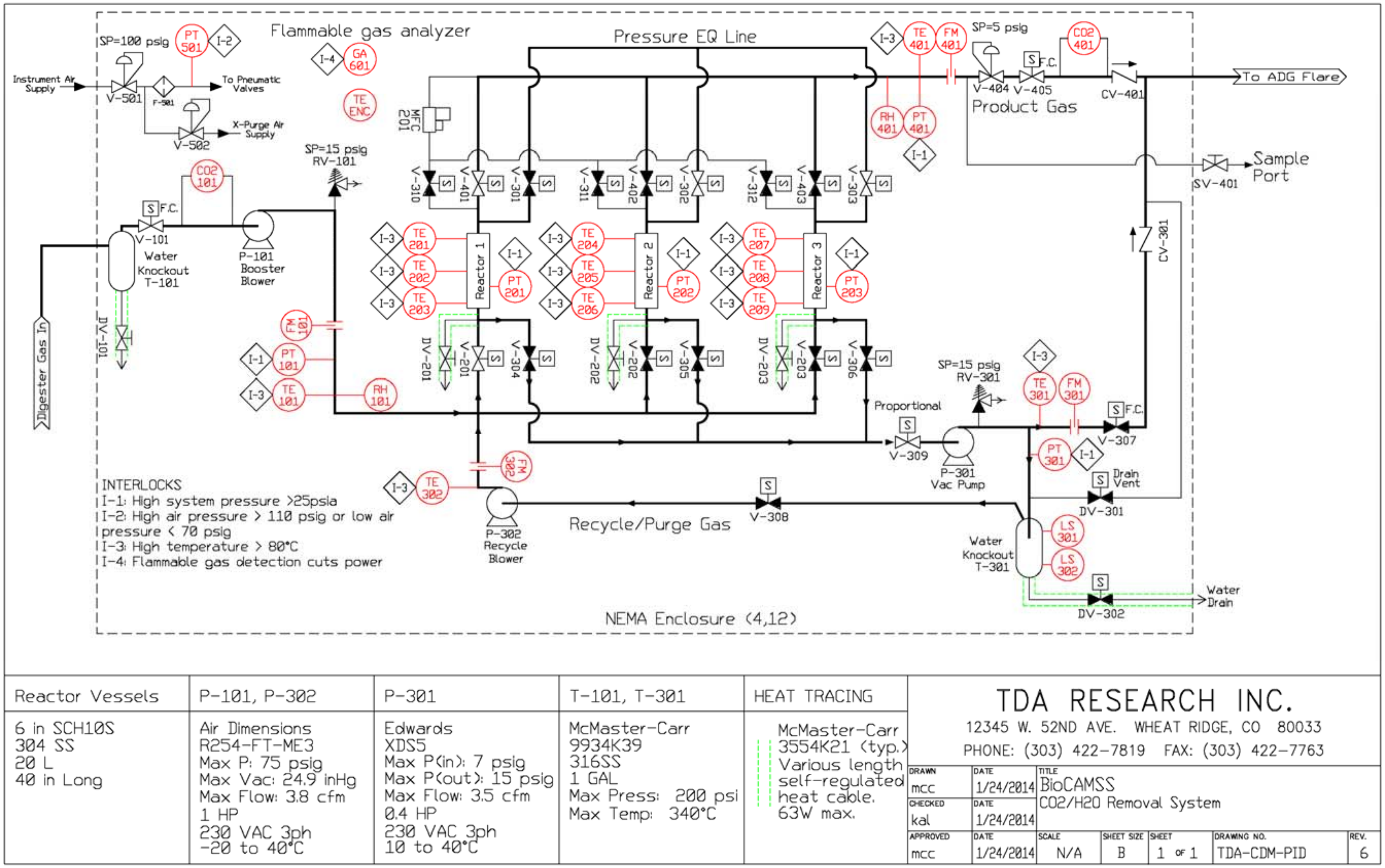

Flammable gas analyzer
Pressure EQ Line
SP=100 psig
PT 501
I-2
Instrument Air Supply
V-501
F-501
To Pneumatic Valves
X-Purge Air Supply
V-502
I-4
GA 601
TE ENC
MFC 201
SP=15 psig
RV-101
CO2 101
S F.C.
V-101
Water Knockout T-101
P-101 Booster Blower
Digester Gas In
DV-101
FM 101
I-1
PT 101
I-3
TE 101
RH 101
V-310
V-401
V-301
V-311
V-402
V-302
V-312
V-403
V-303
TE 201
TE 202
TE 203
Reactor 1
PT 201
TE 204
TE 205
TE 206
Reactor 2
PT 202
TE 207
TE 208
TE 209
Reactor 3
PT 203
DV-201
V-201
V-304
DV-202
V-202
V-305
DV-203
V-203
V-306
I-3
TE 401
FM 401
SP=5 psig
CO2 401
V-404
V-405
CV-401
To ADG Flare
Product Gas
RH 401
PT 401
I-1
Sample Port
SV-401
CV-301
SP=15 psig
RV-301
Proportional
V-309
P-301 Vac Pump
TE 301
FM 301
S F.C.
V-307
PT 301
Drain Vent
DV-301
FM 302
TE 302
P-302 Recycle Blower
Recycle/Purge Gas
V-308
Water Knockout T-301
LS 301
LS 302
DV-302
Water Drain
INTERLOCKS
I-1: High system pressure >25psia
I-2: High air pressure > 110 psig or low air pressure < 70 psig
I-3: High temperature > 80°C
I-4: Flammable gas detection cuts power
NEMA Enclosure (4,12)
Reactor Vessels
6 in SCH10S
304 SS
20 L
40 in Long
P-101, P-302
Air Dimensions
R254-FT-ME3
Max P: 75 psig
Max Vac: 24.9 inHg
Max Flow: 3.8 cfm
1 HP
230 VAC 3ph
-20 to 40°C
P-301
Edwards
XDS5
Max P(in): 7 psig
Max P(out): 15 psig
Max Flow: 3.5 cfm
0.4 HP
230 VAC 3ph
10 to 40°C
T-101, T-301
McMaster-Carr
9934K39
316SS
1 GAL
Max Press: 200 psi
Max Temp: 340°C
HEAT TRACING
McMaster-Carr
3554K21 (typ.)
Various length
self-regulated
heat cable.
63W max.
TDA RESEARCH INC.
12345 W. 52ND AVE. WHEAT RIDGE, CO 80033
PHONE: (303) 422-7819 FAX: (303) 422-7763
DRAWN mcc
DATE 1/24/2014
TITLE BioCAMSS
CO2/H2O Removal System
CHECKED kal
DATE 1/24/2014
APPROVED mcc
DATE 1/24/2014
SCALE N/A
SHEET SIZE B
SHEET 1 OF 1
DRAWING NO. TDA-CDM-PID
REV. 6

Figure 18. Process and Instrumentation Diagram (P&ID) for BioCAMSS.

TDA initially prepared a detailed design of the pilot scale CO_2 and humidity removal unit to meet all of CDM Smith's Requirements. Figure 18 and Figure 19 shows the P&ID and the 3-D layout of the pilot scale unit. A simplified block diagram of the mechanical interface requirements for the prototype unit is provided in Figure 4. Complete design and interface documents were provided to CDM Smith as part of the design package for review on January 9, 2013. Then the design and interfaces (both mechanical and electrical) were revised as needed to address the questions raised by CDM Smith during the review (March 15, 2013). TDA successfully completed the design review for the pilot scale CO_2 and humidity removal Unit in March 2013 and started the fabrication of the prototype unit.

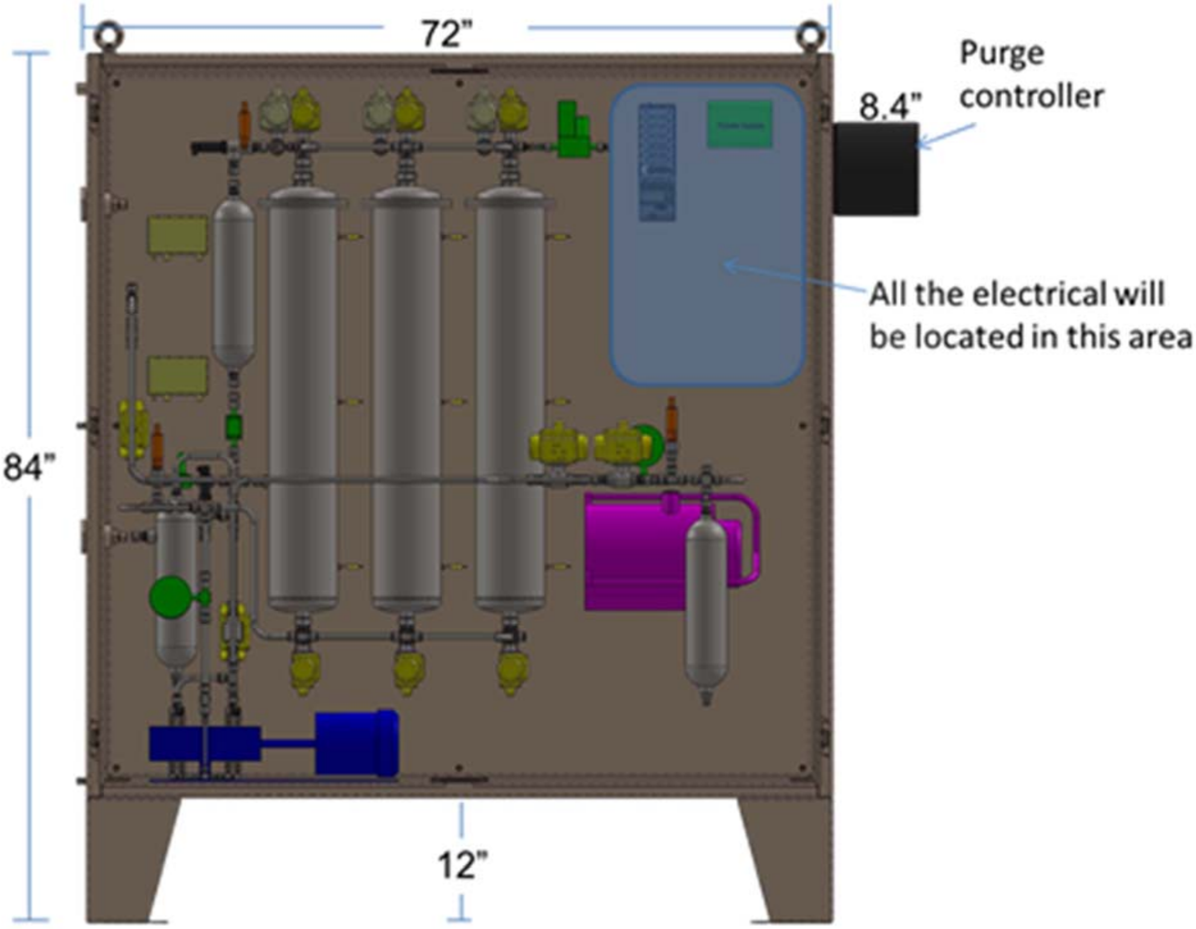


Figure 19. 3-D layout of the pilot scale CO_2 and H_2O removal unit.

VSA System Fabrication

We fabricated the three reactors and built the skid mounted pilot scale unit including the control system following the approved design. The system is rated for Class1 Div 1. Pictures of the VSA system during fabrication showing the major components are provided in Figure 20 through Figure 23.

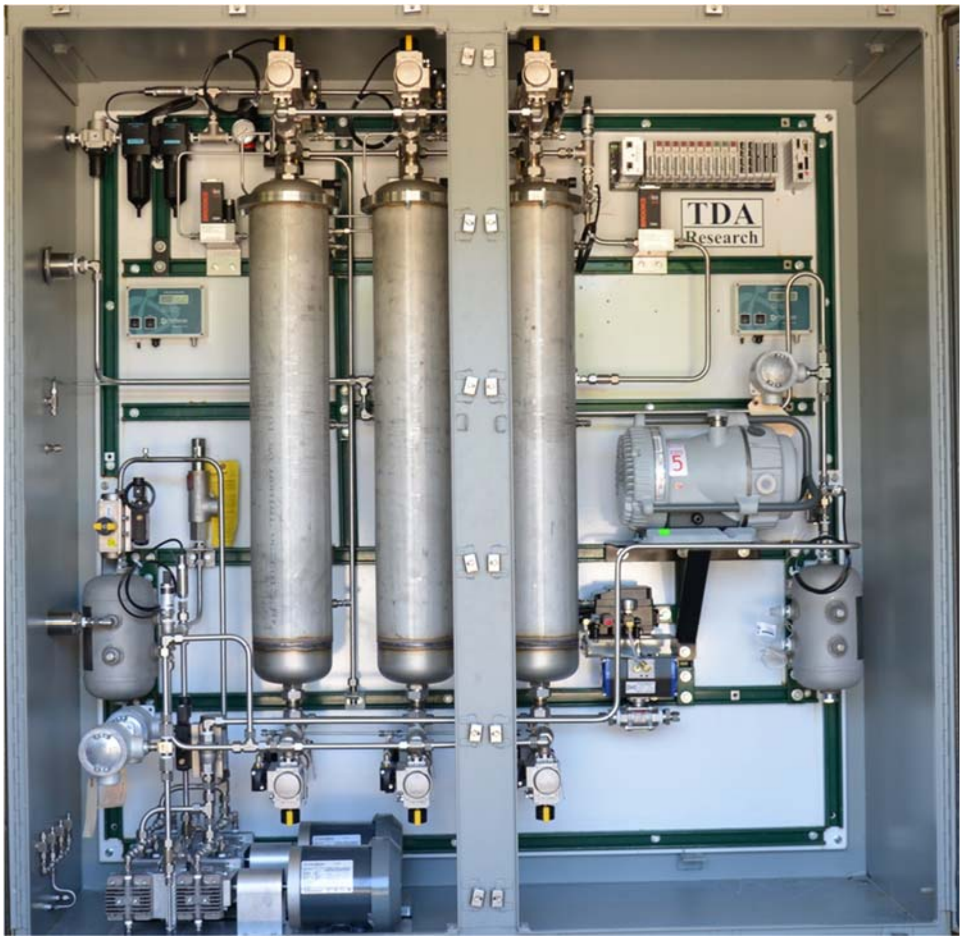


Figure 20. Picture of the pilot scale CO_2 and H_2O removal unit.

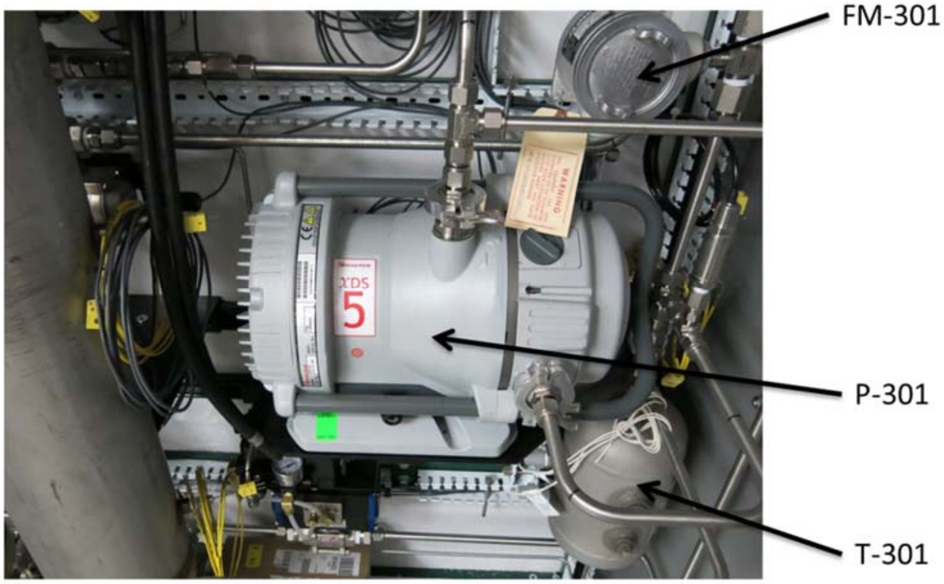


Figure 21. Picture of the pilot scale unit showing the blowdown gas flowmeter (FM-301), water knockout (T-301) and the vacuum pump (P-301).

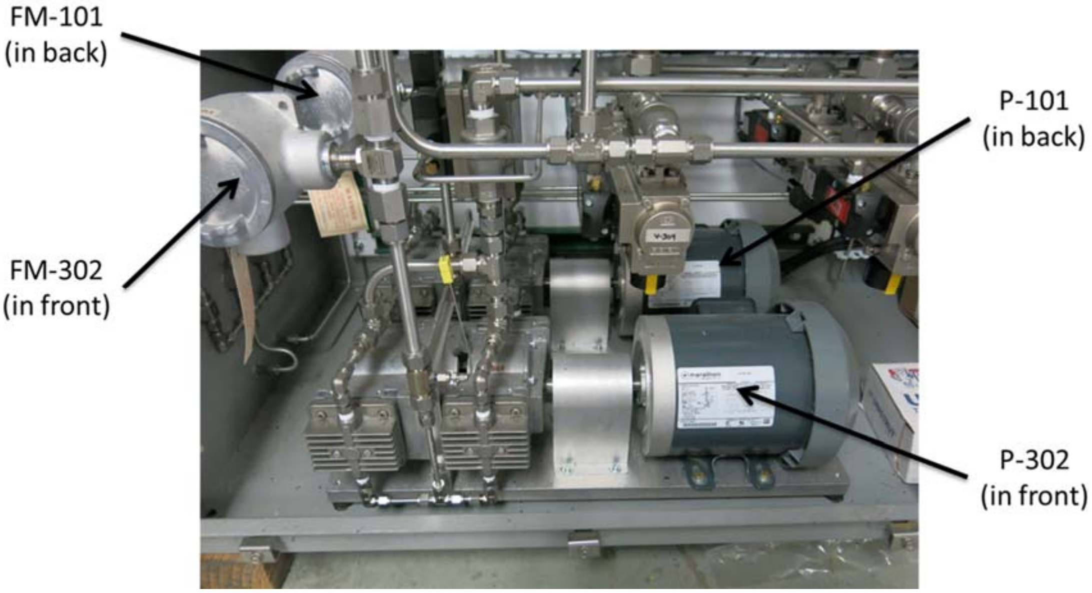

FM-101
(in back)
P-101
(in back)
FM-302
(in front)
P-302
(in front)

Figure 22. Picture of the pilot scale unit showing the feed biogas flowmeter (FM-101), recycle gas flowmeter (FM-302), feed biogas booster blower (P-101) and the recycle gas blower (P-302).

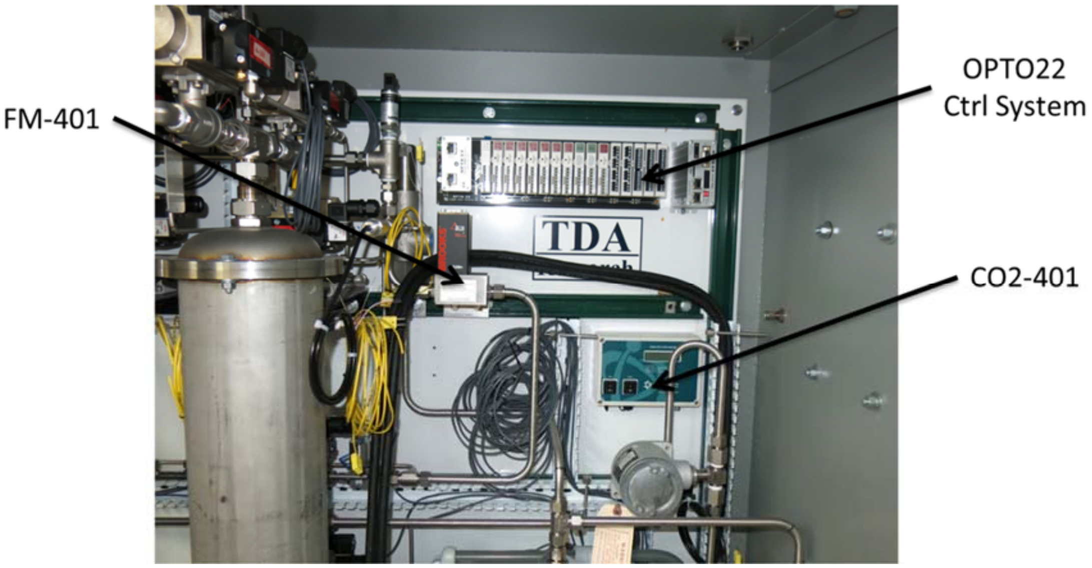

OPTO22
Ctrl System
FM-401
TDA
CO2-401

Figure 23. Picture of the pilot scale unit showing the product methane flowmeter (FM-401), product CO_2 analyzer (CO2-401), and OPTO22 Control System.

CO_2 Sorbent Production for Pilot Unit

TDA scaled–up the production of the CO2 and moisture removal sorbent for biogas purification application and prepared the sorbent needed for the VSA system (pilot unit). We measured the surface area and CO_2 and CH_4 adsorption capacities for each of the preparation batch to ensure that the material prepared meets the specifications of CO_2/CH_4 equilibrium selectivity (on wt. basis) of 6.0 or higher, with surface area of 130-200 m^2/g.

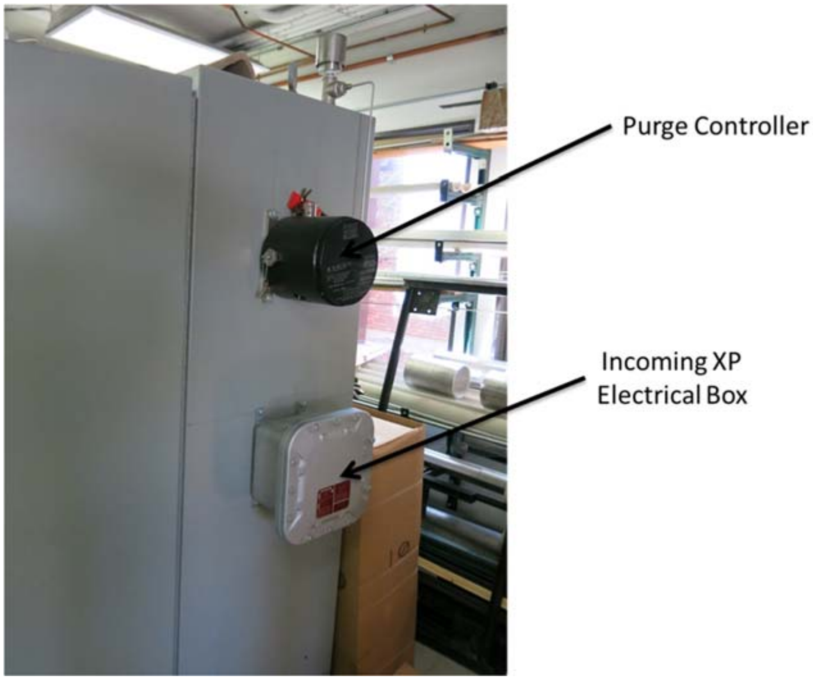


Figure 24. Picture of the pilot scale unit showing the Type X purge controller and the incoming XP electrical box.

The carbon was produced using a continuous rotary kiln, collected and stored in gallon jugs, and the BET surface areas were measured. The sorbent produced for the pilot scale test unit has the following properties: CO_2/CH_4 equilibrium selectivity on wt. basis of 6.3 and above (average of 6.7±0.3) and a sorbent surface area of 166±37 m^2/g. The adsorption data along with selectivity for the sorbent samples that are prepared in our pilot plant facility for the pilot scale test unit are summarized Table 4.

Table 4. Summary of properties of sorbent prepared for pilot scale test unit.

Sample #	Temperature (°C)	Bulk Density (g/cc)	BET Surface Area (m^2/g)	Amount Adsorbed		CO_2/CH_4 wt. ratio @ 1 atm	$t_{1/2}$ (eqm.)		Kinetic Ratio CH_4/CO_2
				CO_2 @ 1 atm	CH_4 @ 1 atm		CO_2 seconds	CH_4 seconds	
TMLR 101013 #4 AMS-187	22	0.285	201	8.32	1.33	6.3	2	7	3.5
	60			5.10	0.77	6.6	2	9	4.5
TMLR 101413 #8 AMS-187	22	0.318	173	7.75	1.17	6.6	3	16	5.3
	60			4.71	0.67	7.0	2	17	8.5
TMLR 101513 #14 AMS-187	22	0.314	176	8.44	1.26	6.7	3	5	1.7
	60			5.10	0.73	7.0	2	8	4.0
TMLR 101513 #18 AMS-187	22	0.300	114	7.82	1.1	7.1	4	27	6.8
	60			4.61	0.66	7.0	2	24	12.0
Pilot Scale Sorbent Average	22	0.304	166	8.08	1.22	6.7	3	14	4.6
	60			4.88	0.71	6.9	2	15	7.3
Pilot Scale Sorbent Std Dev.	22	0.015	37	0.35	0.10	0.3	0.8	10.0	2.2
	60			0.26	0.05	0.2	0.0	7.5	3.8

5.2 PILOT SCALE UNIT

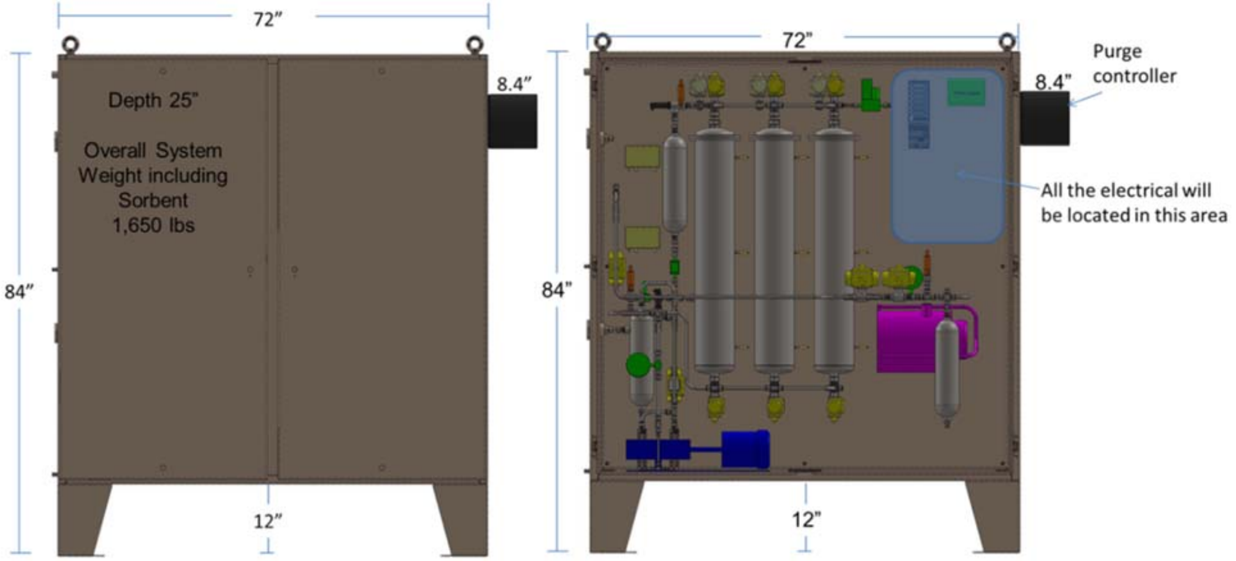

72"
8.4"
Depth 25"
Overall System Weight including Sorbent 1,650 lbs
84"
12"
72"
Purge controller
8.4"
All the electrical will be located in this area
84"
12"

Figure 25. 3-D layout of the pilot scale VSA system for CO_2 and H_2O removal from biogas.

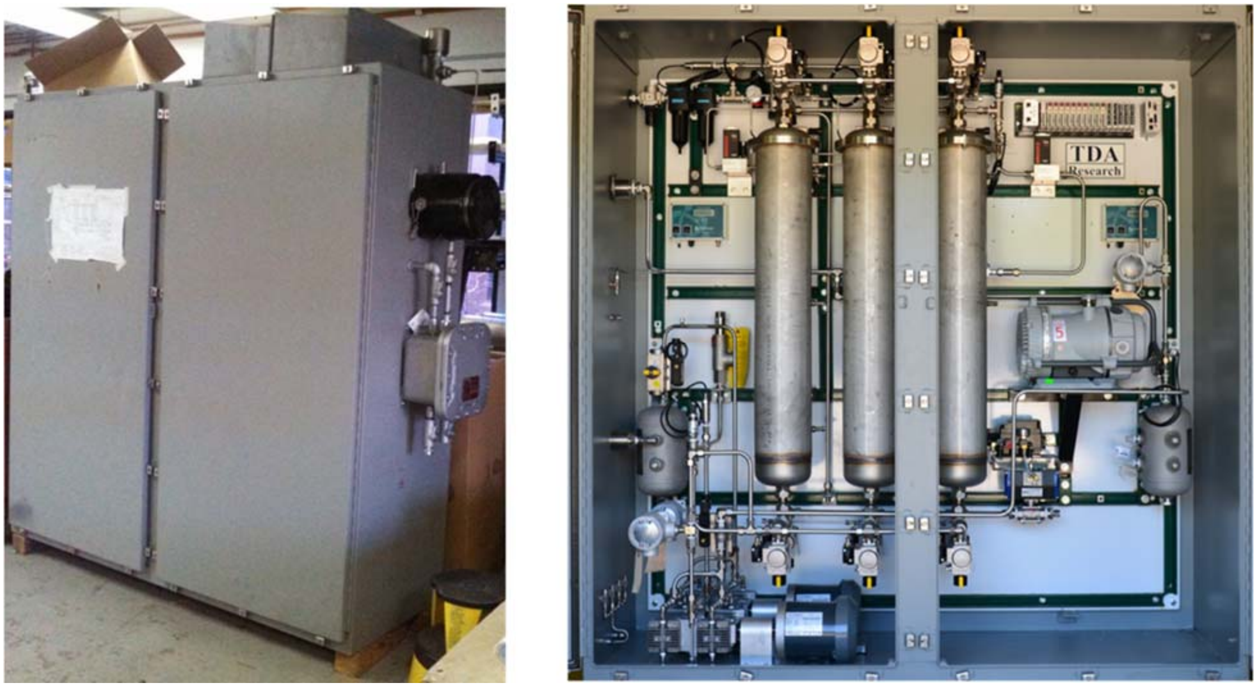
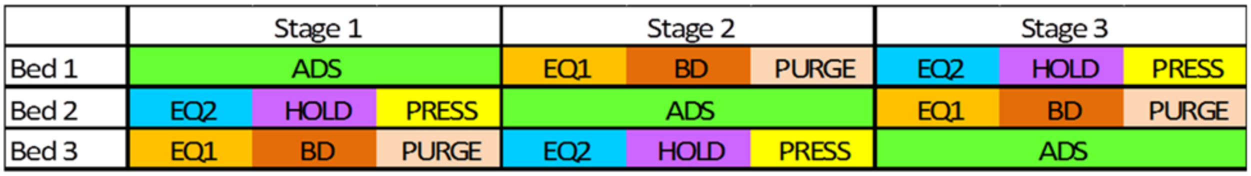

TDA Research

Figure 26. Picture of the pilot scale VSA system for CO_2 and moisture removal from biogas.

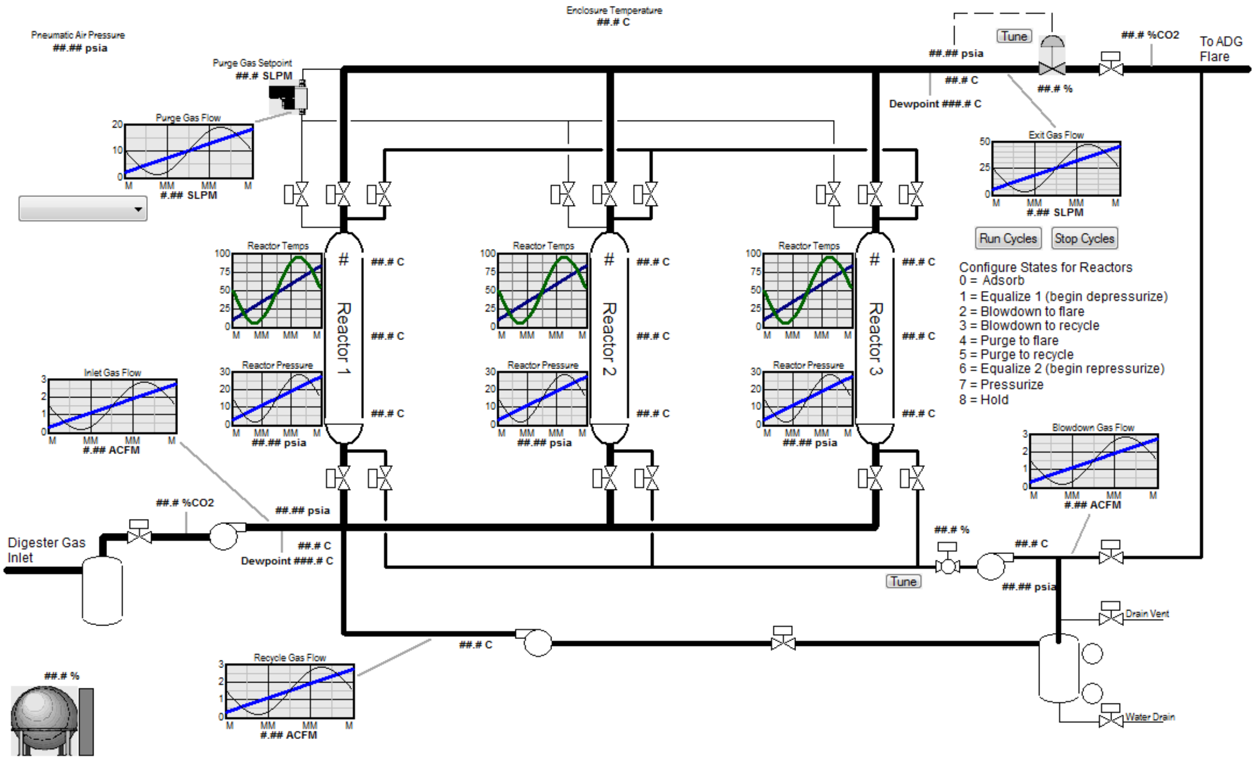
The pilot-scale biogas fully automated vacuum swing adsorption (VSA) based carbon dioxide and moisture removal system for biogas was designed and fabricated. Figure 25 shows the 3-D layout of the pilot unit. This system is part of the biogas purification subsystem and is installed downstream of the SulfaTrap^{TM} desulfurization system, and a biogas storage sphere. The storage sphere was used to store biogas and feed the carbon dioxide and moisture removal system and it can achieve greater than 95% methane (CH_4) purity in the product gas with greater than 90% methane recovery, reducing the inerts to less than 3% (i.e., combined Nitrogen (N_2) and Carbon Dioxide (CO_2)) in the product gas and a moisture content lower than 7 lbs/MMscf. The system was designed and fabricated for operation in a Class 1 Division 1 environment and is skid mounted located inside a NEMA 4 enclosure equipped with a purge system and rated for installation in an outdoor environment. Figure 26 shows the picture of the system after fabrication.

5.3 TREATABILITY OR LABORATORY STUDY RESULTS



	Stage 1			Stage 2			Stage 3		
Bed 1	ADS			EQ1	BD	PURGE	EQ2	HOLD	PRESS
Bed 2	EQ2	HOLD	PRESS	ADS			EQ1	BD	PURGE
Bed 3	EQ1	BD	PURGE	EQ2	HOLD	PRESS	ADS		

Figure 27. 3-bed VSA cycle sequence.



Configure States for Reactors
0 = Adsorb
1 = Equalize 1 (begin depressurize)
2 = Blowdown to flare
3 = Blowdown to recycle
4 = Purge to flare
5 = Purge to recycle
6 = Equalize 2 (begin repressurize)
7 = Pressurize
8 = Hold

Pneumatic Air Pressure
##.## psia
Enclosure Temperature
##.# C
Purge Gas Setpoint
##.# SLPM
Purge Gas Flow
#.## SLPM
Tune
##.## psia
##.# %CO2
To ADG Flare
##.# C
##.# %
Dewpoint ###.# C
Exit Gas Flow
#.## SLPM
Run Cycles
Stop Cycles
Reactor Temps
Reactor Pressure
##.## psia
##.# C
Reactor 1
Reactor 2
Reactor 3
Inlet Gas Flow
#.## ACFM
Blowdown Gas Flow
#.## ACFM
Digester Gas Inlet
##.# %CO2
##.## psia
##.# C
Dewpoint ###.# C
##.# %
Tune
##.## psia
Drain Vent
Water Drain
Recycle Gas Flow
#.## ACFM
##.# %
M
MM

Figure 28. Snap-shot of the OPTO-22 control screen for the 3-bed VSA system.

Tests at TDA using Simulated Biogas

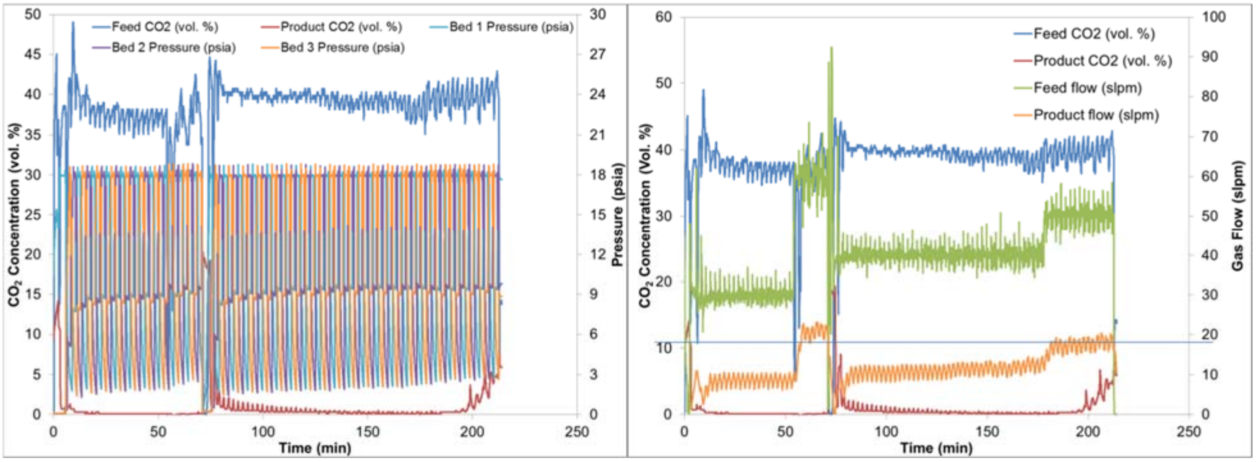


Figure 29. Snap-shot of the 3-bed VSA system operation at TDA using simulated biogas under simple VSA cycle scheme without equalization and desorption product recycle.

Figure 27 shows the 3-bed VSA cycle sequence. The programming of the VSA cycle sequence was done in the OPTO-22 control system. Figure 28 shows the snapshot of the OPTO-22 control screen. We validated the control system for the VSA cycles in the pilot scale unit in the tests at TDA. Figure 29 shows the results from tests at TDA using simulated biogas when the system was operated under a simple VSA scheme without equalization and recycle of the desorption product, which will improve the methane recovery to above 90%.

5.4 FIELD TESTING

Start-up and VSA Cycle Optimization

The purification system was demonstrated in conjunction with a food waste anaerobic digestion study conducted at the U.S. Air Force Academy (USAFA) in Colorado Springs, CO. This particular test site was selected due to the plentiful supply of food and grease trap waste. A variety of food wastes, including pre- and post-consumer food waste, waste cooking oil, and grease trap waste from USAFA was used to produce biogas in the CDM Smith's pilot scale anaerobic digester unit and this biogas was sent to desulfurizer column and the sulfur free biogas was stored in a biogas sphere and once the sphere is full the biogas was sent to TDA's VSA unit to produce pipeline quality bio-methane. TDA's 3-bed VSA system is designed for 24/7 continuous operation and can treat up to 3 scfm. However, we only operated the 3-bed VSA system during regular business hours so that we always have an operator available on-site. This operator's role is only to provide TDA unit the permission to operate. The unit was operated by TDA personnel remotely from our offices in Wheat Ridge, CO and was shut down at the end of the day's operation. We operated the VSA system only when the digester was full, which is typically 2-3 days in a week.

We started the field tests with VSA unit on February 28, 2015 and the biogas sphere contained raw biogas on the first day of test. Then, the desulfurizers were loaded with SulfaTrap^{TM} sample and desulfurized biogas was stored in the sphere, which was later used for breakthrough tests through

March 28, 2014. During these tests, we noticed that when we ran VSA cycles through multiple beds the check valve leaked the CO_2 rich desorption product into the CO_2 free (bio-ethane) product manifold. Hence, we increased the check valve rating to higher pressure say 3-5 psi to prevent back flow this helped in preventing contamination of bio-methane exiting the beds. Then in April 2014, we optimized VSA cycle design, by exploring different cycle design options such as feed end pressurization, product end pressurization, pressure equalization, and biogas flow rate.

System Operation

Table 5. Summary of the field tests carried out with TDA's 3-bed VSA system.

Date	Test Duration (min)	Cycle time (sec)	Number of Cycles	Feed Biogas			Product Bio-methane					Sorbent Capacity (% wt. CO_2)
				Total flow (SCF)	flow (slpm)	CO_2 (vol. %)	Total flow (SCF)	flow (slpm)	CO_2 (vol. %)	CH_4 recovery (vol. %)	CH_4 Purity (vol. %)	
2/28/2014	78.5	810	5.8	28.0	10.1	35.8	6.3	2.262	3.7	34	96.3	0.5
3/6/2014	270.0	1050	15.4	123.6	12.96	45.2	39.5	4.142	13	51	87	1.0
3/14/2014	60.0			101.7	48							
3/18/2014	248.0			420.4	48							
3/28/2014	140.0			237.3	48							
4/1/2014	91.8	810	6.8	123.4	38.1	49.1	58.8	18.1	0.9	67	99.1	3.6
4/8/2014	162.1	1251	12.0	214.4	37.4	49.4	44.7	7.8	0.1	41	99.9	2.6
4/10/2014	134.8	810	10.0	181.2	38.1	49.1	39.2	8.2	0.3	60	99.8	2.6
4/15/2014	121.7	810	9.0	169.6	39.5	51.7	35.9	8.4	0.7	44	99.3	2.8
4/15/2014	94.7	810	7.0	127.9	38.3	51.5	38.5	11.5	0.4	62	99.6	2.7
4/23/2014	108.4	810	8.0	148.3	38.7	50.1	39.9	10.4	1.7	53	98.3	2.7
4/24/2014	378.7	810	28.0	543.4	40.6	52.3	153.6	11.5	0.8	59	99.2	2.9
7/16/2014	81.1	810	6.0	103.1	36.0	50.0	26.4	9.2	2.8	83	97.2	1.5
7/21/2014	9.7	810	0.7	8.0	23.3	58.0	2.8	8.1	1.3	82	98.7	5.6
7/22/2014												
7/23/2014	145.4	1140	7.7	149.9	29.2	58.0	46.9	9.1	1.8	73	98.2	3.3
7/25/2014	155.8	1550	6.0	132.9	24.2	42.0	76.7	13.9	8.7	91	91.3	2.4
7/29/2014	412.2	1110	22.3	282.5	19.4	42.0	157.5	10.8	2.8	93	97.2	1.5
7/30/2014	150.8	1110	8.2	117.3	22.0	42.0	63.3	11.9	1.7	92	98.3	1.7
7/31/2014	168.2	1110	9.1	161.2	27.1	42.0	81.3	13.7	1.3	86	98.7	2.1
8/31/2014	240.5	1110	13.0	247.2	29.1	42.0	132.9	15.6	2.2	91	97.8	2.2

The CDM Smith digester was offline for maintenance during May – June 2014 and the tests were re-started in July 2014. In the tests carried out in July 2014 we operated the VSA system under optimized test conditions and demonstrated high bio-methane purity and recovery. The Summary of the field test results are provided in Table 5.

System Shutdown

The field tests were completed on August 31, 2014 and TDA's unit were shipped back to TDA in the beginning of September 2014.

5.5 SAMPLING METHODS

In order to calculate methane recovery, the volumetric flow rates of the raw biogas feed to TDA's biogas purification system and the bio-methane product (treated biogas) produced were measured using flowmeters upstream (FM-101 Flow Technology's FT series turbine meter) and downstream (FM-401 Brooks Instrument's thermal flowmeter) of the 3-bed VSA system, respectively. We also had in-line CO_2 and humidity probes (from CO_2 meters.com and Kahn Instruments) to quantify the amount of CO_2 and H_2O present in the raw and treated biogas. We also confirmed the methane purity of the raw biogas feed and the treated biogas (bio-methane) using Infrared analyzer in the CDM Smith test Skid to confirm that the bio-methane has greater than 95% methane in it.

CDM Smith also took gas samples of the raw biogas feed before and after both the sulfur sorbent bed and the VSA system and sent them to outside laboratory (ALS Environmental, Simi Valley, CA) for analysis. The samples were received intact under chain of custody by the Laboratory and were stored in accordance with the analytical method requirements till their analysis. The analysis was performed as soon as possible after receipt by the laboratory. The Analysis methods are described in Section 3.0.

5.6 SAMPLING RESULTS

Typical composition of the raw biogas and the bio-methane produced in the field tests are provided in Table 6. The sulfur in the raw biogas was typically around 1,000 – 1,500 ppm H_2S with trace amounts of organic sulfur compounds. SulfaTrap^{TM}-R7 desulfurization sorbent removed the sulfur compounds to less than 0.25 ppmv.

Table 6. Typical composition of raw, sweetened biogas and bio-methane from food wastes during field tests.

Sample Date:	Raw biogas 7/16/2014	Sweetened biogas 7/16/2014	Bio-methane 7/16/2014
CH_4	64.40	61.70	96.35
CO_2	34.80	36.00	2.03
N_2	0.60	1.66	1.11
O_2/Ar	0.23	0.67	0.52

We initially carried out breakthrough tests with the CO_2 sorbent beds in the field using desulfurized food waste derived biogas to measure the capacity of the saturated VSA adsorbent bed, which were above 4.4% wt. CO_2. Figure 30 shows the CO_2 breakthrough for one of the three beds, "CO2_101" is the inlet CO_2 concentration to the VSA bed and "CO2_401" is the exit CO_2 concentration from the VSA bed. We optimized the VSA cycles in the field and the optimized VSA cycle scheme was used to produce high purity bio-methane with methane recovery greater than 90%. VSA cycle schemes with both feed end and product end pressurizations provided working capacities in excess of 2.8% wt. and the CO_2 concentration in the bio-methane product was reduced to less than 0.5% by vol. The dew point of the biogas was reduced from 10-15°C to less than -40°C, providing essentially a dry bio-methane product. Figure 31 and Figure 32 show the CO_2 and H_2O removal, respectively, from actual biogas at USAFA. Figure 33 shows the methane purity of the bio-methane as measured by an IR based methane analyzer. We operated the biogas purification system for a total of 54 hours purifying more than 3,620 SCF of biogas to produce bio-methane with greater than 90% methane recovery.

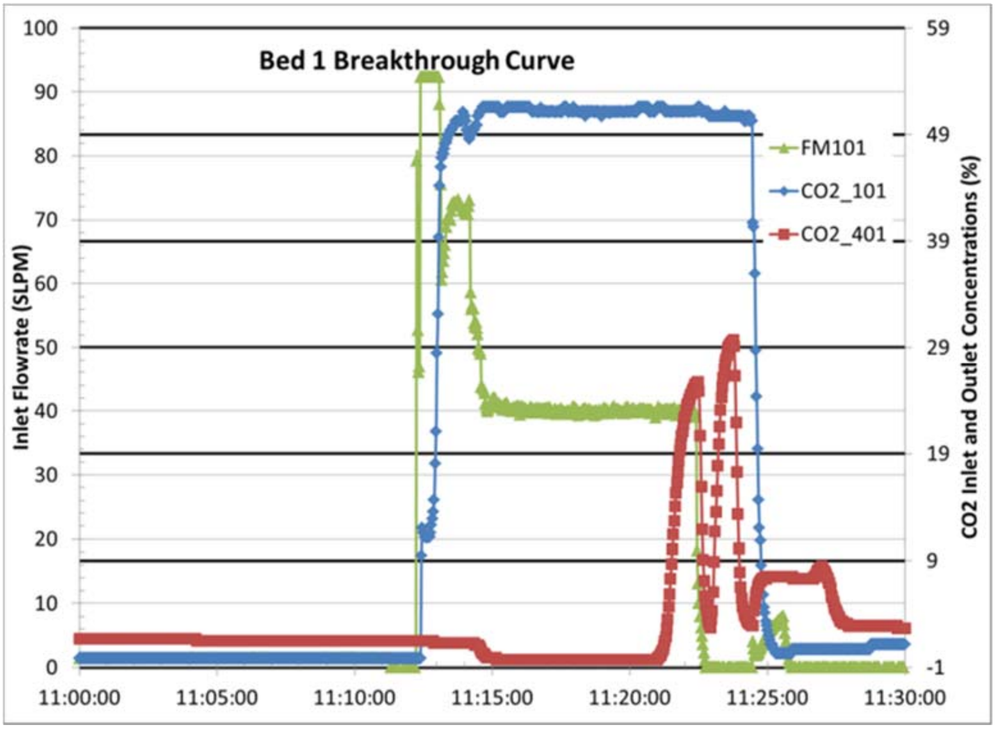


Figure 30. CO_2 Breakthrough curve from single bed saturation experiment conducted with actual biogas at USAFA (Colorado Springs, CO).

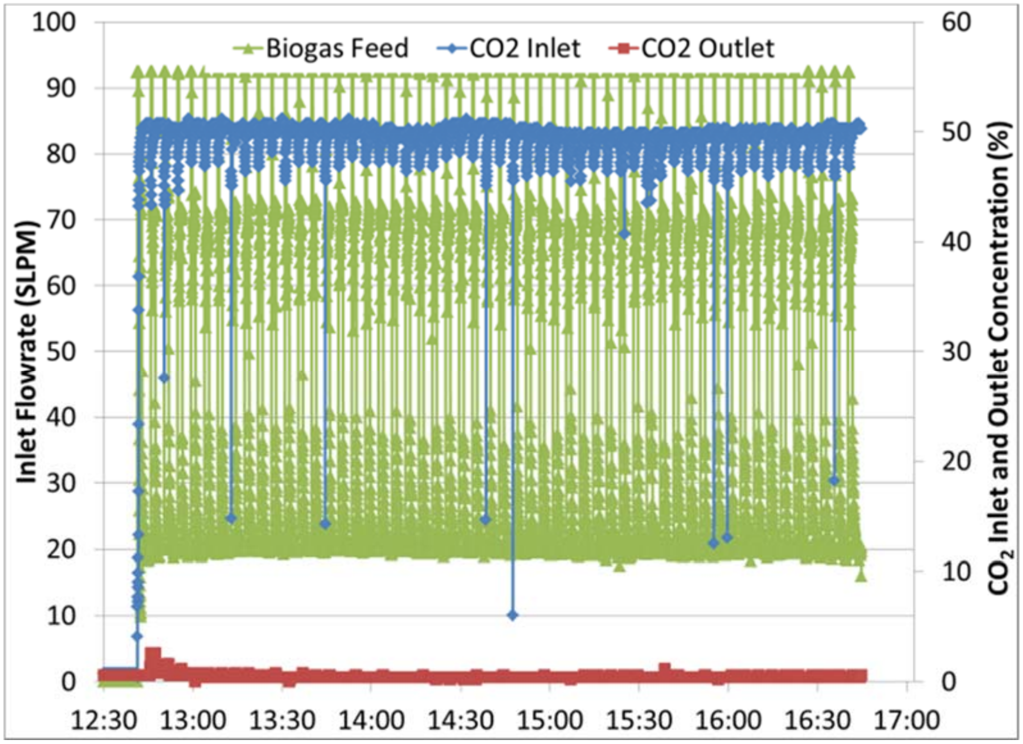


Figure 31. Biogas purification system performance for CO_2 removal from actual biogas at USAFA (Colorado Springs, CO).

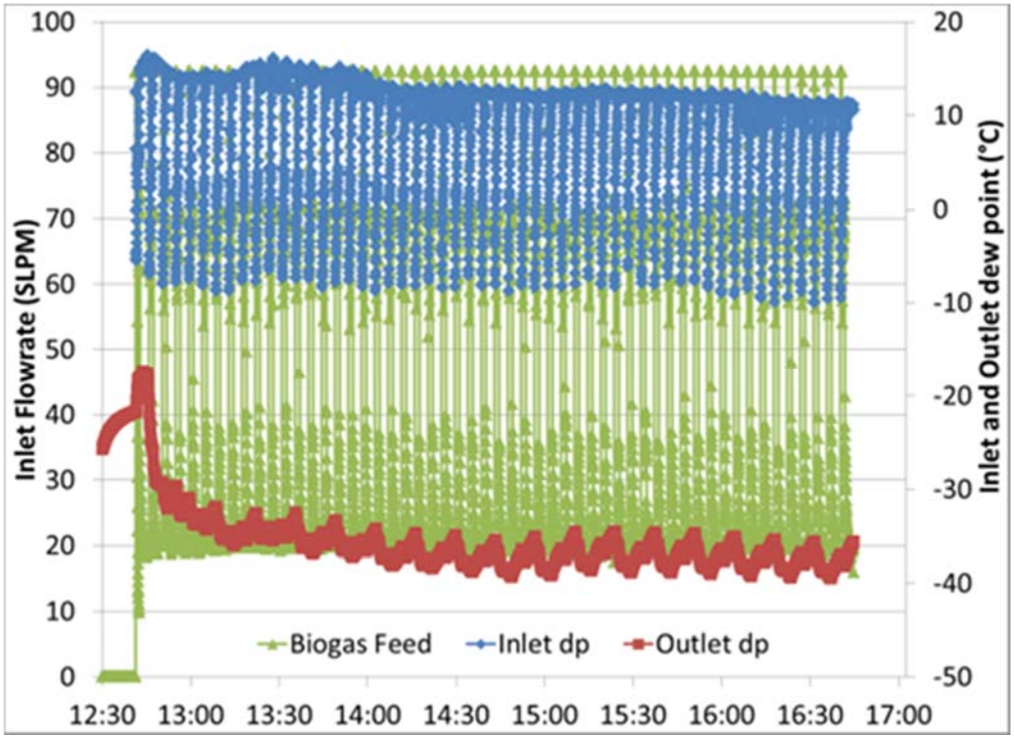


Figure 32. Biogas purification system performance for H_2O removal from actual biogas at USAFA (Colorado Springs, CO).

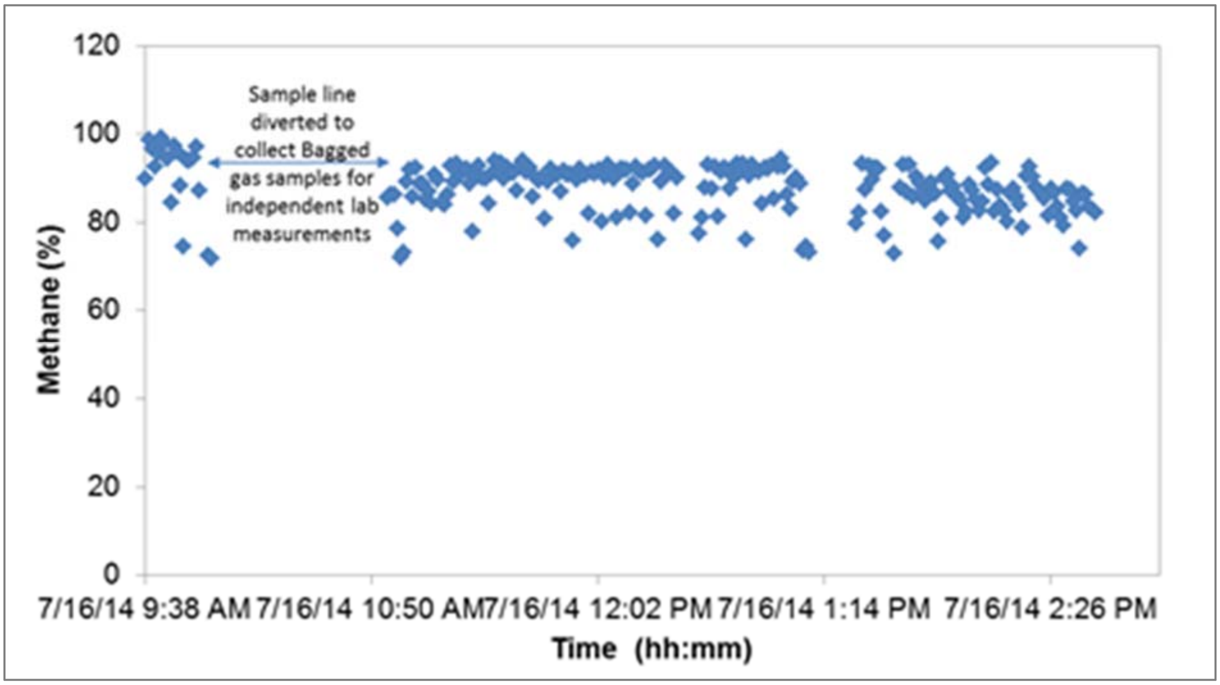
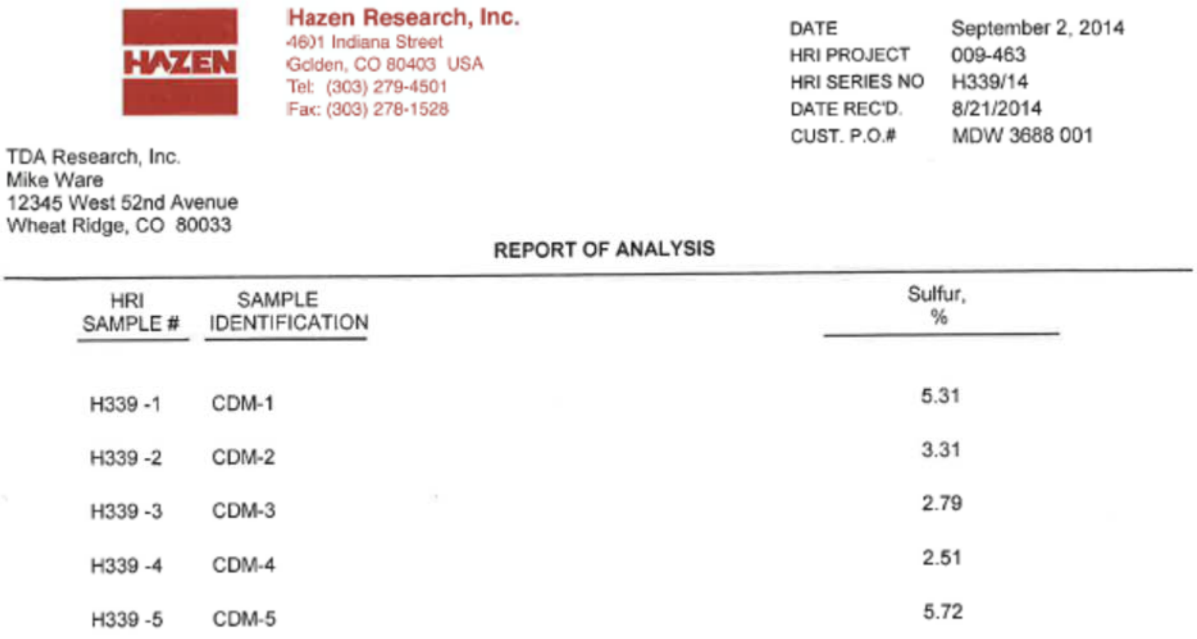


Figure 33. Biogas purification system performance under actual biogas at USAFA (Colorado Springs, CO) showing the high purity bio-methane production.

Post Analysis of Sulfur Sorbent

We carried out post sulfur analysis of the R7 sorbent removed from CDM Smith desulfurizer (reactor). The gas flow direction is from samples coded CDM-1 to CDM-5. With the sorbent being pulled at the following axial positions in the bed z=0; Z=1/4L; Z=1/2L; Z=3/4L, z=L. The exit end showed higher sulfur loading similar to the inlet, while the other locations showed expected trend of deceasing sulfur loading in the gas flow direction. The snapshot of post analysis report provided by Hazen Laboratory in Golden, CO is provided in Table 7.

Table 7. Post sulfur analysis of the sulfur sorbent used in the field tests.



HAZEN

Hazen Research, Inc.
4601 Indiana Street
Golden, CO 80403 USA
Tel: (303) 279-4501
Fax: (303) 278-1528

DATE September 2, 2014
HRI PROJECT 009-463
HRI SERIES NO H339/14
DATE REC'D. 8/21/2014
CUST. P.O.# MDW 3688 001

TDA Research, Inc.
Mike Ware
12345 West 52nd Avenue
Wheat Ridge, CO 80033

REPORT OF ANALYSIS

HRI SAMPLE #	SAMPLE IDENTIFICATION	Sulfur, %
H339 -1	CDM-1	5.31
H339 -2	CDM-2	3.31
H339 -3	CDM-3	2.79
H339 -4	CDM-4	2.51
H339 -5	CDM-5	5.72

6.0 PERFORMANCE ASSESSMENT

6.1 QUANTITATIVE PERFORMANCE OBJECTIVES

Methane Recovery

After, optimization of the VSA cycle parameters in the field tests in July 2014, we were able to achieve greater than 80% methane recovery with the use of VSA cycles that incorporated pressure equalization. This was further improved to 90+% with the use of an advanced VSA cycle scheme with recycle, as shown in the field tests summary provided in Table 5.

Natural Gas Specification

As shown in the results in Table 6 and Figure 31 through Figure 33, TDA's biogas purification system (SulfaTrap^{TM}-R7 and VSA system combination) cleaned up the biogas so that the resulting purified biogas (bio-methane) met the natural gas specification.

- methane purity was greater than 95% as confirmed from the field data from IR based analyzer and the bagged samples analyzed a third party laboratory
- total sulfur concentration in the bio-methane produced was less than 0.25 ppm (well below the target of 4 ppm)
- the total N_2 and CO_2 on an average was less than 2.61% and the average CO_2 content was reduced to less than 1.5% from 48.2% by vol.
- the dew point bio-methane was reduced to less than < 40°C i.e., < 7lbs/MMscf moisture

6.2 QUALITATIVE PERFORMANCE OBJECTIVES

Ease of use

We received feedback from field technician (TDA operator) on usability of the technology and time required to run the system. In these field tests a single field technician was able to effectively operate the system remotely from TDA facilities in Wheat Ridge, CO with minimal to no on-site help.

7.0 COST ASSESSMENT

7.1 FULL SCALE SYSTEM DESIGN

CO_2 and H_2O Removal System

In this full-scale system design for the CO_2 and H_2O removal system we used a 4 bed VSA system instead of a 3-bed VSA system since it provides more flexibility in vacuum swing adsorption cycle scheduling. This allows us to maximize the purge time, which provides higher methane purity and recovery. Table 8 shows the design basis for purifying 2,000 m^3/day of biogas to produce bio-methane with the methane purity target of 99% and 90% methane recovery. Table 9 shows 4-bed VSA cycle schedule with the same purge time as the adsorption time.

Table 8. Full Scale Design Basis.

Biogas flow	2000 m^3/day 49.0 cfm
Feed Composition:	
CH_4	65%
CO_2	35%
Experimental Data:	
Sorbent working capacity	1.8% wt. CO_2
Simulation Data:	
Adsorption Product Purity	99.2%
Desorption Product Purity	87.8%
Methane Recovery	92.6%
Total Gas Processed per pass	3360 m^3/day 82.4 cfm
Number of Beds	4
Full Cycle time	12
Adsorption time	3
Full cycles per day	120

Table 10 shows the bed sizing for a 2,000 m^3/day of biogas flow. We estimated the size of the VSA beds to be 600 L each with the methane purity target of 99% and along with a 90% methane recovery. Figure 34 shows the PFD for the 4-bed VSA system with the stream numbers marked. Table 11 shows the stream summary around the 4-bed VSA system for a 2,000 m^3/day of biogas flow.

Table 9. 4-bed VSA cycle schedule.

Time	Stage 1			Stage 2			Stage 3			Stage 3		
(min)	3			1	1	1	3			1	1	1
Bed 1	ADS			EQD1	Hold	BD	PURGE			EQR1	Hold	PRESS
Bed 2	EQR1	Hold	PRESS	ADS			EQD1	Hold	BD	PURGE		
Bed 3	PURGE			EQR1	Hold	PRESS	ADS			EQD1	Hold	BD
Bed 4	EQD1	Hold	BD	PURGE			EQR1	Hold	PRESS	ADS		

3- bed 1 EQ VSA Cycle Steps:

Step 1 Adsorption at 19 psia (ADS)
Step 2 Equalization to 8 psia (EQD1)
Step 3 Hold
Step 4 Blowdown to 2 psia (BD)
Step 5 Product Purge at 2 psia (PURGE)
Step 6 Equalization to 8 psia (EQR1)
Step 7 Hold
Step 8 Product pressurization to 19 psia (PRESS)

Table 10. 4-bed VSA bed sizing for 2,000 m^3/day biogas flow.

CO_2 to be removed	17.2 cfm 206.0 cf/cycle 51.5 cf/cycle/bed 2.9 kg/cycle/bed
Sorbent needed per bed	156.4 kg/bed 592.6 L/bed
Design Factor (1.0125)	600 L/bed
Total Sorbent needed	634 kg 2400 L
L/D	4.9
Bed Outer Diameter	22 "
Bed Inner Diameter	21.25 "
Bed Length	8.6 ft

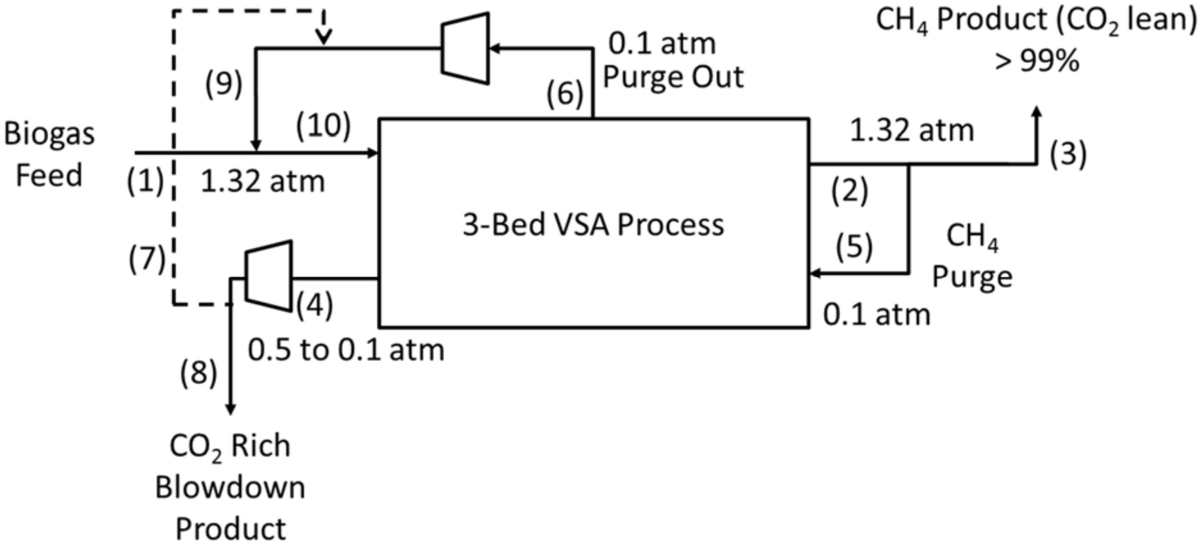

CH4 Product (CO2 lean)
> 99%
0.1 atm
Purge Out
(6)
(9)
(10)
Biogas
Feed
(1)
1.32 atm
1.32 atm
(3)
(2)
3-Bed VSA Process
CH4
Purge
(5)
(7)
(4)
0.1 atm
0.5 to 0.1 atm
(8)
CO2 Rich
Blowdown
Product

Figure 34. Streams around the 4-bed VSA system marked in the simplified PFD.

Table 11. Stream data for 4-bed VSA system.

Stream No.	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Description	Biogas Feed	Adsorption Out	CH_4 Product	Blowdown Product	CH_4 Purge	Purge Out	BD Recycle	Desorption Product	Recycle Stream	Feed to Beds
P (atm)	1.32	1.32	1.32	0.5->0.1	0.10	0.10	0.10	0.10	1.32	1.32
Flow rate (scfm)	49.0	33.6	29.8	33.8	3.8	18.6	14.5	19.3	33.2	82.4
CH_4 (scfm)	31.9	33.3	29.5	4.1	3.8	4.1	1.8	2.3	5.9	37.7
CO_2 (scfm)	17.2	0.3	0.2	29.7	0.0	14.6	12.7	16.9	27.3	44.5

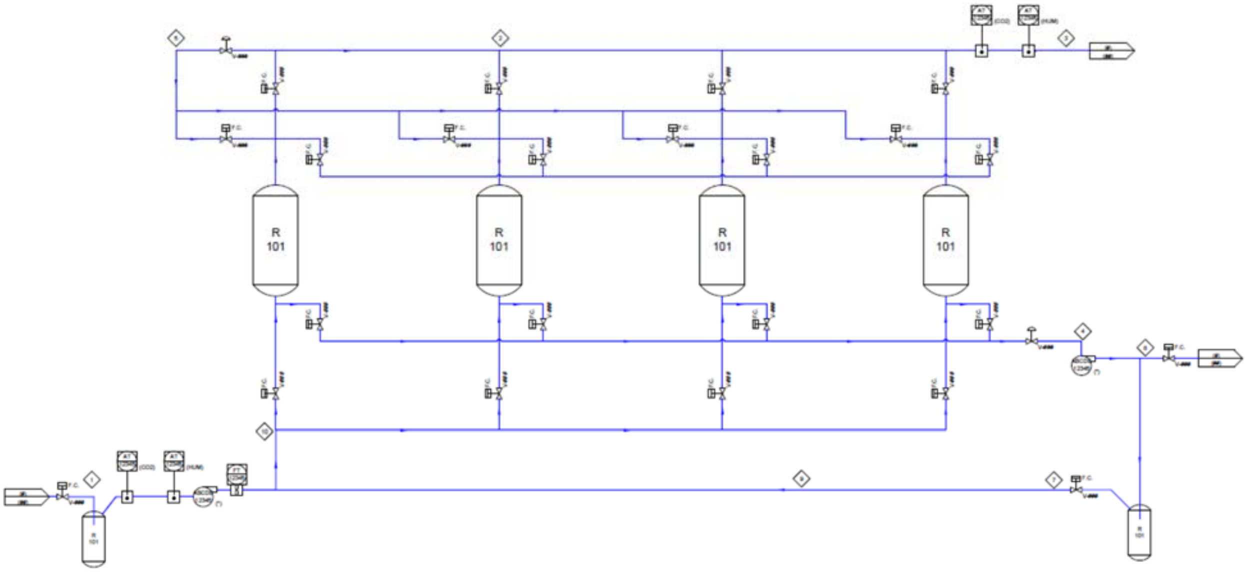

R 101
R 101
R 101
R 101

Figure 35. P&ID for the 4-bed VSA system including process instrumentation for control.

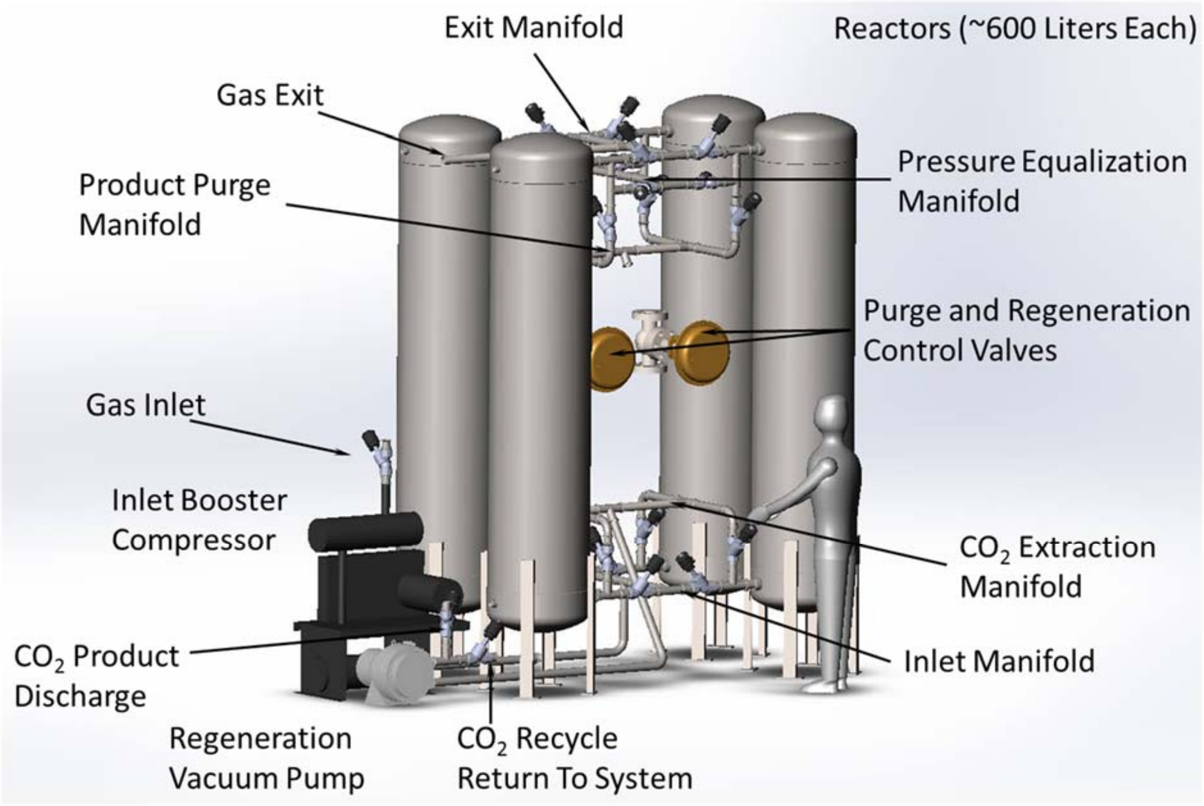

Exit Manifold
Reactors (~600 Liters Each)
Gas Exit
Product Purge Manifold
Pressure Equalization Manifold
Purge and Regeneration Control Valves
Gas Inlet
Inlet Booster Compressor
CO$_2$ Extraction Manifold
CO$_2$ Product Discharge
Inlet Manifold
Regeneration Vacuum Pump
CO$_2$ Recycle Return To System

Figure 36. 3-D layout of a 2,000 m^3/day VSA based biogas purification system.

Figure 35 shows the P&ID of the 4-bed VSA system including the process instrumentation needed to control the VSA cycle schedule. Figure 36 shows the preliminary 3-D layout for the 4-bed VSA system.

Sulfur Removal System

In this full-scale system design for the sulfur removal system we used a lead-lag system with two beds and a bed life of 6 months. Table 12 shows the sulfur sorbent bed sizing for a 2,000 m^3/day of biogas flow. We assumed an average sulfur level of 1,000 ppmv H_2S in the raw biogas. We estimated the size of the sulfur sorbent bed for 6-month bed life to be 1,544 L to remove more than 99.9% of the sulfur present in the biogas. Table 13 shows the reactor sizing for the lead-lag system. The system consists of two lead-lag beds of outer diameter 36” and bed height of 8’ each with an individual L/D of 2.7. Figure 37 shows the P&ID of the 4-bed VSA system including the process instrumentation needed to control the VSA cycle schedule. Figure 38 shows the preliminary 3-D layout for the 4-bed VSA system.

Table 12. Sulfur sorbent bed sizing for 2,000 m^3/day biogas flow.

Basis		
Sulfur Level	1000.00	ppmv
Gas Flow Rate	2,000	m^3/day
Sulfur Breakthrough	0.0	ppmv
Sulfur to be Removed	2.86	kg/day
Expendable Sorbent System		
Number of Beds per Set	2	
Number of Sets	1	
Sulfur Capacity	27.0%	wt. S
Sorbent Life (Replacement)	183	days
Sorbent Needed per Bed	1,934	kg
Sorbent Needed for All Beds	3,868	kg
Sorbent Bed Volume	1,547	L
System Sizing Factor	1.0	
Sorbent Density	1.25	g/cc
Void Fraction	0.45	
Pressure Drop Through the Beds During Adsorption	0.02	psi

Table 13. Reactor sizing for 2,000 m^3/day biogas flow.

Reactor Sizing		
Outer Diameter	36.00	in
Inner Diameter	35.38	in
Vessel Cylinder Height	8.0	ft
Overall Vessel Height	9.5	ft
L/D	2.7	
Volume	1,547	L
Type	Welded Cylindrical	
Materials of Construction	304L SA312	
Pressure Rating	162	psig
Weight (Empty)	654	kg
Weight Filled with Sorbent	2,588	kg

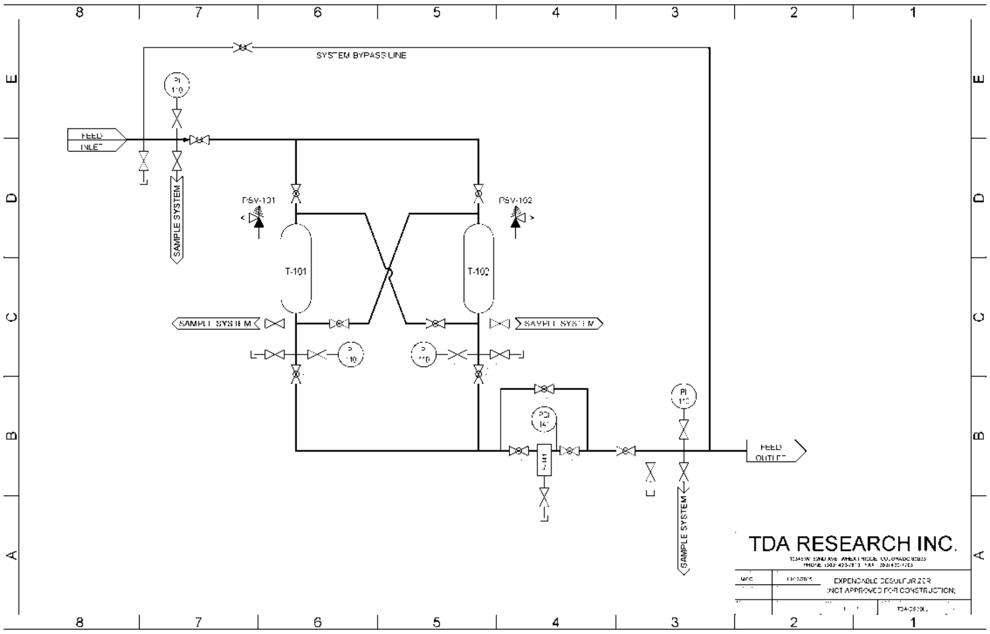

SYSTEM BYPASS LINE
PI 110
FEED INLET
SAMPLE SYSTEM
PSV-101
PSV-102
T-101
T-102
SAMPLE SYSTEM
SAMPLE SYSTEM
PI 110
PI 110
PDI 141
PI 110
FEED OUTLET
SAMPLE SYSTEM
TDA RESEARCH INC.
EXPENDABLE DESULFURIZER
(NOT APPROVED FOR CONSTRUCTION)

Figure 37. P&ID for the lead-lag sulfur removal.

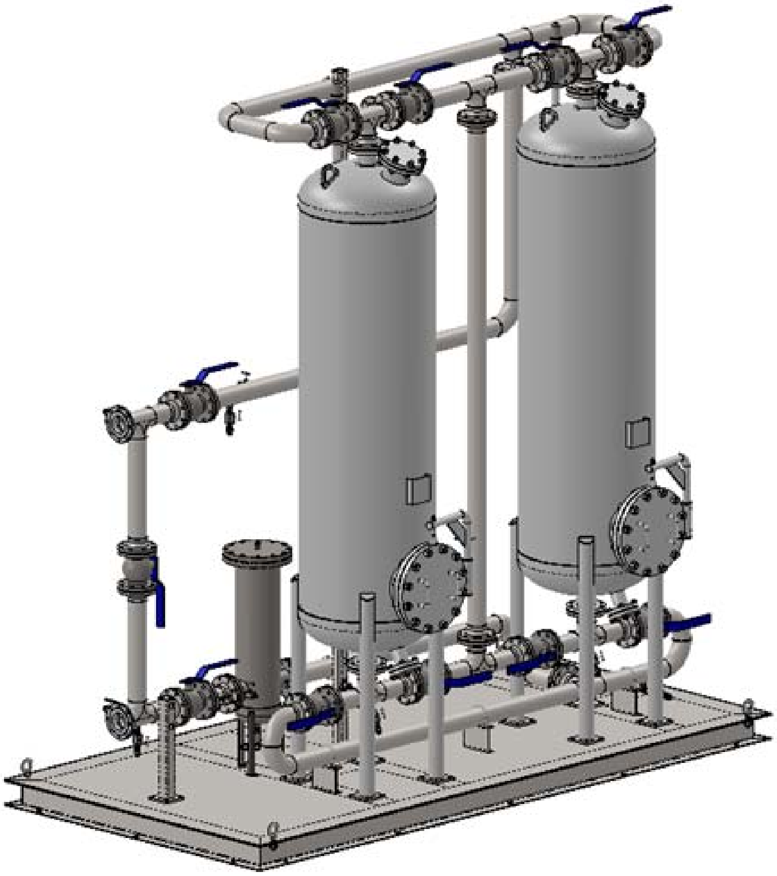


Figure 38. 3-D layout of a 2,000 m^3/day Lead-lag SulfaTrap^{TM} sulfur removal system.

7.2 COST MODEL

The cost model is described in the schematic below:

Total Direct and Indirect Cost (TD&IDC) = Bare Equipment Cost + Installation Cost

Total Plant Cost (TPC) = TD&IDC + Engineering + Overhead & Adminstration
+ Contingency + Fees

Total Capital Requirement (TCR) = TPC + + Startup Cost + Spare Parts
+ Initial Sorbent Inventory + Facilities + Land

Operating & Maintenance (O&M) Cost = Operating Labor + Sorbent Replacement
+ Parasitic Power + Sorbent Disposal + Overhead

Annual Operating Cost (AOC) = O&M cost+ Capital Recovery

$$\text{Cost of CO}_2 \text{ removal } (\$/m^3\ CH_4 \text{ produced}) = \frac{AOC\ for\ CO_2\ removal}{m^3\ CH_4\ produced}$$

$$\text{Cost of CO}_2 \text{ removal } (\$/\text{MMBTU}) = \frac{\text{Cost of CO}_2 \text{ removal } (\$/m^3\ CH_4 \text{ produced})}{Heating\ value\ of\ CH_4\ (MMBTU)/m^3\ CH_4\ produced}$$

$$\text{Cost of sulfur removal } (\$/\text{kg sulfur removed}) = \frac{AOC\ for\ sulfur\ removal}{kg\ sulfur\ removed}$$

7.3 COST DRIVERS

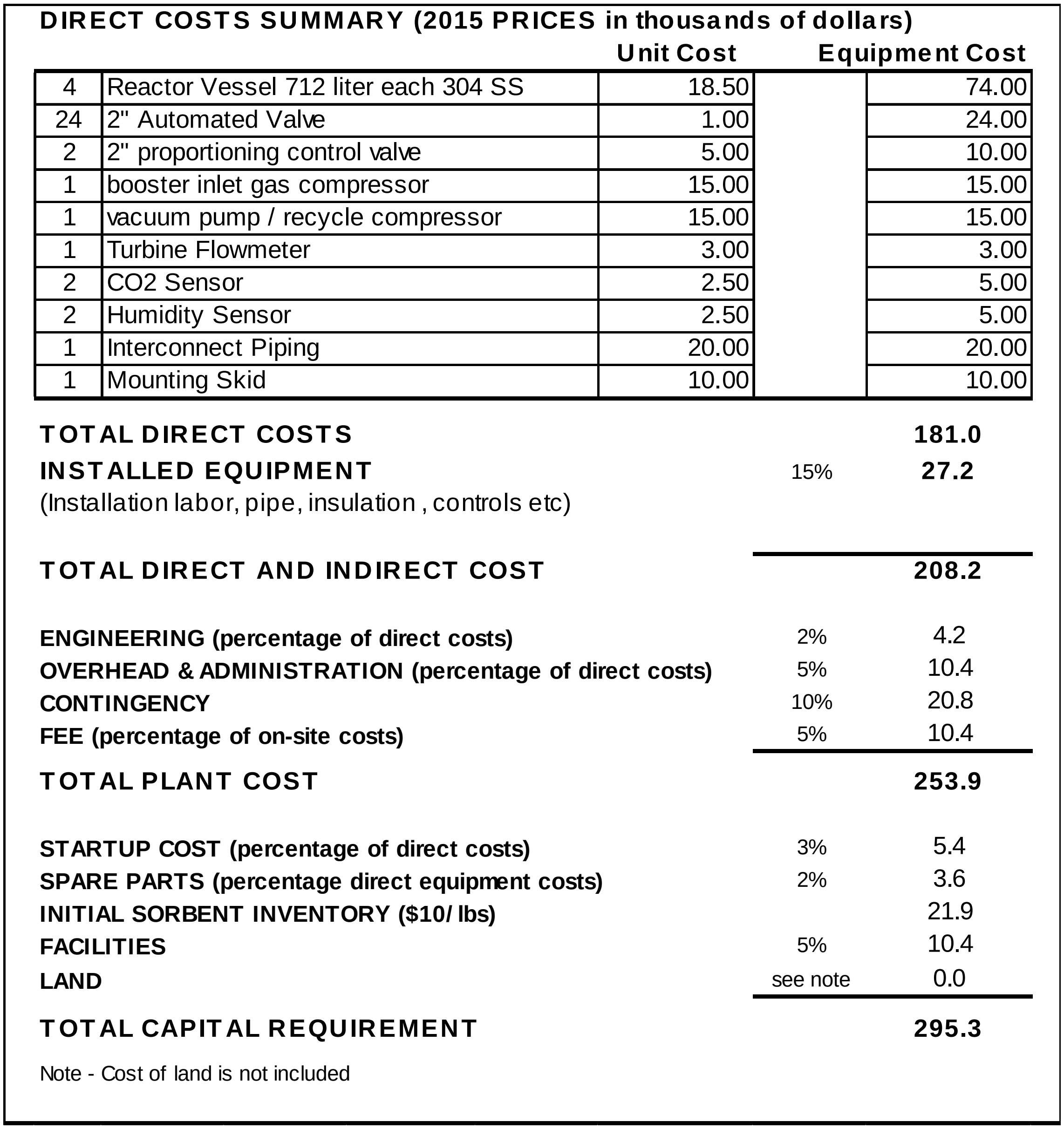
The important cost drivers are the operating and maintenance cost and the amount of methane recovered in the bio-methane product. There are no site-specific characteristic that will significantly impact cost. Higher methane recovery implies higher value in the product stream.

7.4 COST ANALYSIS

We estimated the bare equipment cost (direct cost) and used 15% of the bare equipment cost for installation, 2% for engineering, 5% for overhead, 10% for contingency and 5% for fees to estimate the total plant cost. In order to estimate the total capital required we used 2% of direct cost for startup cost, 3% of direct costs for spare parts, 5% for facilities, and a sorbent cost of $10/lbs for CO_2 sorbent and $12/L for sulfur sorbent. This capital requirement does not include any land cost since we expect that to be part of the digestion system. We used capital recovery factor of 5%, sorbent replacement frequency of 4 yrs for CO2 sorbent and 6 months for sulfur sorbent with a disposal cost of $500/tonne, operating labor cost at $15/hr, overhead at 20% of direct labor cost and parasitic power at $0.10/kWh to estimate operating and maintenance (O&M) cost.

TDA's CO_2 removal system once starts operation requires minimal to no operator time, hence we used 0.1 person time during regular business hours, a total of 208 hours per year, which also includes the sorbent change out labor. We estimated the bare equipment (direct) cost of the 4-bed VSA system to be $181,000. We estimated the capital cost including installation, start-up, initial sorbent inventory, etc to be $295.3k. Table 14 shows the details of the capital cost estimate. We estimated the annual operational maintenance (O&M) cost including the capital recovery, sorbent replacement, vacuum power cost and the labor cost to be $35.8k. Table 15 shows the details of the O&M cost estimate.

Table 14.Capital cost estimate for the full-scale system sized to handle 2,000 m^3/day of biogas



DIRECT COSTS SUMMARY (2015 PRICES in thousands of dollars)

		Unit Cost		Equipment Cost
4	Reactor Vessel 712 liter each 304 SS	18.50		74.00
24	2" Automated Valve	1.00		24.00
2	2" proportioning control valve	5.00		10.00
1	booster inlet gas compressor	15.00		15.00
1	vacuum pump / recycle compressor	15.00		15.00
1	Turbine Flowmeter	3.00		3.00
2	CO2 Sensor	2.50		5.00
2	Humidity Sensor	2.50		5.00
1	Interconnect Piping	20.00		20.00
1	Mounting Skid	10.00		10.00

TOTAL DIRECT COSTS		**181.0**
INSTALLED EQUIPMENT (Installation labor, pipe, insulation , controls etc)	15%	**27.2**
TOTAL DIRECT AND INDIRECT COST		**208.2**
ENGINEERING (percentage of direct costs)	2%	4.2
OVERHEAD & ADMINISTRATION (percentage of direct costs)	5%	10.4
CONTINGENCY	10%	20.8
FEE (percentage of on-site costs)	5%	10.4
TOTAL PLANT COST		**253.9**
STARTUP COST (percentage of direct costs)	3%	5.4
SPARE PARTS (percentage direct equipment costs)	2%	3.6
INITIAL SORBENT INVENTORY ($10/ lbs)		21.9
FACILITIES	5%	10.4
LAND	see note	0.0
TOTAL CAPITAL REQUIREMENT		**295.3**

Note - Cost of land is not included

We estimated the vacuum power requirement to be 14.6 kWe, the sorbent bed size to be 600 L/bed, the operating power cost was \$0.04 per m^3 CH_4 produced and the total operating cost including the sorbent replacement cost was \$0.07 per m^3 CH_4 produced with a methane purity and recovery of 99.5% and 80.3%, respectively. The methane recovery can be further increased to 90% or above by relaxing the methane purity to 96%+% and increasing operating power cost to \$0.05 per m^3 CH_4 produced, which results in a total operating cost (including sorbent replacement) of \$0.08 per m^3 CH_4 produced.

Table 15. O&M cost estimate for the full-scale system sized to handle 2,000 m^3/day of biogas.

Operating & Maintenance Costs		$/year	
Operating labor	$	3,120	0.1 person 1-shift/$15/hr
Sorbent replacement cost	$	4,386	4 yr life
Parasitic Power Cost	$	12,790	14.6 kW @$0.10/kWh
Disposal, $500/tonne	$	125	
Overhead	$	624	20% of direct labor cost
Total O&M	$	21,044	
Capital recovery, 5%	$	14,767	
Annual Operating Costs	$	35,811	
Cost of CO_2 removal	**$**	**0.08**	**per m^3 CH4**
	$	**2.32**	**per MMBTU**

Sulfur Removal System

We also completed a detailed cost analysis to estimate the cost of the sulfur removal. In this analysis we calculated the fixed and operating and maintenance costs including the capital charge for the lead-lag reactor system used for desulfurization. The cost of SulfaTrap^{TM}-R7E at large production volumes is estimated to be \$12 per L of sorbent and the reactors are sized such that the lead reactor is replaced every 6 months and the lag reactor then becomes the lead reactor for the next 6 month interval. We estimated the bare equipment (direct) cost of the lead-lag system to be \$24,400. We estimated the capital cost including installation, start-up, initial sorbent inventory, etc. to be \$74k. Table 16 shows the details of the capital cost estimate. Table 17 shows the details of the O&M cost estimate. We estimated the total annualized operating maintenance cost including the capital charge for sorbent reactors to be \$43,057 and the cost of sulfur removal is \$41.3 per kg of sulfur.

Table 16.Capital cost estimate for the sulfur sorbent system.

DIRECT COSTS SUMMARY (2015 PRICES in thousands of dollars)

Equipment Cost		**Unit Cost**	Total Cost
2	Vessels 36in X 96in shell, 0.312in wt, 304L SA312	5.00	10.00
14	1.5in ball valves, manual, 150# RF, (feed lines)	0.20	2.80
2	SS ASME relief valve, 2"x3"	0.40	0.80
1	Inlet filter, 1.5in	1.50	1.50
1	Process Gages	2.00	2.00
5	Drain/instrument isolation needle valve, 1/2" FNPT, SS	0.05	0.25
12	Vent/sample isolation needle valve, 1/4" FNPT, SS	0.05	0.60
4	1" purge isolation ball valve, 316SS	0.06	0.24
1	Interconnect Piping	3.20	3.20
1	Mounting Skid	3.00	3.00

TOTAL DIRECT COSTS		**24.4**
INSTALLED EQUIPMENT (Installation labor, pipe, insulation , controls etc)	15%	**3.7**
TOTAL DIRECT AND INDIRECT COST		**28.0**
ENGINEERING (percentage of direct costs)	2%	0.6
OVERHEAD & ADMINISTRATION (percentage of direct costs)	5%	1.4
CONTINGENCY	10%	2.8
FEE (percentage of on-site costs)	5%	1.4
TOTAL PLANT COST		**34.2**
STARTUP COST (percentage of direct costs)	3%	0.7
SPARE PARTS (percentage direct equipment costs)	2%	0.5
INITIAL SORBENT INVENTORY ($12/ L)		37.1
FACILITIES	5%	1.4
LAND	see note	0.0
TOTAL CAPITAL REQUIREMENT		**74.0**

Note - Cost of land is not included

Table 17. O&M cost estimate for sulfur removal sorbent to handle 2,000 m^3/day of biogas.

Operating & Maintenace Costs	**$/year**	
Operating Labor	$ 780	1 hr per week @$15/hr
Sorbent Replacement Cost	$37,056	sorbent unit cost @ $12/L
Sorbent Changeout Labor	$ 180	12 man hr per replacement @ 15/hr
Disposal, $500/tonne	$ 1,930	
Overhead	$ 192	20% of direct labor
Total O&M	**$39,358**	
Capital recovery, 5%	**$3,699**	
Annual operating Cost	$43,057	
Cost of sulfur removal	**$ 41.31**	**per kg sulfur**

8.0 IMPLEMENTATION ISSUES

We encountered liquid water condensation at the bottom of the desulfurization sorbent reactor, which could be a possible reason for the premature breakthrough observed in the sulfur sorbent reactor compared to the bench-scale reactor tests in the laboratory.

In the field tests only one flare header was provided, which necessitated that we combine both the bio-methane product and the CO_2 rich desorption product before sending to the flare. This resulted in backflow across the check valve used on the bio-methane product line which contaminated the bio-methane product. This was later resolved in the field tests by using a high psi check valve. This issue will not be encountered in the full-scale system, since the bio-methane produced will be sent to either transportation vehicle fueling station or to the natural gas pipeline and the CO_2 desorption product is the only stream that will be sent to the flare.

9.0 REFERENCES

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Matsuzaki, Y., Yasuda, I. in: H. Yokokawa, S.C. Singhal (Eds.), Proceedings of the Seventh International Symposium on Solid Oxide Fuel Cells (SOFC VII), Tsukuba, Ibaraki, Japan, 3–8 June 2001, p. 769.

Munz, B. G., & Hays, J. P. (n.d.). *Biogas to Pipeline-Quality Gas Using Pressure-Swing Adsorption.* Retrieved October 10, 2011, from Burns & McDonald: http://www.burnsmcd.com/BenchMark/Article/Biogas-to-Pipeline-Quality-Gas-Using-Pressure-Swing-Adsorption

Nozic, M. (2006). *Removal of Carbon Dioxide from Biogas.* Lund, Swede

Zicari, Steven. (January, 2003). *Removal of Hydrogen Sulfide from Biogas Using Cow-Manure Compost*. Cornell University: Master of Science Thesis

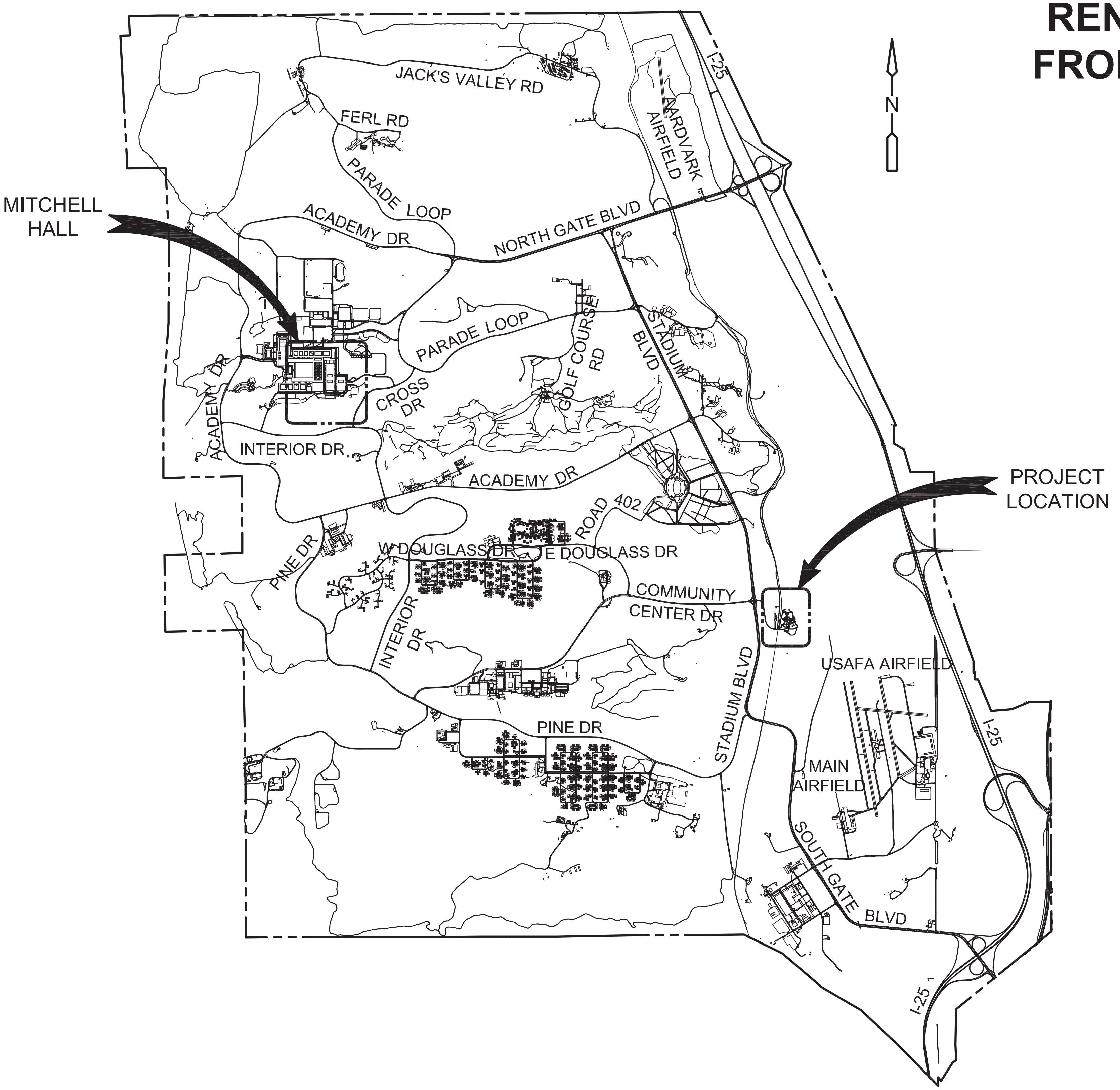
APPENDICES

Appendix A: Points of Contact

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone Fax E-mail	Role in Project
Dr. Ambal Jayaraman	TDA Research, Inc. 12345 W 52nd Avenue Wheat Ridge, CO 80033	Ph:303-940-5391 Fax: 303-422-7763 ajayaraman@tda.com	Project Manager for TDA Subcontract VSA Process Design
Dr. Gokhan Alptekin	TDA Research, Inc. 12345 W 52nd Avenue Wheat Ridge, CO 80033	Ph:303-940-2349 Fax: 303-422-7763 galptekin@tda.com	Sulfur Sorbent Selection
Dr. Steve Dietz	TDA Research, Inc. 12345 W 52nd Avenue Wheat Ridge, CO 80033	Ph:303-940-2312 Fax: 303-422-7763 sdietz@tda.com	CO_2 Sorbent Production
Mathew Cates	TDA Research, Inc. 12345 W 52nd Avenue Wheat Ridge, CO 80033	Ph:303-940-2350 Fax: 303-422-7763 mcates@tda.com	VSA System Design and Fabrication
Kerry Libberton	TDA Research, Inc. 12345 W 52nd Avenue Wheat Ridge, CO 80033	Ph:303-940-2342 Fax: 303-422-7763 kerrylib@tda.com	VSA System Fabrication and Testing

Appendix G: Engineering Drawings

RENEWABLE ENERGY PRODUCTION FROM DOD INSTALLATION WASTE BY ANAEROBIC DIGESTION PILOT PLANT DESIGN



N
MITCHELL HALL
PROJECT LOCATION
JACK'S VALLEY RD
FERL RD
PARADE LOOP
ACADEMY DR
NORTH GATE BLVD
AARDVARK AIRFIELD
I-25
PARADE LOOP
CROSS DR
GOLF COURSE RD
STADIUM BLVD
ACADEMY DR
INTERIOR DR
ACADEMY DR
ROAD 402
PINE DR
W DOUGLASS DR
E DOUGLASS DR
COMMUNITY CENTER DR
INTERIOR DR
USAFA AIRFIELD
STADIUM BLVD
PINE DR
MAIN AIRFIELD
I-25
SOUTH GATE BLVD
I-25

SHEET INDEX:

Drawing No.	Title	Sheet No.
G101	Title Sheet, Vicinity Map and Sheet Index	1
G102	Location Map and Facility Plan	2
G103	Legend - P&ID 1	3
G104	Legend - P&ID 2	4
G105	Legend - P&ID 3	5
P101	Process Piping and Instrumentation Diagram	6
P102	Process Gas System HVAC and Combustible Gas Detection	7
P103	Water Supply & Plumbing System	8
P104	Instrument & Service Air System Diagram	9
P105	Process Drain System Diagram	10
M101	Pilot Equipment Plan and Section	11
M102	Pilot Equipment Sections	12
M103	Mechanical Site Plan	13
E-1	Electrical Legend	14
E-2	Single Line Diagram	15
E-3	Pilot Equipment Electrical Plans	16
E-4	Electrical Notes	17
E-5	Control Diagrams 1 of 2	18
E-6	Control Diagrams 2 of 2	19

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REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY:
DRAWN BY: J. WEINER
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CROSS CHK'D BY:
APPROVED BY:
DATE: APRIL 2011

LINE IS 1 INCH
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SCALE ACCORDINGLY

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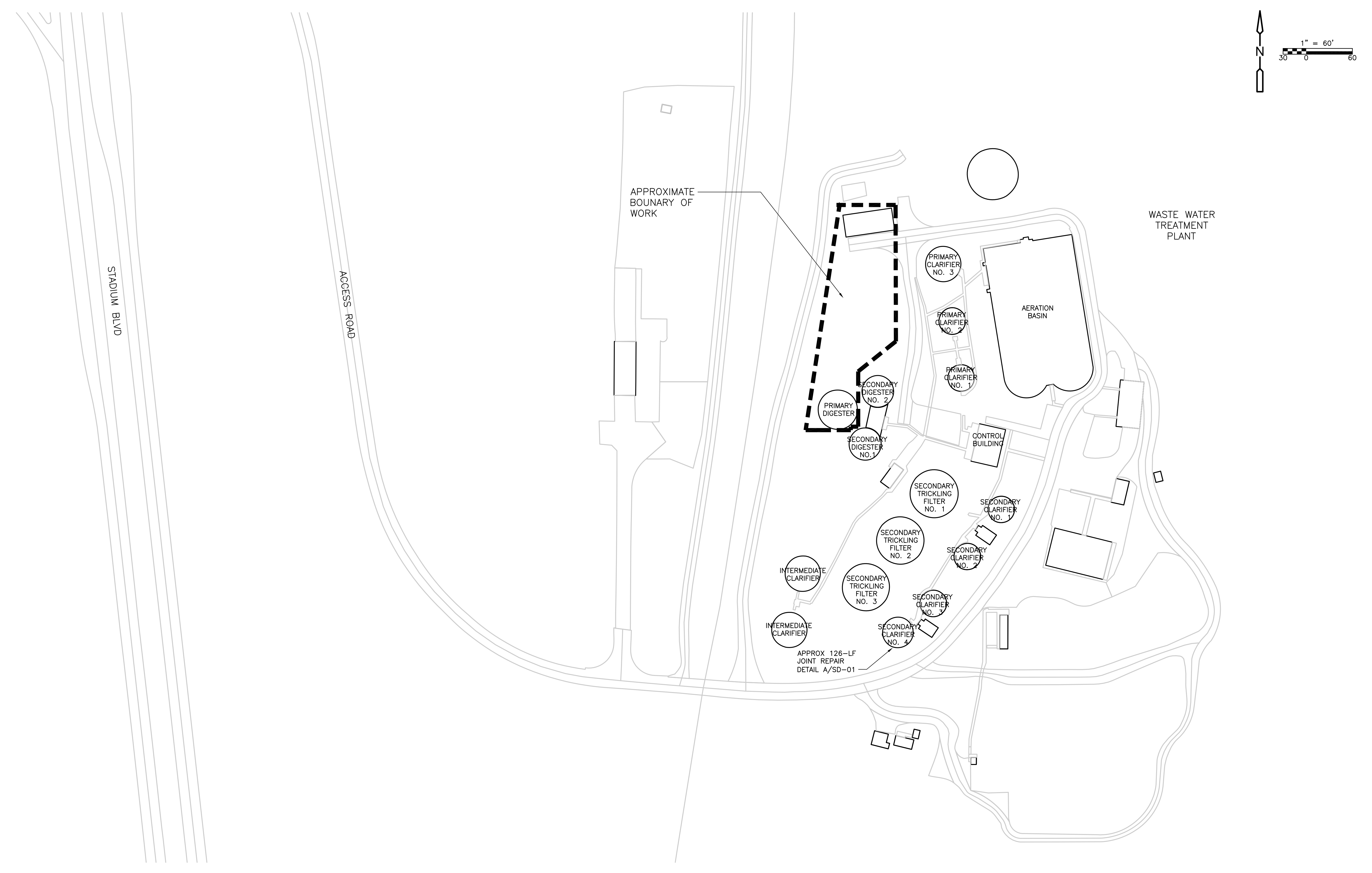
1218 3rd Avenue, Suite 100
Seattle, CA 98101
Phone: 206-336-4900
consulting • engineering • construction • operations

Renewable Energy Production from DoD Installation Solid Waste by Anaerobic Digestion

TITLE SHEET, VICINITY MAP AND SHEET INDEX

PROJECT NO. 50957–73968
FILE NAME: G101
DRAWING NO.
GI01
SHEET NO.
1 OF 28


A
B
C
D
E
F
G
H
1
2
3
4
N
1" = 60'
30
0
60
STADIUM BLVD
ACCESS ROAD
APPROXIMATE BOUNARY OF WORK
WASTE WATER TREATMENT PLANT
PRIMARY CLARIFIER NO. 3
PRIMARY CLARIFIER NO. 2
PRIMARY CLARIFIER NO. 1
AERATION BASIN
PRIMARY DIGESTER
SECONDARY DIGESTER NO. 2
SECONDARY DIGESTER NO.1
CONTROL BUILDING
SECONDARY TRICKLING FILTER NO. 1
SECONDARY TRICKLING FILTER NO. 2
SECONDARY TRICKLING FILTER NO. 3
SECONDARY CLARIFIER NO. 1
SECONDARY CLARIFIER NO. 2
SECONDARY CLARIFIER NO. 3
SECONDARY CLARIFIER NO. 4
INTERMEDIATE CLARIFIER
INTERMEDIATE CLARIFIER
APPROX 126-LF JOINT REPAIR DETAIL A/SD-01

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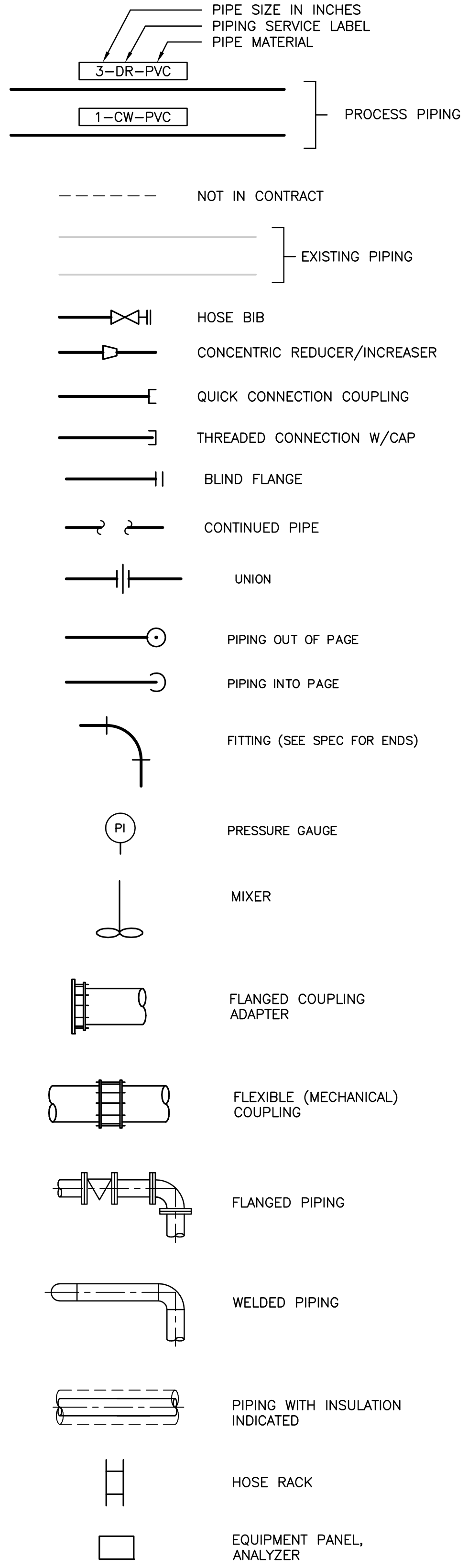
LOCATION MAP AND FACILITY PLAN

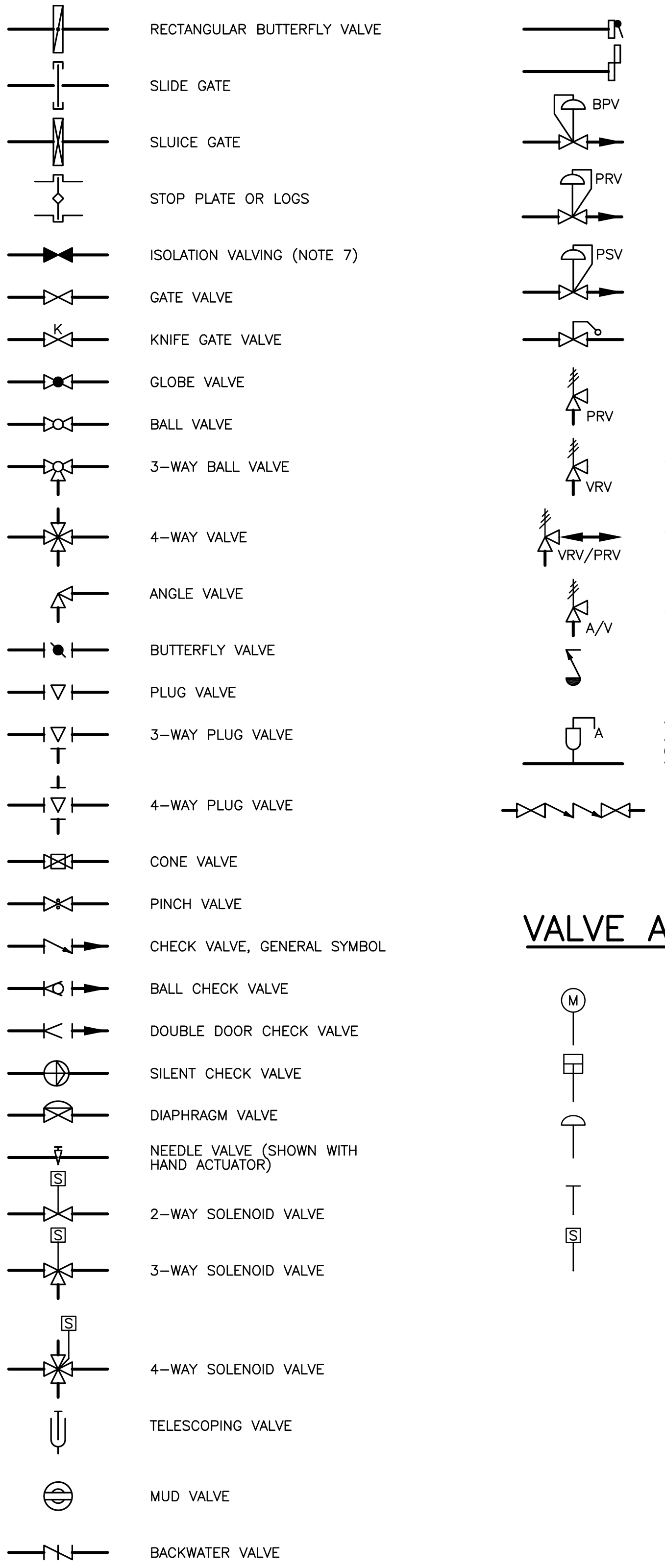
PROJECT NO. 50957–73968
FILE NAME: G102
DRAWING NO.
GI02
SHEET NO.
2 OF 28

PIPING SYMBOLS



- PIPE SIZE IN INCHES
- PIPING SERVICE LABEL
- PIPE MATERIAL
- PROCESS PIPING
- NOT IN CONTRACT
- EXISTING PIPING
- HOSE BIB
- CONCENTRIC REDUCER/INCREASER
- QUICK CONNECTION COUPLING
- THREADED CONNECTION W/CAP
- BLIND FLANGE
- CONTINUED PIPE
- UNION
- PIPING OUT OF PAGE
- PIPING INTO PAGE
- FITTING (SEE SPEC FOR ENDS)
- PRESSURE GAUGE
- MIXER
- FLANGED COUPLING ADAPTER
- FLEXIBLE (MECHANICAL) COUPLING
- FLANGED PIPING
- WELDED PIPING
- PIPING WITH INSULATION INDICATED
- HOSE RACK
- EQUIPMENT PANEL, ANALYZER

VALVE AND GATE SYMBOLS

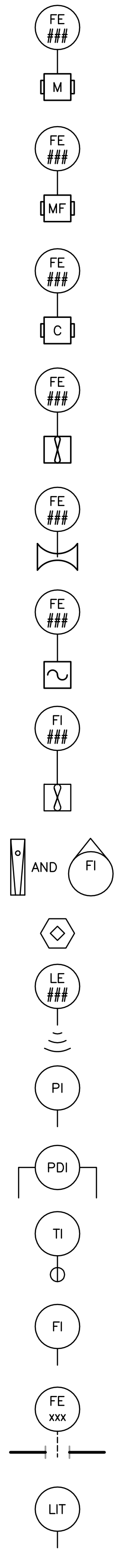


- RECTANGULAR BUTTERFLY VALVE
- SLIDE GATE
- SLUICE GATE
- STOP PLATE OR LOGS
- ISOLATION VALVING (NOTE 7)
- GATE VALVE
- KNIFE GATE VALVE
- GLOBE VALVE
- BALL VALVE
- 3-WAY BALL VALVE
- 4-WAY VALVE
- ANGLE VALVE
- BUTTERFLY VALVE
- PLUG VALVE
- 3-WAY PLUG VALVE
- 4-WAY PLUG VALVE
- CONE VALVE
- PINCH VALVE
- CHECK VALVE, GENERAL SYMBOL
- BALL CHECK VALVE
- DOUBLE DOOR CHECK VALVE
- SILENT CHECK VALVE
- DIAPHRAGM VALVE
- NEEDLE VALVE (SHOWN WITH HAND ACTUATOR)
- 2-WAY SOLENOID VALVE
- 3-WAY SOLENOID VALVE
- 4-WAY SOLENOID VALVE
- TELESCOPING VALVE
- MUD VALVE
- BACKWATER VALVE
- FLAP GATE
- SHEAR GATE
- BACK PRESSURE VALVE
- PRESSURE REDUCING OR REGULATING VALVE
- PRESSURE SUSTAINING VALVE
- FLOAT VALVE
- PRESSURE RELIEF VALVE
- VACUUM RELIEF VALVE
- VACUUM & PRESSURE RELIEF VALVE
- AIR/VACUUM RELIEF VALVE
- FOOT VALVE WITH STRAINER
- A – AIR RELEASE
- A/V – AIR/VACUUM
- C – COMBINATION
- V – VACUUM RELEASE
- BACK FLOW PREVENTER

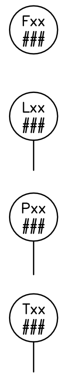
VALVE AND GATE OPERATORS

- MOTOR OPERATOR
- CYLINDER OPERATOR
- DIAPHRAGM OPERATOR
- MANUAL (HAND) OPERATOR
- SOLENOID OPERATOR

PRIMARY ELEMENTS



- MAGNETIC FLOW METER
- MASS FLOW METER
- CORIOLIS FLOW METER
- PROPELLER OR TURBINE FLOW METER
- VENTURI TUBE METER
- ULTRASONIC FLOW METER
- POSITIVE DISPLACEMENT METER
- ROTAMETER
- BATCH METER
- ULTRASONIC LEVEL ELEMENT
- PRESSURE GAUGE
- DIFFERENTIAL PRESSURE GAUGE
- TEMPERATURE GAUGE WITH THERMO WELL
- FLOW METER MECHANICAL READOUT
- ORIFICE PLATE
- LEVEL INDICATING TRANSMITTER



- FLOW DEVICE (SEE INSTRUMENTATION FUNCTIONAL CODE TABLE FOR DEFINITION OF "xx")
- LEVEL DEVICE (SEE INSTRUMENTATION FUNCTIONAL CODE TABLE FOR DEFINITION OF "xx")
- PRESSURE DEVICE (SEE INSTRUMENTATION FUNCTIONAL CODE TABLE FOR DEFINITION OF "xx")
- TEMPERATURE DEVICE (SEE INSTRUMENTATION FUNCTIONAL CODE TABLE FOR DEFINITION OF "xx")

NOTES:

1. REFER TO SHEETS G104 AND G105 FOR ADDITIONAL INSTRUMENTATION EQUIPMENT IDENTIFICATION, LINE SYMBOLS, ADDITIONAL ABBREVIATIONS AND INSTRUMENT TAGGING CONVENTIONS.
2. THIS SHEET AND SHEETS G104 AND G105 ARE GENERAL LEGEND SHEETS. SOME SYMBOLS OR NOTATIONS MAY NOT BE USED ON THIS CONTRACT.
3. PIPING AND STRUCTURES ARE SHOWN FOR GENERAL UNDERSTANDING OF THE PROCESS ONLY. IN GENERAL, NOT ALL PIPES, VALVES, FITTINGS, EQUIPMENT, AND APPURTENANCES ARE SHOWN.
4. DASHED LINES FOR ELECTRICAL SIGNALS DO NOT REPRESENT THE NUMBER OF WIRES. SEE ELECTRICAL DRAWINGS AND SPECIFICATIONS FOR ACTUAL NUMBER OF WIRES REQUIRED.
5. THE PROCESS & INSTRUMENTATION DRAWINGS ARE SCHEMATIC. THEY SHALL BE USED IN CONJUNCTION WITH ALL OTHER CONTRACT DOCUMENTS TO DEFINE ALL DETAILS OF THE CONTRACT WORK.
6. ALL NECESSARY VALVES ARE NOT SHOWN ON THE P&ID'S FOR CLARITY. PROVIDE ISOLATION VALVES ON ALL SAMPLE LINES TO SENSORS, TWO VALVE MANIFOLDS FOR ALL ABSOLUTE AND GAUGE PRESSURE DEVICES, AND FIVE VALVE MANIFOLDS FOR ALL DIFFERENTIAL PRESSURE DEVICES.
7. MATERIALS OF CONSTRUCTION SHALL BE DETERMINED FROM THE BILL OF MATERIALS AND DETAILED DRAWINGS.
8. REDUCERS, TEES AND OTHER PIPELINE FITTINGS ARE TYPICALLY NOT SHOWN ON THE P&ID'S UNLESS NEEDED TO CLARIFY THE PROCESS LINE FUNCTIONS.

PIPE MATERIAL IDENTIFICATION:

BR	BRASS
CPVC	CHLORINATED POLYVINYL CHLORIDE
COP	COPPER
HDPE	HIGH DENSITY POLYETHYLENE
PVC	POLYVINYL CHLORIDE
PU	POLYURETHANE
SS	STAINLESS STEEL
STL	STEEL

REV. NO.	DATE	DRWN	CHKD	REMARKS

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Anaerobic Digestion

LEGEND - P&ID 1

PROJECT NO. 50957-73968
FILE NAME: G103LGPD
DRAWING NO.
GI03
SHEET NO.
3 OF 28

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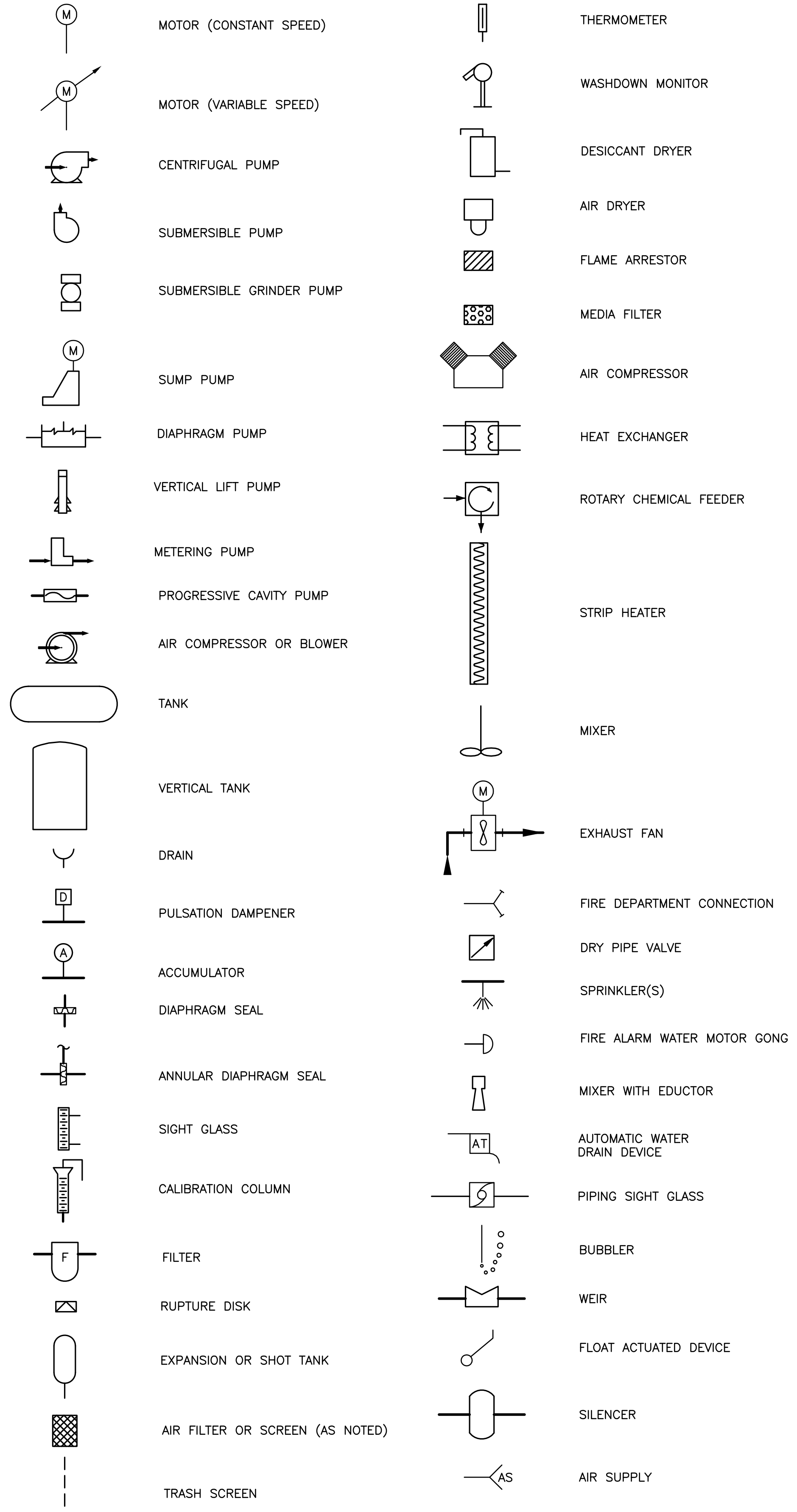
MISCELLANEOUS SYMBOLS


MOTOR (CONSTANT SPEED)
MOTOR (VARIABLE SPEED)
CENTRIFUGAL PUMP
SUBMERSIBLE PUMP
SUBMERSIBLE GRINDER PUMP
SUMP PUMP
DIAPHRAGM PUMP
VERTICAL LIFT PUMP
METERING PUMP
PROGRESSIVE CAVITY PUMP
AIR COMPRESSOR OR BLOWER
TANK
VERTICAL TANK
DRAIN
PULSATION DAMPENER
ACCUMULATOR
DIAPHRAGM SEAL
ANNULAR DIAPHRAGM SEAL
SIGHT GLASS
CALIBRATION COLUMN
FILTER
RUPTURE DISK
EXPANSION OR SHOT TANK
AIR FILTER OR SCREEN (AS NOTED)
TRASH SCREEN
THERMOMETER
WASHDOWN MONITOR
DESICCANT DRYER
AIR DRYER
FLAME ARRESTOR
MEDIA FILTER
AIR COMPRESSOR
HEAT EXCHANGER
ROTARY CHEMICAL FEEDER
STRIP HEATER
MIXER
EXHAUST FAN
FIRE DEPARTMENT CONNECTION
DRY PIPE VALVE
SPRINKLER(S)
FIRE ALARM WATER MOTOR GONG
MIXER WITH EDUCTOR
AUTOMATIC WATER DRAIN DEVICE
PIPING SIGHT GLASS
BUBBLER
WEIR
FLOAT ACTUATED DEVICE
SILENCER
AIR SUPPLY

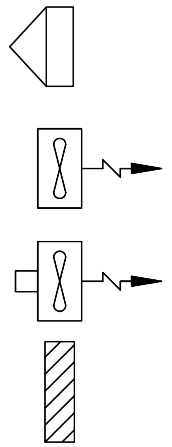
EQUIPMENT ABBREVIATIONS

ALR PNL	ALARM PANEL
BAC	BACKFLOW PREVENTER
BAT	BATTERY
BC	BATTERY CHARGER
CPR	COMPRESSOR
EF	EXHAUST FAN
F	FAN
FA	FLAME ARRESTOR
HB	HEAT BLANKET
HMI	HUMAN/MACHINE INTERFACE
HTR	HEATER
ME	MISCELLANEOUS EQUIPMENT
MIX	MIXER
OD	ODOR CONTROL
P	PUMP
PCP	PILOT CONTROL PANEL
PLC	PROGRAMMABLE LOGIC CONTROLLER (LOCATED IN PCP)
SF	SUPPLY FAN
T	TANK
VSA	VACUUM SWING ADSORBTION SYSTEM
WGB	WASTE GAS BURNER

FLOW STREAM IDENTIFICATION

AHP	AIR, HIGH PRESSURE PROCESS
ALP	AIR, LOW PRESSURE PROCESS
ASP	AIR, SUPPLY
CW	CITY WATER
DF	DIGESTER FEED
DG	DIGESTER GAS
DOF	DIGESTER OVERFLOW
DR	DRAIN, PROCESS
DS	DIGESTED SLUDGE
DST	DIGESTED SLUDGE TRANSFER
FA	FOUL AIR
T	TELEPHONE

HVAC SYMBOLS


STORM HOOD
WALL FAN
UNIT HEATER
WALL LOUVER

MECHANICAL EQUIPMENT CODE

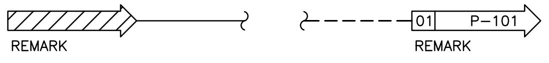
EXAMPLES:

P–101	PUMP NUMBERED 101
MIX–101	MIXER NUMBERED 101

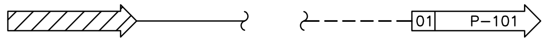
EQUIPMENT NUMBERS ARE SEQUENTIAL STARTING AT 101 FOR EACH TYPE OF EQUIPMENT.

INTERFACE SYMBOLS

OFF PAGE CONNECTORS



01 = CONNECTION NUMBER
P103 = DESTINATION DRAWING NO.
P101 = SOURCE DRAWING NO.



INTERFACE TO OR FROM PROCESS EXTERNAL TO PROJECT.

ADDTIONAL ABBREVIATIONS

BV	BALL VALVE
HV	HAND VALVE
FV	FOOT VALVE
LCV	LOCAL CONTROL VALVE
NC	NORMALLY OPEN
NO	NORMALLY CLOSED
NV	NEEDLE VALVE
PCV	PRESSURE CONTROLLING VALVE
PRV	PRESSURE RELIEF VALVE
SV	SOLENOID VALVE

REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: C. McPHERSON
DRAWN BY: J. WEINER
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: APRIL 2011

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Renewable Energy Production from
DoD Installation Solid Waste by
Anaerobic Digestion

LEGEND - P&ID 2

PROJECT NO. 50957–73968
FILE NAME: G104LGPD
DRAWING NO.
GI04
SHEET NO.
4 OF 28

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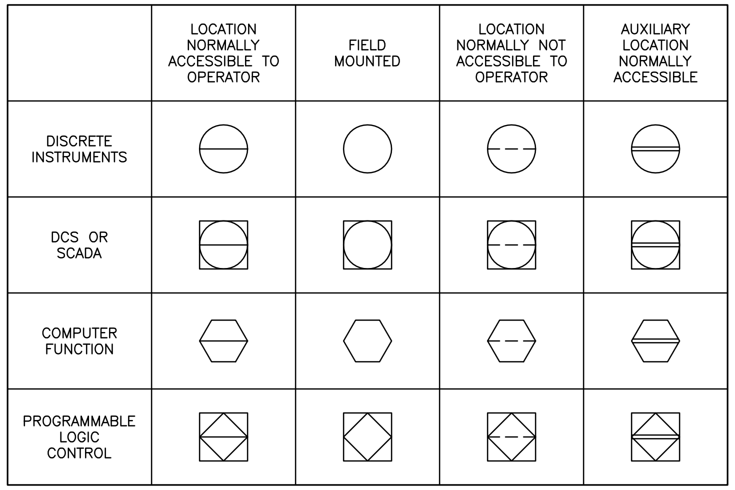
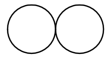
GENERAL INSTRUMENT OR FUNCTION SYMBOLS


LOCATION NORMALLY ACCESSIBLE TO OPERATOR
FIELD MOUNTED
LOCATION NORMALLY NOT ACCESSIBLE TO OPERATOR
AUXILIARY LOCATION NORMALLY ACCESSIBLE
DISCRETE INSTRUMENTS
DCS OR SCADA
COMPUTER FUNCTION
PROGRAMMABLE LOGIC CONTROL


INDICATES A SINGLE INSTRUMENT OR OTHER COMPONENT HAVING MULTIPLE FUNCTIONS

MCC INDICATES INTERLOCK OR LOGIC AT MOTOR CONTROL CENTER OR MOTOR STARTER

I INDICATES GENERAL OR MISCELLANEOUS HARDWIRED INTERLOCK

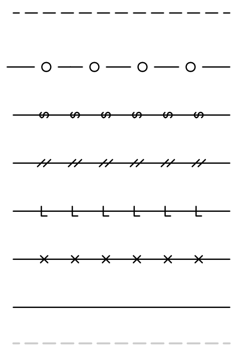
SCR SILICON CONTROLLED RECTIFIER

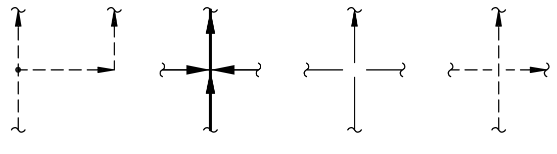
VFD VARIABLE FREQUENCY DRIVE

SS SOLID STATE SOFT STARTER

INSTRUMENT LINE SYMBOLS

MAJOR PROCESS LINES SHOWN BOLD, MINOR LINES SHOWN NONBOLD


ELECTRICAL SIGNAL
LOGICAL SIGNAL PATH (SOFTWARE LINK)
ELECTROMAGNETIC OR SONIC SIGNAL
PNEUMATIC SIGNAL
HYDRAULIC SIGNAL
CAPILLARY TUBE
INSTRUMENT SUPPLY OR CONNECTION TO PROCESS
SCREENED INSTRUMENT LINES INDICATE EXISTING LINES TO REMAIN AS IS (ELECTRIC SIGNAL SHOWN—TYPICAL FOR OTHER SIGNALS)


CONNECTING LINES
NON—CONNECTING LINES

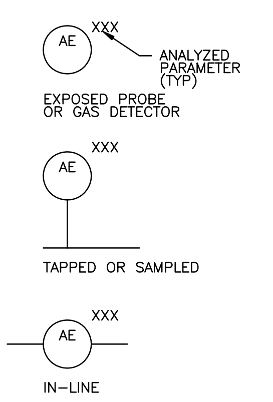
INSTRUMENTATION FUNCTIONAL CODE

	FIRST LETTER		SUCCEEDING LETTERS		
	MEASURED OR INITIATING VARIABLE	(MODIFIER)	READOUT OR PASSIVE FUNCTION	OUTPUT FUNCTION	(MODIFIER)
A	ANALYSIS		ALARM		
B			(1)	(1)	(1)
C	(1)			CONTROL	
D	DENSITY(1)	DIFFERENTIAL			
E	VOLTAGE		SENSOR (PRIMARY ELEMENT)		
F	FLOW RATE	RATIO			
G	(1)		GLASS OR VIEWING DEVICE		
H	HAND (MANUAL)				HIGH (OPENED)
I	CURRENT		INDICATE		
J	POWER	SCAN			
K	TIME	TIME RATE OF CHANGE		CONTROL STATION	
L	LEVEL		PILOT LIGHT		LOW (CLOSED)
M	(1)	MOMENTARY		(1)	MIDDLE OR INTERMEDIATE
N	(1)		(1)	(1)	(1)
O	(1)		ORIFICE		(1)
P	PRESSURE OR VACUUM		POINT (TEST CONNECTION)		
Q	QUANTITY	INTEGRATE OR TOTALIZE			
R			RECORD		
S	SPEED OR FREQUENCY	SAFETY		SWITCH	
T	TEMPERATURE			TRANSMIT	
U	MULTIVARIABLE (2)		MULTIFUNCTION (2)	MULTIFUNCTION (2)	MULTIFUNCTION (2)
V	VIBRATION, MECH ANAL.			VALVE, DAMPER OR LOUVER	
W	WEIGHT OR FORCE		WELL		
X	STATUS (3)				
Y	EVENT, STATE OR PRESENCE			RELAY, COMPUTE OR CONVERT	
Z	POSITION			DRIVE, ACTUATE OR UNCLASSIFIED FINAL ELEMENT	

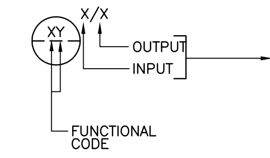
TABLE NOTES:

1. USER'S CHOICE.
2. WHEN USED SYMBOL OR SIGNAL LINE IS ANNOTATED.
3. PROJECT SPECIFIC FUNCTION.

ANALYSIS INSTRUMENTS

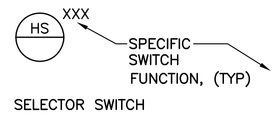

AE
XXX
ANALYZED PARAMETER (TYP)
EXPOSED PROBE OR GAS DETECTOR
AE
XXX
TAPPED OR SAMPLED
AE
XXX
IN—LINE

SIGNAL CONVERTERS


XY
X/X
OUTPUT
INPUT
FUNCTIONAL CODE

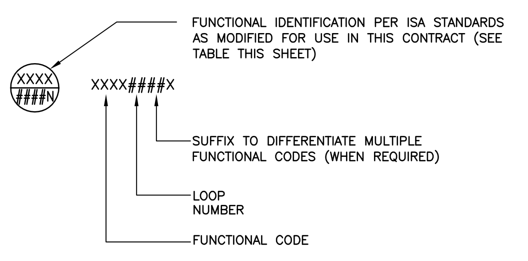
E = VOLTAGE
F = FREQUENCY
H = HYDRAULIC
I = CURRENT
P = PNEUMATIC
PF = PULSE FREQUENCY
PD = PULSE DURATION
R = RESISTANCE
☑ = SQUARE ROOT EXTRACTION
Σ = SUM

HAND SWITCHES


HS
XXX
SPECIFIC SWITCH FUNCTION, (TYP)
SELECTOR SWITCH

AO = AUTO/OFF
AM = AUTO/MANUAL
CM = COMPUTER/MANUAL
CL = COMPUTER/LOCAL
FR = FORWARD/REVERSE
FOR = FORWARD/OFF/REVERSE
FS = FAST/SLOW
FOS = FAST/OFF/SLOW
HOA = HAND/OFF/AUTO
LLS = LEAD/LAG/STANDBY
LOR = LOCAL/OFF/REMOTE
LOS = LOCKOUT/STOP
LR = LOCAL/REMOTE
OC = OPEN/CLOSE
OCA = OPEN/CLOSE/AUTO
OO = ON/OFF
OSC = OPEN/STOP/CLOSE
SS = START/STOP
SOR = START/OFF/RESET

INSTRUMENTATION TAGGING


XXXX
####N
XXXX####X

FUNCTIONAL IDENTIFICATION PER ISA STANDARDS AS MODIFIED FOR USE IN THIS CONTRACT (SEE TABLE THIS SHEET)

SUFFIX TO DIFFERENTIATE MULTIPLE FUNCTIONAL CODES (WHEN REQUIRED)

LOOP NUMBER

FUNCTIONAL CODE

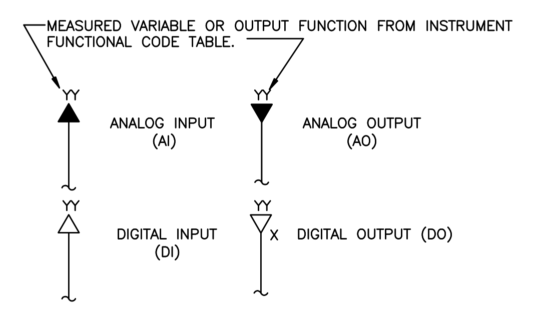
EXAMPLE

FIT = FUNCTIONAL CODE = FLOW INDICATOR TRANSMITTER
1101 = LOOP NUMBER
A = FUNCTIONAL SUFFIX CODE
COMPLETE INSTRUMENT TAG NUMBER IS FIT1101A

GENERAL NOTES

1. REFER TO DRAWING G103 FOR ADDITIONAL NOTES.

I/O SIGNALS


MEASURED VARIABLE OR OUTPUT FUNCTION FROM INSTRUMENT FUNCTIONAL CODE TABLE.
YY
YY
ANALOG INPUT (AI)
ANALOG OUTPUT (AO)
YY
YY
DIGITAL INPUT (DI)
X
DIGITAL OUTPUT (DO)

COLOR CODES

1. UNLESS OTHERWISE NOTED, THE FOLLOWING COLOR CODE SHALL BE USED FOR LENSES OF ALL INDICATING LIGHTS.

FUNCTION	COLOR
ON	RED
OFF	GREEN
CLOSED	GREEN
OPEN	RED
LOW	AMBER
FAIL	AMBER
HIGH	AMBER
AUTOMATIC	WHITE
MANUAL	BLUE
LOCAL	BLUE
REMOTE	WHITE

2. UNLESS OTHERWISE NOTED, THE FOLLOWING COLOR CODE SHALL BE USED FOR PUSHBUTTONS.

FUNCTION	COLOR
STOP	BLACK
RESET	BLACK
EMERGENCY STOP	RED
OPEN	RED
CLOSE	GREEN
ON	RED
OFF	GREEN
FAULT	AMBER
HIGH PRESSURE	AMBER

C:\cdmxm\tsegaa\d0561267\G105.dwg 2/1/2012 10:19:09 AM

REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: C. McPHERSON
DRAWN BY: J. WEINER
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: APRIL 2011

LINE IS 1 INCH
AT FULL SIZE
(34X22)
SCALE ACCORDINGLY

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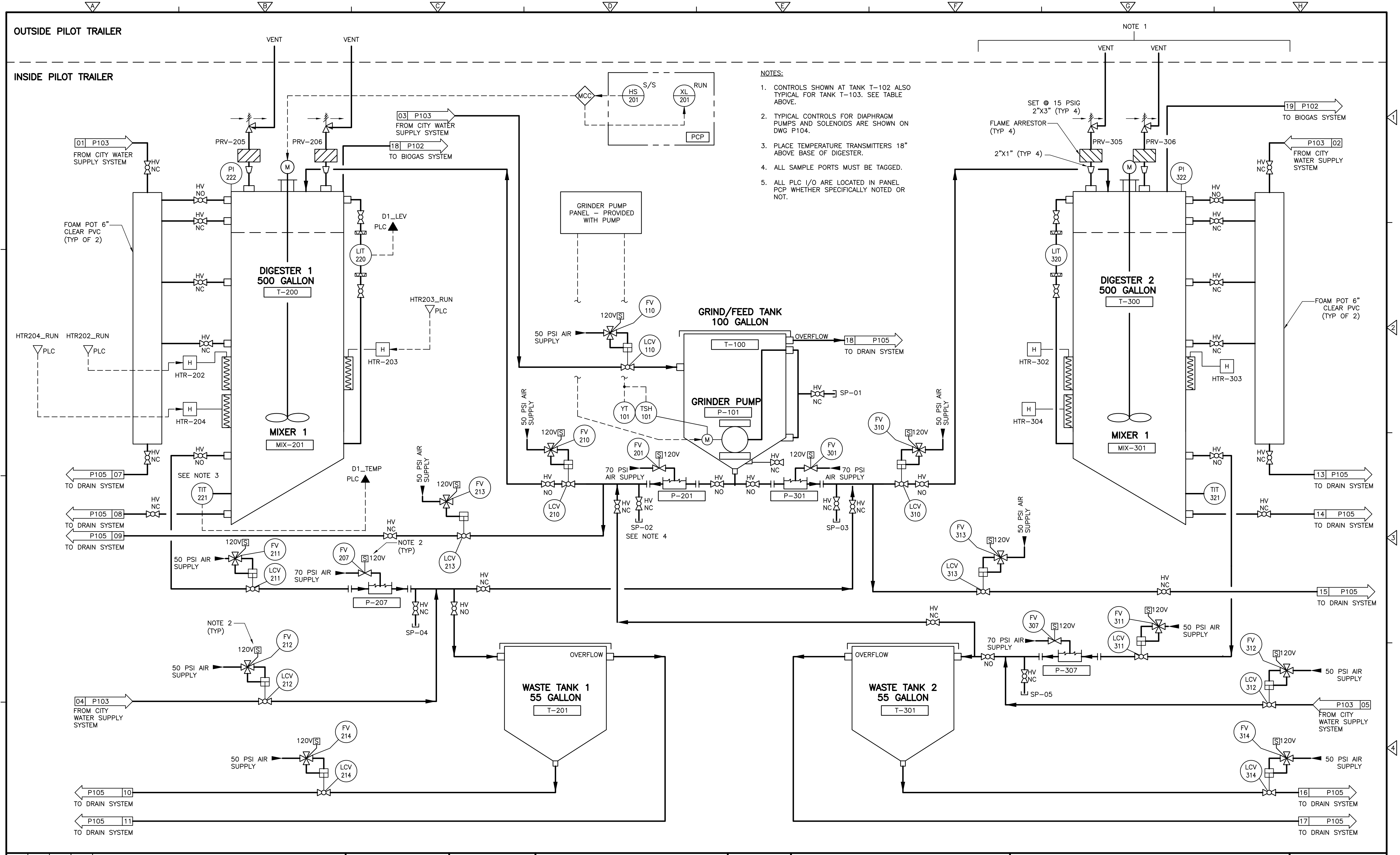
Renewable Energy Production from
DoD Installation Solid Waste by
Anaerobic Digestion

LEGEND - P&ID 3

PROJECT NO. 50957—73968
FILE NAME: G105
DRAWING NO.
GI05
SHEET NO.
5 OF 28


OUTSIDE PILOT TRAILER
INSIDE PILOT TRAILER
VENT
VENT
NOTE 1
VENT
VENT
MCC
S/S
HS 201
RUN
XL 201
PCP
01 P103 FROM CITY WATER SUPPLY SYSTEM
03 P103 FROM CITY WATER SUPPLY SYSTEM
18 P102 TO BIOGAS SYSTEM
19 P102 TO BIOGAS SYSTEM
P103 02 FROM CITY WATER SUPPLY SYSTEM
PRV-205
PRV-206
PRV-305
PRV-306
SET @ 15 PSIG 2"X3" (TYP 4)
FLAME ARRESTOR (TYP 4)
2"X1" (TYP 4)
PI 222
PI 322
M
HV NO
HV NC
FOAM POT 6" CLEAR PVC (TYP OF 2)
D1_LEV PLC
LIT 220
LIT 320
DIGESTER 1 500 GALLON
T-200
DIGESTER 2 500 GALLON
T-300
HTR203_RUN PLC
HTR204_RUN PLC
HTR202_RUN PLC
H
HTR-202
HTR-203
HTR-204
HTR-302
HTR-303
HTR-304
MIXER 1
MIX-201
MIX-301
P105 07 TO DRAIN SYSTEM
SEE NOTE 3
TIT 221
TIT 321
D1_TEMP PLC
P105 08 TO DRAIN SYSTEM
P105 09 TO DRAIN SYSTEM
GRINDER PUMP PANEL – PROVIDED WITH PUMP
120V S
FV 110
LCV 110
50 PSI AIR SUPPLY
GRIND/FEED TANK 100 GALLON
T-100
OVERFLOW
18 P105 TO DRAIN SYSTEM
GRINDER PUMP
P-101
YT 101
TSH 101
SP-01
FV 210
LCV 210
FV 201
FV 301
FV 310
LCV 310
70 PSI AIR SUPPLY
P-201
P-301
SP-02 SEE NOTE 4
SP-03
FV 213
LCV 213
NOTE 2 (TYP)
FV 211
LCV 211
FV 207
P-207
SP-04
13 P105 TO DRAIN SYSTEM
14 P105 TO DRAIN SYSTEM
15 P105 TO DRAIN SYSTEM
FV 313
LCV 313
FV 212
LCV 212
04 P103 FROM CITY WATER SUPPLY SYSTEM
WASTE TANK 1 55 GALLON
T-201
WASTE TANK 2 55 GALLON
T-301
FV 307
FV 311
LCV 311
P-307
SP-05
FV 312
LCV 312
P103 05 FROM CITY WATER SUPPLY SYSTEM
FV 214
LCV 214
FV 314
LCV 314
P105 10 TO DRAIN SYSTEM
P105 11 TO DRAIN SYSTEM
16 P105 TO DRAIN SYSTEM
17 P105 TO DRAIN SYSTEM
A B C D E F G H
1 2 3 4

NOTES:

1. CONTROLS SHOWN AT TANK T-102 ALSO TYPICAL FOR TANK T-103. SEE TABLE ABOVE.
2. TYPICAL CONTROLS FOR DIAPHRAGM PUMPS AND SOLENOIDS ARE SHOWN ON DWG P104.
3. PLACE TEMPERATURE TRANSMITTERS 18" ABOVE BASE OF DIGESTER.
4. ALL SAMPLE PORTS MUST BE TAGGED.
5. ALL PLC I/O ARE LOCATED IN PANEL PCP WHETHER SPECIFICALLY NOTED OR NOT.

REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: C. McPHERSON
DRAWN BY: K. TALBOT
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: AUGUST 2012

LINE IS 1 INCH
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Renewable Energy Production from DoD Installation Solid Waste by Anaerobic Digestion

PROCESS PIPING AND INSTRUMENTATION DIAGRAM

PROJECT NO. 50957-73968
FILE NAME: P101PPID
DRAWING NO.
P101
SHEET NO.
6 OF 28

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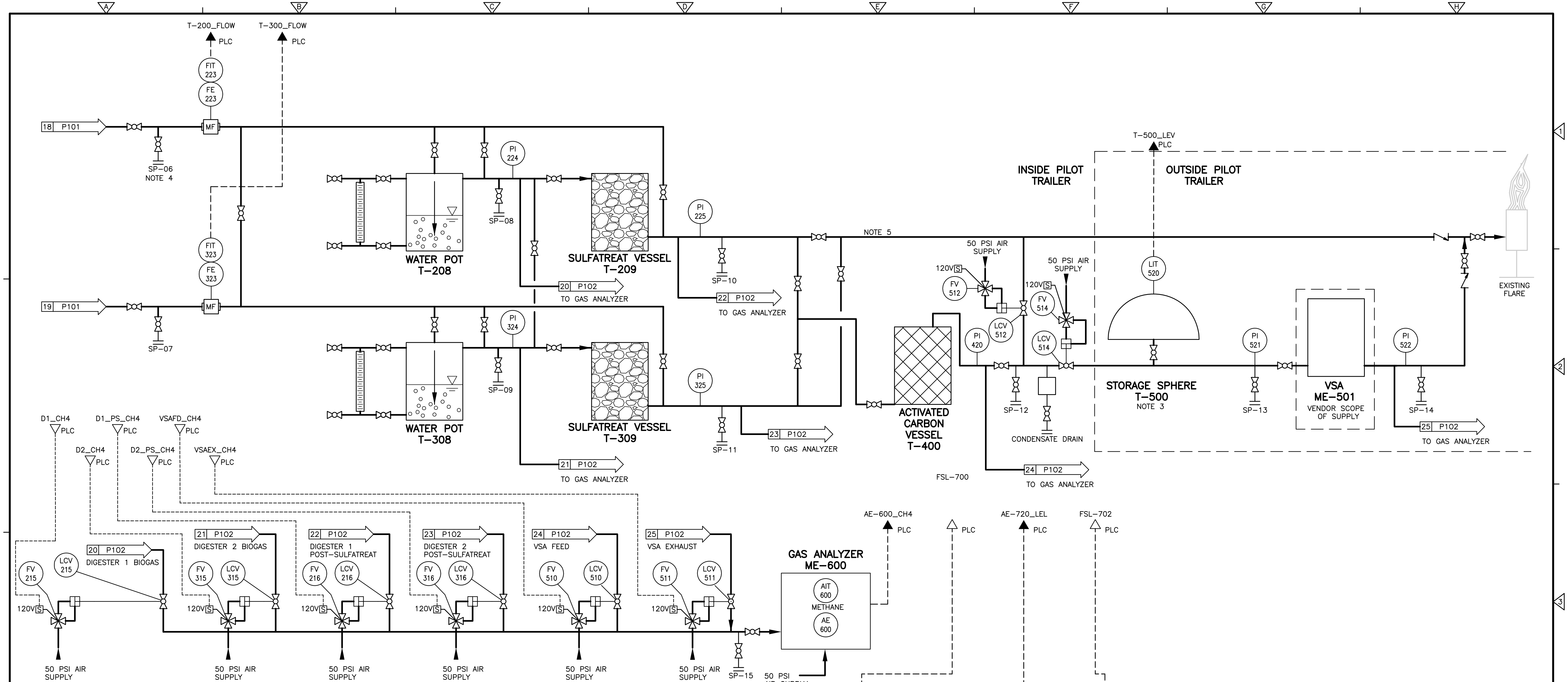
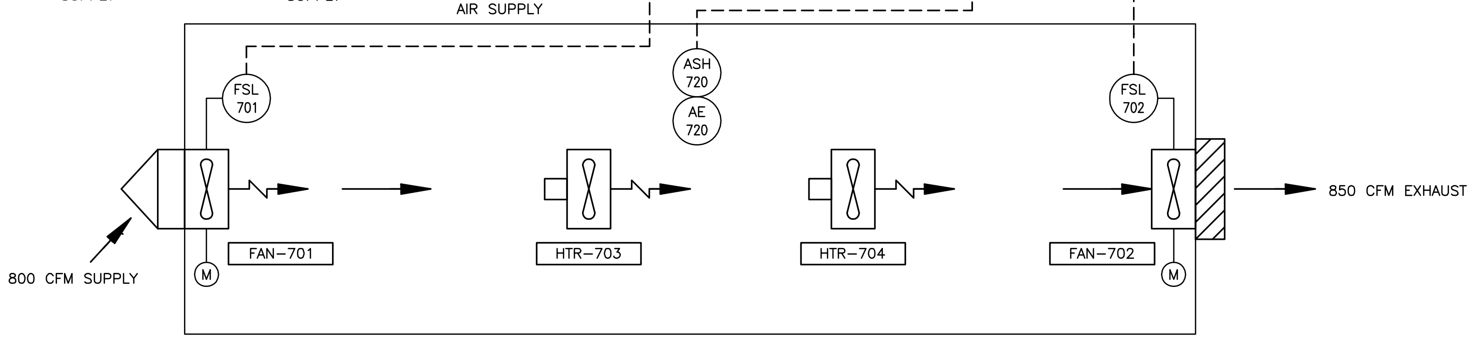

A
B
C
D
E
F
G
H
1
2
3
4
T-200_FLOW
PLC
T-300_FLOW
PLC
FIT 223
FE 223
18 P101
MF
SP-06
NOTE 4
FIT 323
FE 323
19 P101
MF
SP-07
PI 224
SP-08
WATER POT
T-208
SULFATREAT VESSEL
T-209
20 P102
TO GAS ANALYZER
PI 225
SP-10
22 P102
TO GAS ANALYZER
PI 324
SP-09
WATER POT
T-308
SULFATREAT VESSEL
T-309
21 P102
TO GAS ANALYZER
PI 325
SP-11
23 P102
TO GAS ANALYZER
NOTE 5
50 PSI AIR SUPPLY
120V S
FV 512
LCV 512
50 PSI AIR SUPPLY
120V S
FV 514
LCV 514
PI 420
ACTIVATED CARBON VESSEL
T-400
SP-12
CONDENSATE DRAIN
24 P102
TO GAS ANALYZER
FSL-700
INSIDE PILOT TRAILER
OUTSIDE PILOT TRAILER
T-500_LEV
PLC
LIT 520
STORAGE SPHERE
T-500
NOTE 3
PI 521
SP-13
VSA
ME-501
VENDOR SCOPE OF SUPPLY
PI 522
SP-14
25 P102
TO GAS ANALYZER
EXISTING FLARE
D1_CH4
PLC
D1_PS_CH4
PLC
VSAFD_CH4
PLC
D2_CH4
PLC
D2_PS_CH4
PLC
VSAEX_CH4
PLC
20 P102
DIGESTER 1 BIOGAS
21 P102
DIGESTER 2 BIOGAS
22 P102
DIGESTER 1 POST-SULFATREAT
23 P102
DIGESTER 2 POST-SULFATREAT
24 P102
VSA FEED
25 P102
VSA EXHAUST
FV 215
LCV 215
FV 315
LCV 315
FV 216
LCV 216
FV 316
LCV 316
FV 510
LCV 510
FV 511
LCV 511
120V S
50 PSI AIR SUPPLY
SP-15
50 PSI AIR SUPPLY
GAS ANALYZER
ME-600
AIT 600
METHANE
AE 600
AE-600_CH4
PLC
PLC
AE-720_LEL
PLC
FSL-702
PLC

PROCESS GAS SYSTEM


FSL 701
ASH 720
AE 720
FSL 702
FAN-701
HTR-703
HTR-704
FAN-702
M
800 CFM SUPPLY
850 CFM EXHAUST

HVAC AND COMBUSTIBLE GAS DETECTION (PROCESS SIDE)

NOTES:

1. ALL PLC I/O ARE LOCATED IN PANEL PCP.
2. PRESSURE SUSTAINING VALVE SET AT 3-INCHES OF WATER COLUMN ABOVE THE PRESSURE OF THE U.S. AIR FORCE ACADEMY BIOGAS SYSTEM. CONTRACTOR TO FIELD VERIFY.
3. STORAGE SPHERE SCOPE OF SUPPLY INCLUDES BACKWARD CURVED CENTRIFUGAL FAN.
4. ALL SAMPLING PORTS ON GAS SYSTEM SHALL HAVE 1/4 -INCH BARBED CONNECTION.
5. BALL DRAIN VALVES SHALL BE INSTALLED AT LOW POINTS IN BIOGAS CONVEYANCE SYSTEM; LOCATIONS TO BE FIELD-SITED BY INSTALLATION CONTRACTOR

REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: C. McPHERSON
DRAWN BY: K. TALBOT
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: AUGUST 2012

LINE IS 1 INCH
AT FULL SIZE
(34X22)
SCALE ACCORDINGLY

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Renewable Energy Production from DoD Installation Solid Waste by Anaerobic Digestion

PROCESS GAS SYSTEM
HVAC AND COMBUSTIBLE GAS DETECTION

PROJECT NO. 50957-73968
FILE NAME: P102PRGS
DRAWING NO.
P102
SHEET NO.
7 OF 28

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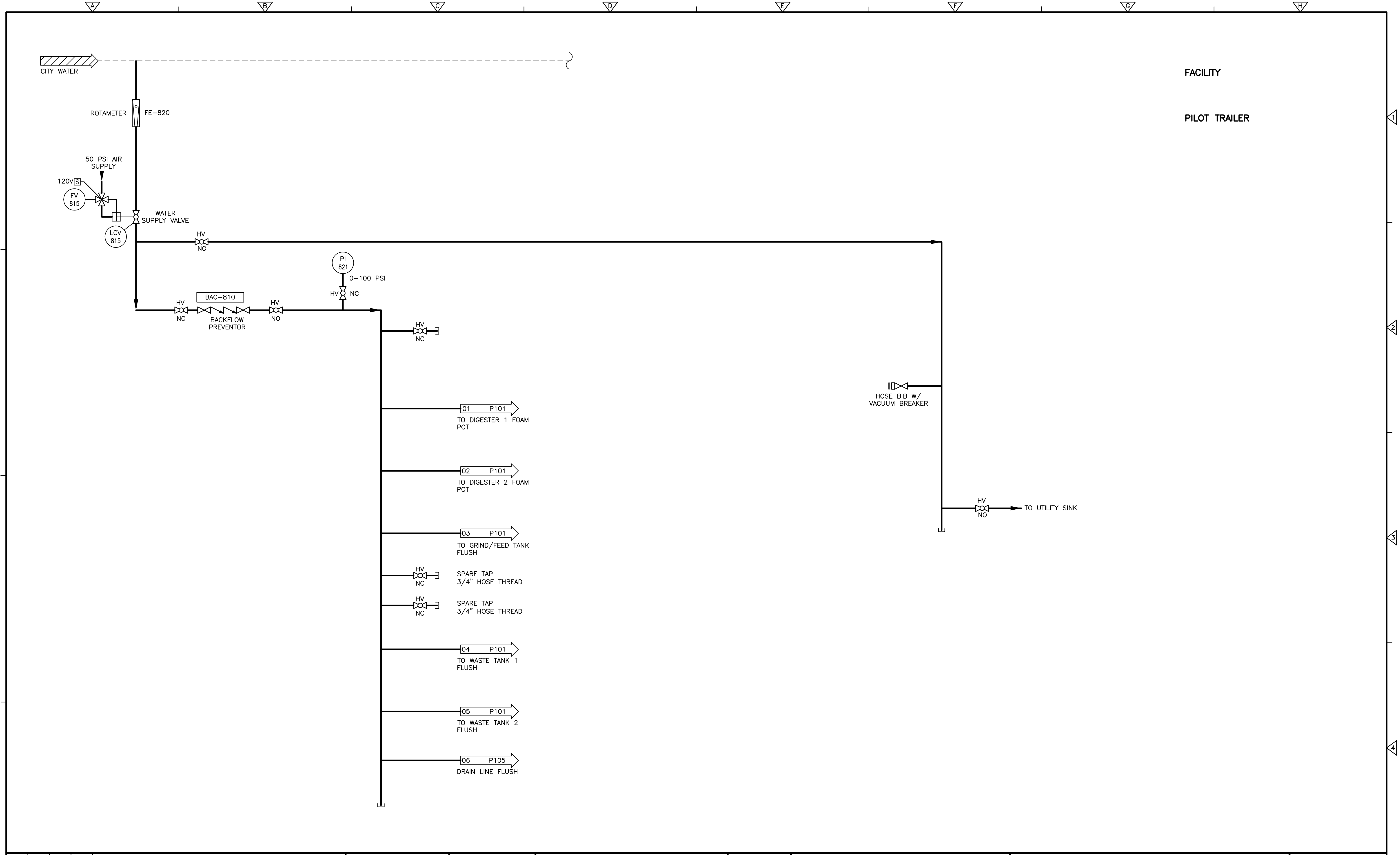
A
B
C
D
E
F
G
H
1
2
3
4
CITY WATER
FACILITY
PILOT TRAILER
ROTAMETER
FE–820
50 PSI AIR SUPPLY
120V S
FV 815
LCV 815
WATER SUPPLY VALVE
HV
NO
PI 821
0–100 PSI
HV NC
BAC–810
BACKFLOW PREVENTOR
HV
NO
HV
NO
HV
NC
01 P101
TO DIGESTER 1 FOAM POT
02 P101
TO DIGESTER 2 FOAM POT
03 P101
TO GRIND/FEED TANK FLUSH
HV
NC
SPARE TAP 3/4" HOSE THREAD
HV
NC
SPARE TAP 3/4" HOSE THREAD
04 P101
TO WASTE TANK 1 FLUSH
05 P101
TO WASTE TANK 2 FLUSH
06 P105
DRAIN LINE FLUSH
HOSE BIB W/ VACUUM BREAKER
HV
NO
TO UTILITY SINK

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REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: C. McPHERSON
DRAWN BY: K. TALBOT
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: AUGUST 2012

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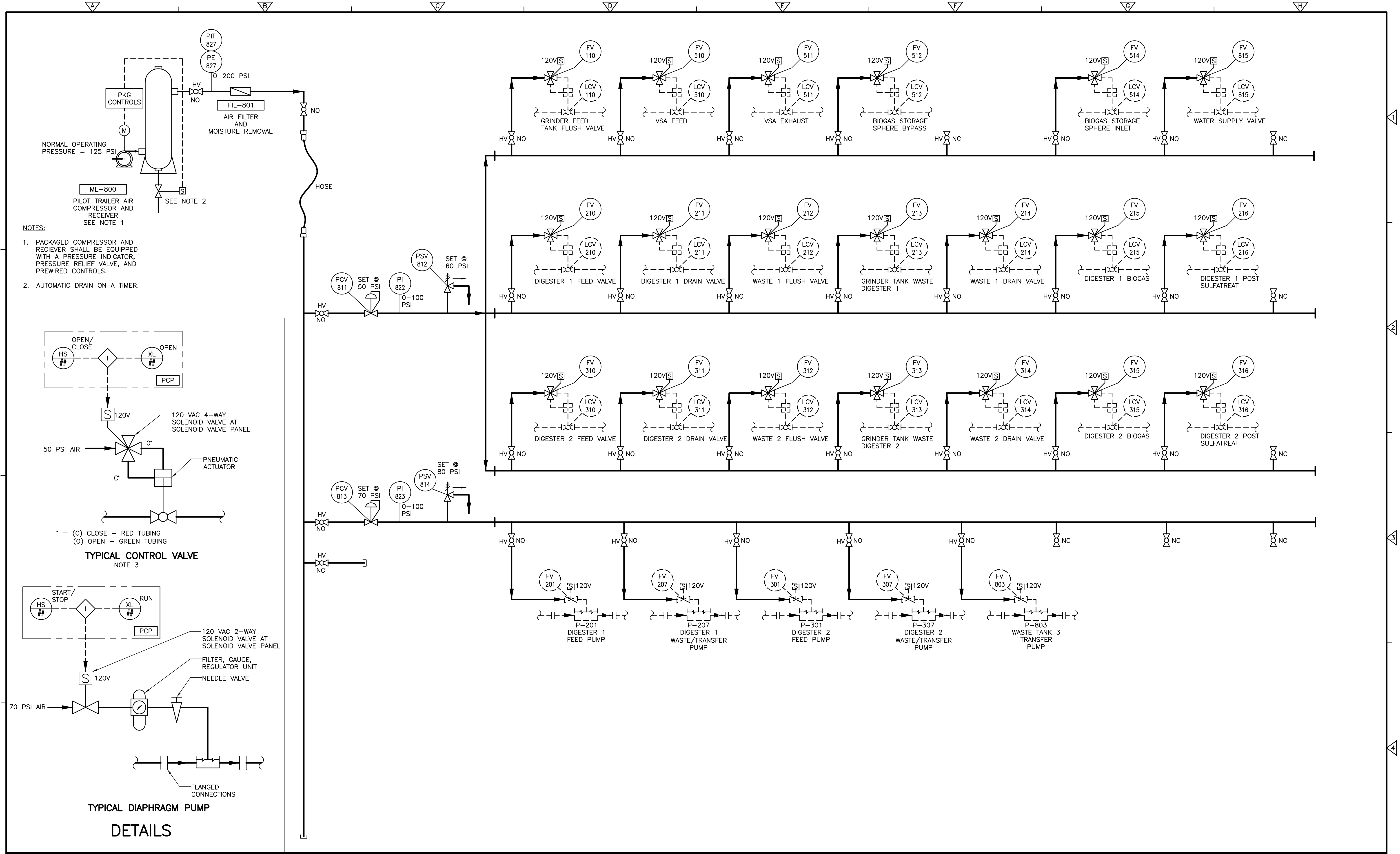
Renewable Energy Production from
DoD Installation Solid Waste by
Anaerobic Digestion

WATER SUPPY & PLUMBING SYSTEM

PROJECT NO. 50957–73968
FILE NAME: P103WSPS
DRAWING NO.
P103
SHEET NO.
8 OF 28


PIT 827
PE 827
0–200 PSI
HV
NO
FIL–801
AIR FILTER AND MOISTURE REMOVAL
PKG CONTROLS
M
NORMAL OPERATING PRESSURE = 125 PSI
S
SEE NOTE 2
ME–800
PILOT TRAILER AIR COMPRESSOR AND RECEIVER
SEE NOTE 1
NOTES:
1. PACKAGED COMPRESSOR AND RECIEVER SHALL BE EQUIPPED WITH A PRESSURE INDICATOR, PRESSURE RELIEF VALVE, AND PREWIRED CONTROLS.
2. AUTOMATIC DRAIN ON A TIMER.
HOSE
PCV 811
SET @ 50 PSI
PI 822
0–100 PSI
PSV 812
SET @ 60 PSI
PCV 813
SET @ 70 PSI
PI 823
0–100 PSI
PSV 814
SET @ 80 PSI
HV NC
FV 110
LCV 110
GRINDER FEED TANK FLUSH VALVE
FV 510
LCV 510
VSA FEED
FV 511
LCV 511
VSA EXHAUST
FV 512
LCV 512
BIOGAS STORAGE SPHERE BYPASS
FV 514
LCV 514
BIOGAS STORAGE SPHERE INLET
FV 815
LCV 815
WATER SUPPLY VALVE
FV 210
LCV 210
DIGESTER 1 FEED VALVE
FV 211
LCV 211
DIGESTER 1 DRAIN VALVE
FV 212
LCV 212
WASTE 1 FLUSH VALVE
FV 213
LCV 213
GRINDER TANK WASTE DIGESTER 1
FV 214
LCV 214
WASTE 1 DRAIN VALVE
FV 215
LCV 215
DIGESTER 1 BIOGAS
FV 216
LCV 216
DIGESTER 1 POST SULFATREAT
FV 310
LCV 310
DIGESTER 2 FEED VALVE
FV 311
LCV 311
DIGESTER 2 DRAIN VALVE
FV 312
LCV 312
WASTE 2 FLUSH VALVE
FV 313
LCV 313
GRINDER TANK WASTE DIGESTER 2
FV 314
LCV 314
WASTE 2 DRAIN VALVE
FV 315
LCV 315
DIGESTER 2 BIOGAS
FV 316
LCV 316
DIGESTER 2 POST SULFATREAT
120V S
HV NO
NC
FV 201
P–201
DIGESTER 1 FEED PUMP
FV 207
P–207
DIGESTER 1 WASTE/TRANSFER PUMP
FV 301
P–301
DIGESTER 2 FEED PUMP
FV 307
P–307
DIGESTER 2 WASTE/TRANSFER PUMP
FV 803
P–803
WASTE TANK 3 TRANSFER PUMP
OPEN/ CLOSE
OPEN
HS ##
I
XL ##
PCP
S 120V
120 VAC 4–WAY SOLENOID VALVE AT SOLENOID VALVE PANEL
50 PSI AIR
O*
C*
PNEUMATIC ACTUATOR
* = (C) CLOSE – RED TUBING
(O) OPEN – GREEN TUBING
TYPICAL CONTROL VALVE
NOTE 3
START/ STOP
RUN
120 VAC 2–WAY SOLENOID VALVE AT SOLENOID VALVE PANEL
FILTER, GAUGE, REGULATOR UNIT
NEEDLE VALVE
70 PSI AIR
FLANGED CONNECTIONS
TYPICAL DIAPHRAGM PUMP
DETAILS

REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: C. McPHERSON
DRAWN BY: K. TALBOT
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: AUGUST 2012

LINE IS 1 INCH
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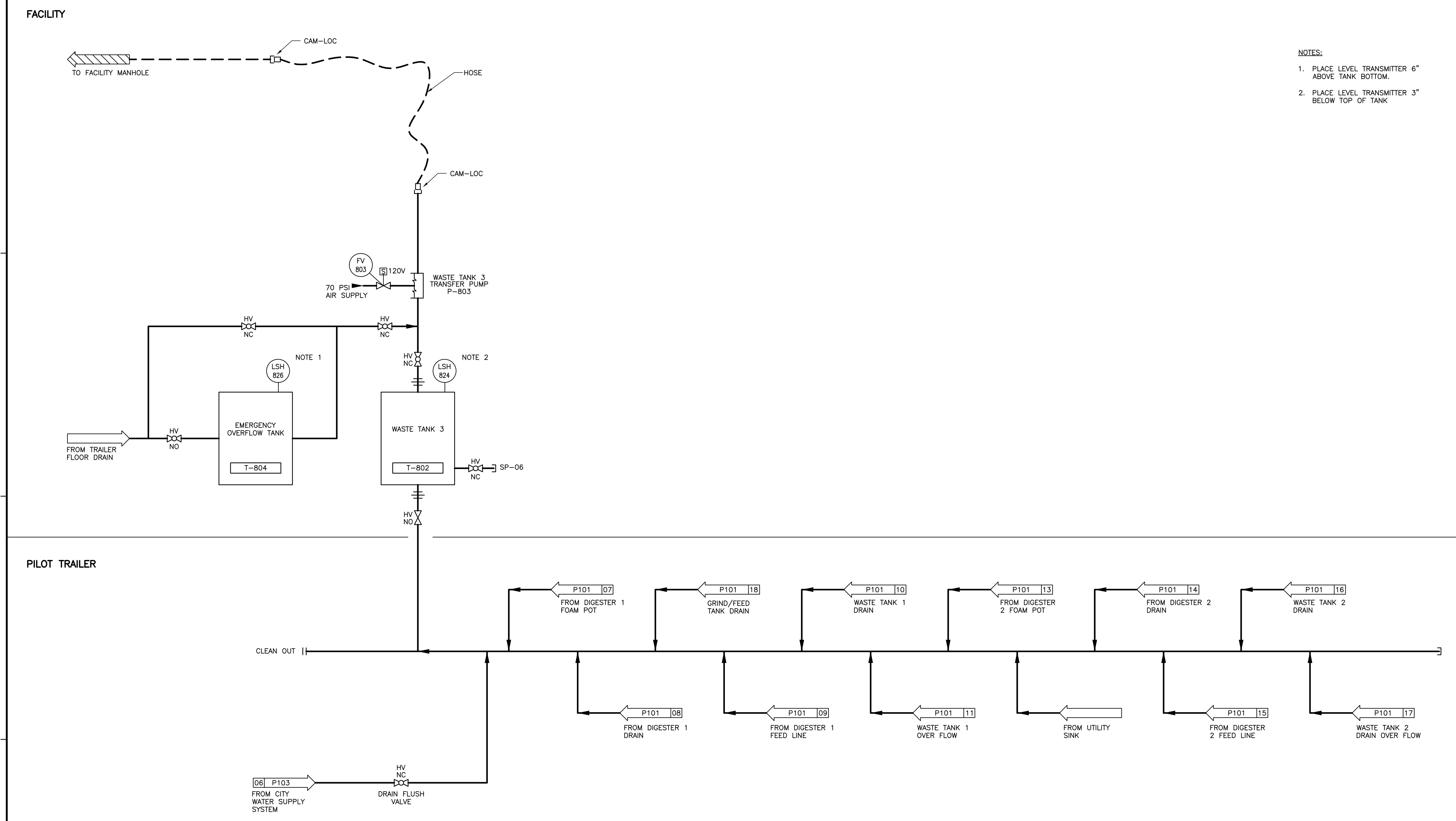
Renewable Energy Production from DoD Installation Solid Waste by Anaerobic Digestion

INSTRUMENT & SERVICE AIR SYSTEM DIAGRAM

PROJECT NO. 50957–73968
FILE NAME: P104ISAD
DRAWING NO.
P104
SHEET NO.
9 OF 28


FACILITY
CAM-LOC
TO FACILITY MANHOLE
HOSE
CAM-LOC
FV 803
S 120V
70 PSI AIR SUPPLY
WASTE TANK 3 TRANSFER PUMP P-803
HV NC
HV NC
HV NC
NOTE 1
NOTE 2
LSH 826
LSH 824
FROM TRAILER FLOOR DRAIN
HV NO
EMERGENCY OVERFLOW TANK
T-804
WASTE TANK 3
T-802
HV NC
SP-06
HV NO
PILOT TRAILER
P101 07 FROM DIGESTER 1 FOAM POT
P101 18 GRIND/FEED TANK DRAIN
P101 10 WASTE TANK 1 DRAIN
P101 13 FROM DIGESTER 2 FOAM POT
P101 14 FROM DIGESTER 2 DRAIN
P101 16 WASTE TANK 2 DRAIN
CLEAN OUT
P101 08 FROM DIGESTER 1 DRAIN
P101 09 FROM DIGESTER 1 FEED LINE
P101 11 WASTE TANK 1 OVER FLOW
FROM UTILITY SINK
P101 15 FROM DIGESTER 2 FEED LINE
P101 17 WASTE TANK 2 DRAIN OVER FLOW
06 P103 FROM CITY WATER SUPPLY SYSTEM
HV NC
DRAIN FLUSH VALVE

NOTES:

1. PLACE LEVEL TRANSMITTER 6" ABOVE TANK BOTTOM.
2. PLACE LEVEL TRANSMITTER 3" BELOW TOP OF TANK

Xref's: [CDM_2234] Images: []
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REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: C. McPHERSON
DRAWN BY: K. TALBOT
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: AUGUST 2012

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AT FULL SIZE
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SCALE ACCORDINGLY

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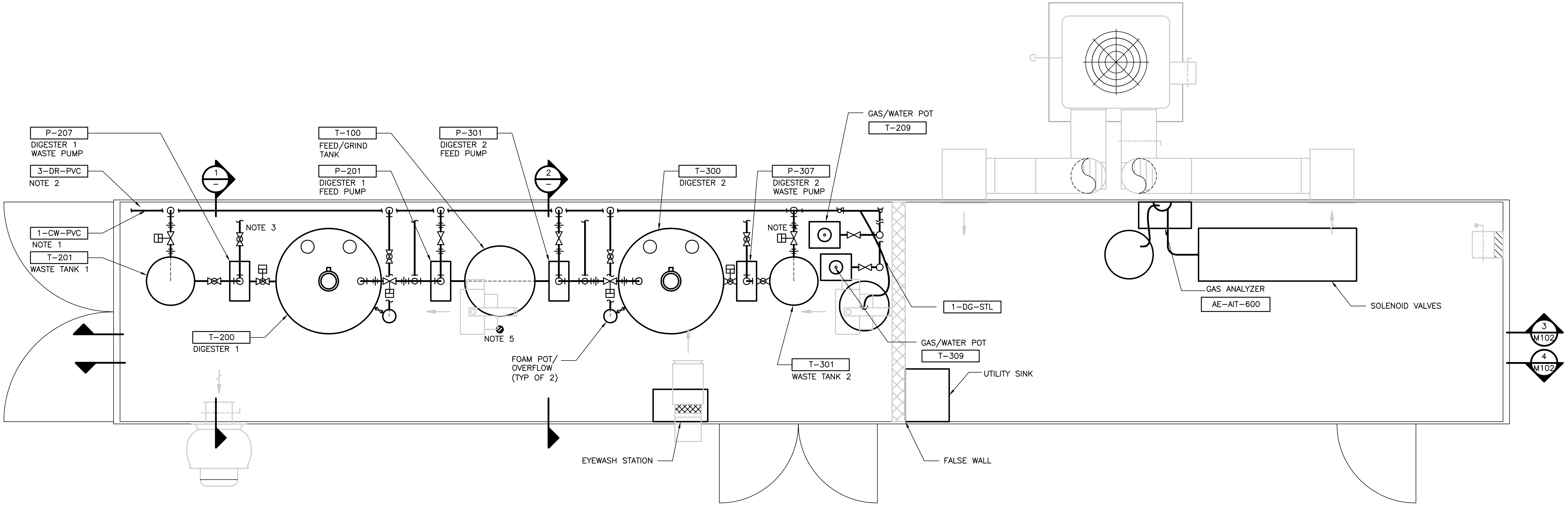
Renewable Energy Production from
DoD Installation Solid Waste by
Anaerobic Digestion

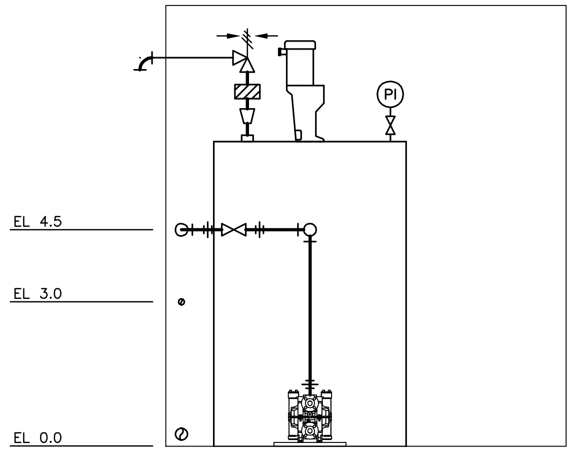
PROCESS DRAIN SYSTEM DIAGRAM

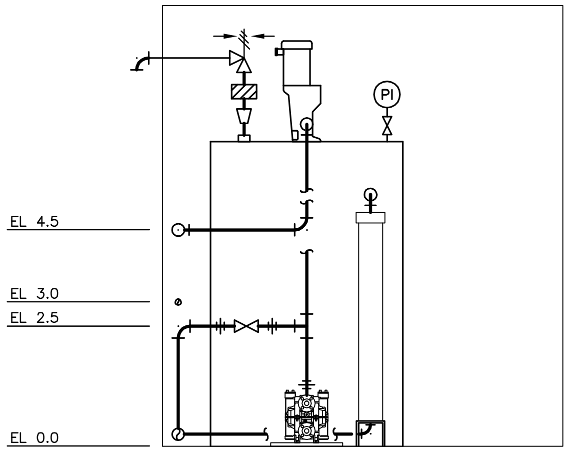
PROJECT NO. 50957-73968
FILE NAME: P105PRSD
DRAWING NO.
P105
SHEET NO.
10 OF 28


P–207
DIGESTER 1
WASTE PUMP
3–DR–PVC
NOTE 2
1–CW–PVC
NOTE 1
T–201
WASTE TANK 1
T–100
FEED/GRIND
TANK
P–201
DIGESTER 1
FEED PUMP
P–301
DIGESTER 2
FEED PUMP
1
–
2
–
NOTE 3
T–200
DIGESTER 1
NOTE 5
FOAM POT/
OVERFLOW
(TYP OF 2)
T–300
DIGESTER 2
P–307
DIGESTER 2
WASTE PUMP
NOTE 4
GAS/WATER POT
T–209
1–DG–STL
GAS/WATER POT
T–309
T–301
WASTE TANK 2
UTILITY SINK
EYEWASH STATION
FALSE WALL
GAS ANALYZER
AE–AIT–600
SOLENOID VALVES
3
M102
4
M102

PLAN

1/2" = 1'–0"


PI
EL 4.5
EL 3.0
EL 0.0


PI
EL 4.5
EL 3.0
EL 2.5
EL 0.0

SECTION 1
–

1/2" = 1'–0"

SECTION 2
–

1/2" = 1'–0"

1/2" = 1'– 0"
1 0 1 2

NOTES:

1. CITY WATER SUPPLY LINE FOR SYSTEM FLUSHES AND UTILITY SINK. SUPPORTED OFF OF NORTH WALL AT EL 3.0. FIELD CONNECTIONS/ROUTING AS SHOWN ON P101.
2. DRAIN PIPE AT BASE OF NORTH WALL AT EL 0.2. CONNECTIONS AS SHOWN ON P101 AND P105.
3. SLUDGE TRANSFER LINE FROM DIGESTER 1 WASTE PUMP TO DIGESTER 2 FEED LINE ALONG NORTH WALL AT EL 4.3 AS SHOWN ON P101.
4. SLUDGE TRANSFER LINE FROM DIGESTER 2 WASTE PUMP TO DIGESTER 1 FEED LINE ALONG NORTH WALL AT EL 4.5 AS SHOWN ON P101.
5. PROVIDE 3–INCH FLOOR DRAIN WITH CONNECTION TO EMERGENCY OVERFLOW TANK AS SHOWN ON P105. SLOPE PILOT TRAILER TO CENTRAL DRAIN.
6. WALLS OF TRAILER SHALL BE STRUCTURALLY REINFORCED AS NEEDED TO SUPPORT EQUIPMENT PIPING AND APPURTENANCES.
7. DRAIN LINE SHALL BE MOUNTED UNDERNEATH TRAILER.

REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: C. McPHERSON
DRAWN BY: K. TALBOT
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: AUGUST 2012

LINE IS 1 INCH
AT FULL SIZE
(34X22)
SCALE ACCORDINGLY

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Camp Dresser & McKee Inc.
1218 3rd Avenue, Suite 100
Seattle, CA 98101
Phone: 206-336-4900
consulting • engineering • construction • operations

Renewable Energy Production from
DoD Installation Solid Waste by
Anaerobic Digestion

PILOT EQUIPMENT
PLAN AND SECTION

PROJECT NO. 50957–73968
FILE NAME: M101PEPL
DRAWING NO.
M101
SHEET NO.
12 OF 28

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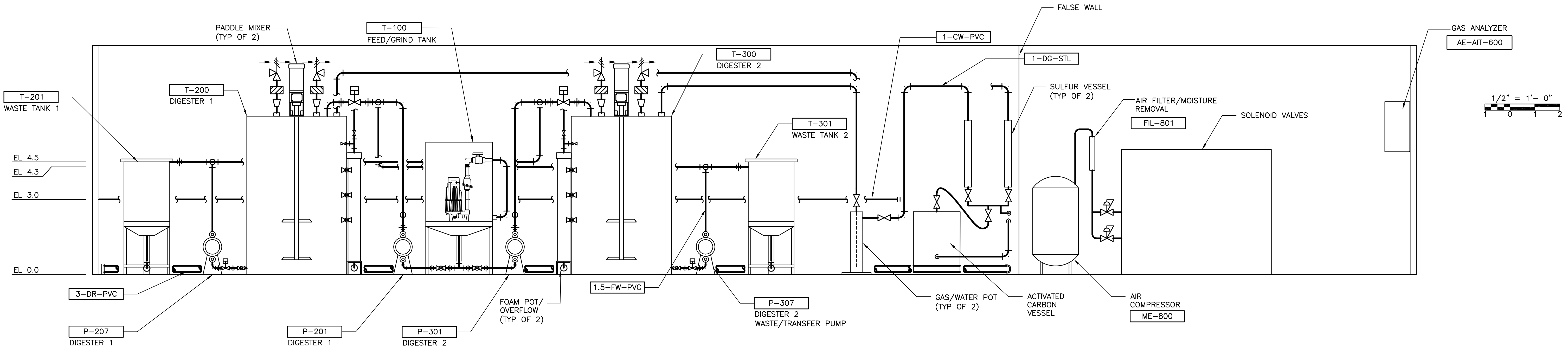
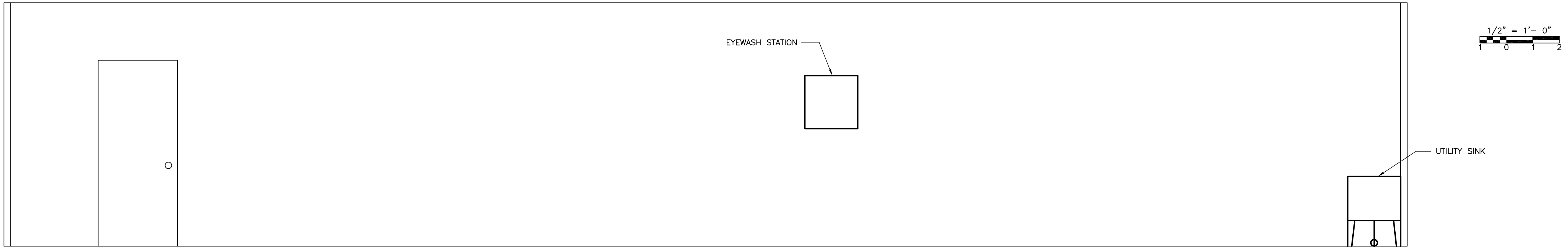

PADDLE MIXER (TYP OF 2)
T-100 FEED/GRIND TANK
T-300 DIGESTER 2
1-CW-PVC
FALSE WALL
1-DG-STL
GAS ANALYZER AE-AIT-600
T-201 WASTE TANK 1
T-200 DIGESTER 1
SULFUR VESSEL (TYP OF 2)
AIR FILTER/MOISTURE REMOVAL FIL-801
SOLENOID VALVES
T-301 WASTE TANK 2
EL 4.5
EL 4.3
EL 3.0
EL 0.0
3-DR-PVC
P-207 DIGESTER 1 WASTE/TRANSFER PUMP
P-201 DIGESTER 1 FEED PUMP
P-301 DIGESTER 2 FEED PUMP
FOAM POT/ OVERFLOW (TYP OF 2)
1.5-FW-PVC
P-307 DIGESTER 2 WASTE/TRANSFER PUMP
GAS/WATER POT (TYP OF 2)
ACTIVATED CARBON VESSEL
AIR COMPRESSOR ME-800
1/2" = 1'- 0"
1 0 1 2

SECTION 3
1/2" = 1'-0"
M101


EYEWASH STATION
UTILITY SINK
1/2" = 1'- 0"
1 0 1 2

SECTION 4
1/2" = 1'-0"
M101

NOTES:

PIPE MATERIAL AND SERVICE SHALL BE AS FOLLOWS:

Service	Size	Symbol	Material	Rating
City Water	1"	CW	PVC	SCH 80
Digester Gas	1"	DG	STEEL	ASTM A53
Food Waste	1"	FW	PVC	SCH 80
Drain	3"	DR	PVC	SCH 40
Service Air	1/4" Tubing	SA	Nylon	200 psi minimum
Service Air	1"	SA	Copper	ASTM B88

REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: C. McPHERSON
DRAWN BY: K. TALBOT
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: AUGUST 2012

LINE IS 1 INCH
AT FULL SIZE
(34X22)
SCALE ACCORDINGLY

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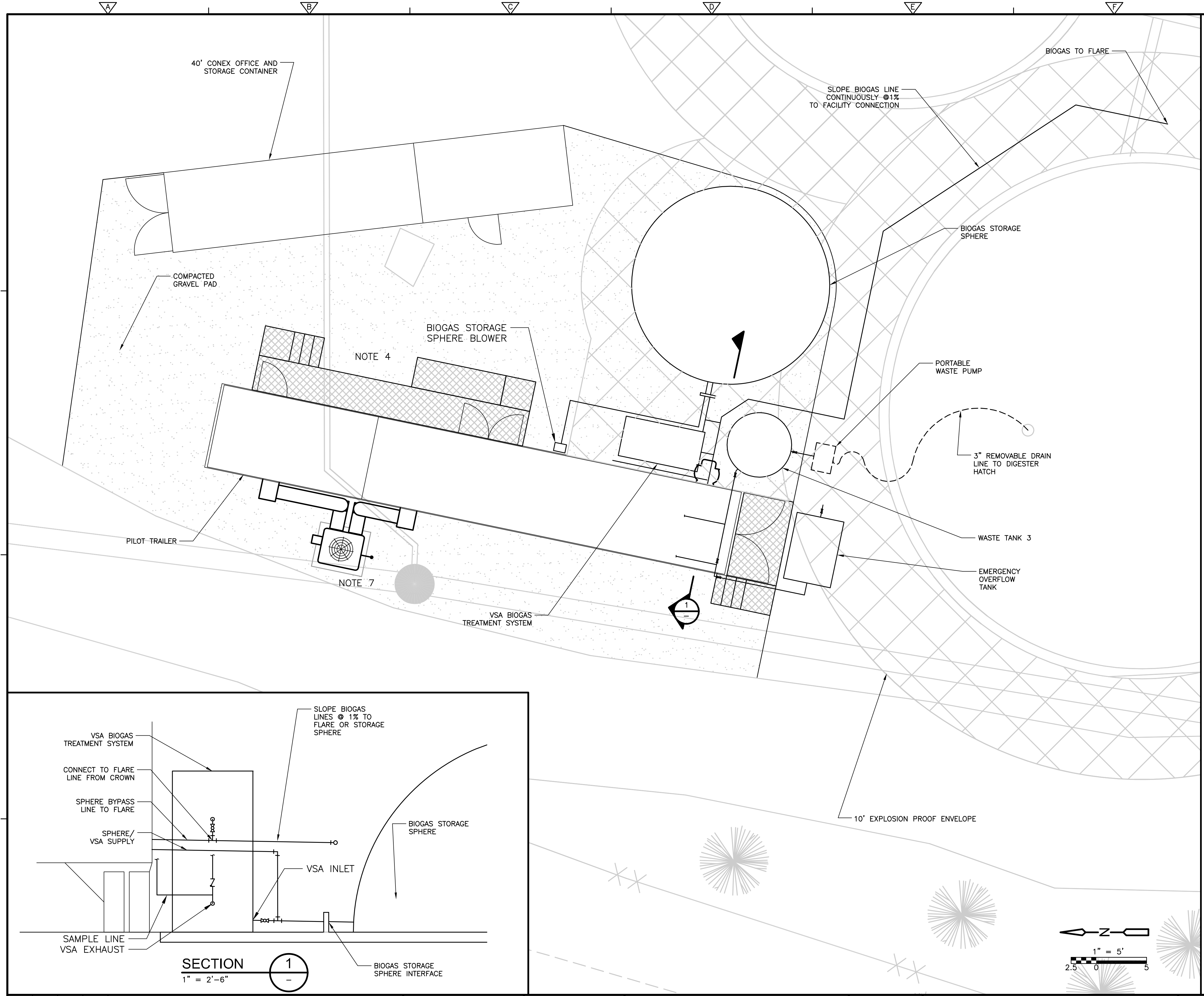
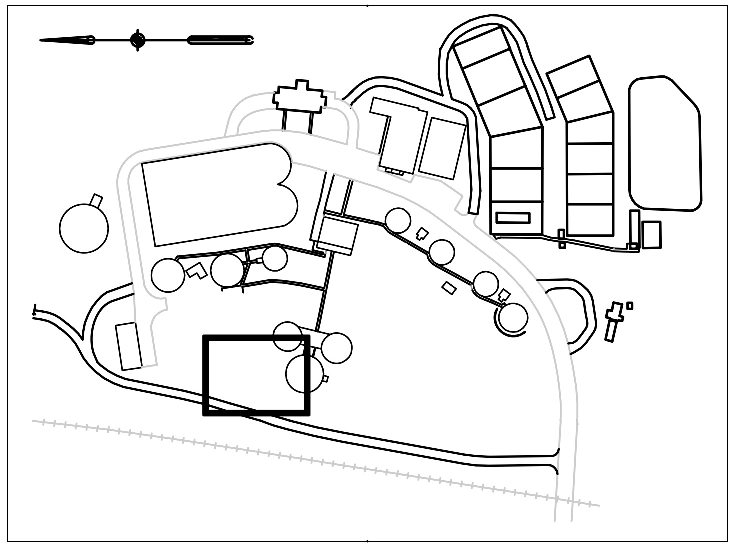
Renewable Energy Production from
DoD Installation Solid Waste by
Anaerobic Digestion

PILOT EQUIPMENT
SECTIONS

PROJECT NO. 50957-73968
FILE NAME: M102PESC
DRAWING NO.
M102
SHEET NO.
13 OF 28


40' CONEX OFFICE AND STORAGE CONTAINER
COMPACTED GRAVEL PAD
NOTE 4
BIOGAS STORAGE SPHERE BLOWER
BIOGAS TO FLARE
SLOPE BIOGAS LINE CONTINUOUSLY @1% TO FACILITY CONNECTION
BIOGAS STORAGE SPHERE
PORTABLE WASTE PUMP
3" REMOVABLE DRAIN LINE TO DIGESTER HATCH
WASTE TANK 3
EMERGENCY OVERFLOW TANK
PILOT TRAILER
NOTE 7
VSA BIOGAS TREATMENT SYSTEM
1
10' EXPLOSION PROOF ENVELOPE
N
1" = 5'
2.5
0
5
VSA BIOGAS TREATMENT SYSTEM
CONNECT TO FLARE LINE FROM CROWN
SPHERE BYPASS LINE TO FLARE
SPHERE/ VSA SUPPLY
SLOPE BIOGAS LINES @ 1% TO FLARE OR STORAGE SPHERE
VSA INLET
BIOGAS STORAGE SPHERE
SAMPLE LINE
VSA EXHAUST
BIOGAS STORAGE SPHERE INTERFACE
SECTION
1
1" = 2'-6"



KEY MAP

NOTES:

1. UNDERGROUND UTILITIES ARE SHOWN BASED ON PLANT RECORD DRAWINGS WHICH REPRESENT THE BEST INFORMATION AVAILABLE. THE TYPE, SIZE, LOCATION, AND NUMBER ARE APPROXIMATE AS SHOWN BY THESE DRAWINGS.
2. PRIOR TO COMMENCEMENT OF ANY EXCAVATION, CONTRACTOR SHALL LOCATE AND MARK THE ACTUAL LOCATION OF UNDERGROUND UTILITIES.
3. PROVIDE 1" CITY WATER CONNECTION FROM DIGESTER CONTROL BUILDING HOSE BIB. FREEZE PROTECT AND INSULATE AS NECESSARY.
4. PROVIDE STAIR ACCESS TO THE TRAILER ON THE NORTH END AND RAMPED ACCESS TO THE TRAILER ON THE SOUTH END.
5. ALL EXPOSED LINES AND TANKS SHALL BE INSULATED AND FREEZE PROTECTED.
6. CONTRACTOR SHALL LEVEL SITE AS NECESSARY AND PROVIDE EQUIPMENT PIPE LINE.
7. HEAT PUMP SHALL BE PROTECTED FROM SNOW AND WIND LOAD USING A PREFABRICATED OR CUSTOM SHELTER.

ANCHORAGE AS NECESSARY

REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY:
DRAWN BY:
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: AUGUST 2012

LINE IS 1 INCH
AT FULL SIZE
(34X22)
SCALE ACCORDINGLY

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Renewable Energy Production from DoD Installation Solid Waste by Anaerobic Digestion

MECHANICAL SITE PLAN

PROJECT NO. 50957–73968
FILE NAME: M103
DRAWING NO.
M103
SHEET NO.
OF 28

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PACKAGED AIR CONDITIONING UNIT SCHEDULE

MARK	SERVES	AIRFLOW (CFM)	OUTSIDE AIR (CFM)	EXTERNAL STATIC PRESSURE (IN WG)	TYPE	COOLING DATA						HEATING CAPACITY (MBH)	ELECTRIC RESISTANCE HEATER					ELECTRICAL DATA									BASIS OF DESIGN	NOTES
																			CONDENSER FAN(S)		COMPRESSOR(S)							
						TONS	TOTAL CAP (MBH)	SENS CAP (MBH)	ENT DB (DEG F)	ENT WB (DEG F)	LVG AIR TEMP DB/WB (DEG F)		MODEL	CAPACITY (KW)	STAGES	VOLTS/PHASE	MCA	EVAP FAN HP	QTY	(HP) EACH	QTY	RLA (EACH)	MCA	MAX OVER CURRENT (AMPS)	VOLTS/PHASE	EER		
AC-1	ESTCP	1200	300	0.5	PACKAGED HEAT PUMP	3	26.5	22.8	80.0	67.0	61/60	51.2	BAYHTRV115	15	2	240/1	78	0.5	1	0.2	1	15.4	25.5	40	230/1	11	TRANE 4WCC3036A1000	1, 2, 3, 4

NOTES:

1. PROVIDE PLEATED FILTERS WITH MERV 8 EFFICIENCY.
2. PROVIDE OUTSIDE AIR DAMPER.
3. PROVIDE THERMOSTAT AND LOW AMBIENT CONTROL TO 0°F.
4. PROVIDE MANUAL OUTSIDE AIR HOOD.

FAN SCHEDULE

MARK	SERVES	FAN DATA				CFM	ESP (IN WG)	MOTOR				BASIS OF DESIGN	NOTES
		FAN TYPE	WHEEL TYPE	WHEEL DIA	BLADE TYPE			FAN (RPM)	DRIVE TYPE	HP	VOLTS/ PHASE		
SF-1	ESTCP	INLINE	CENTRIFUGAL	8	BI	750	0.11	1725	BELT	0.25	460/3	COOK 80SQN-B	1, 3, 4
EF-1	ESTCP	WALL MOUNTED	CENTRIFUGAL	12	BI	850	0.125	1140	DIRECT	0.25	460/3	COOK 120W11D	4

NOTES:

1. PROVIDE BELT GUARD AND OUTLET GUARD.
2. BI=BACKWARDS INCLINED.
3. PROVIDE VIBRATION ISOLATION SPRINGS.
4. EXPLOSION PROOF ASSEMBLY.

UNIT HEATER SCHEDULE

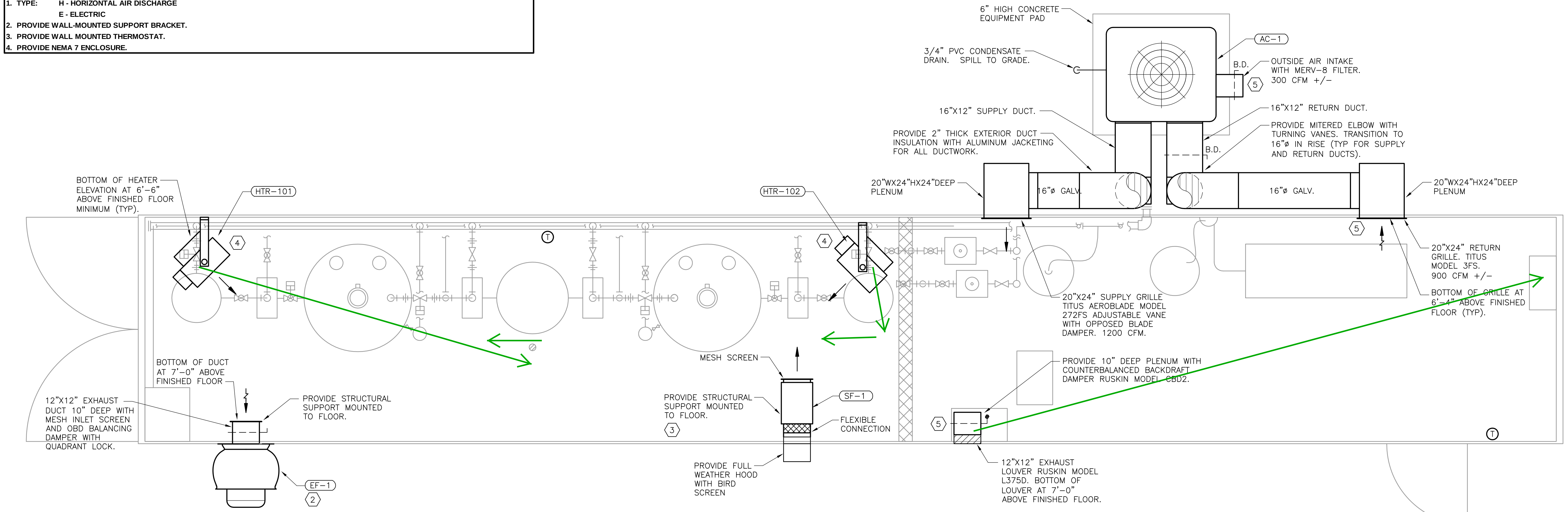
MARK	SERVES	TYPE (NOTE 1)	CAPACITY (KW)	NOMINAL CFM	MOTOR HP	VOLTAGE/ PHASE	BASIS OF DESIGN	NOTES
HTR-101	ESTCP	H, E	15	1200	1/4	480/3	OUELLET OHX15034	2, 3, 4
HTR-102	ESTCP	H, E	15	1200	1/4	480/3	OUELLET OHX15034	2, 3, 4

NOTES:

1. TYPE: H - HORIZONTAL AIR DISCHARGE
   E - ELECTRIC
2. PROVIDE WALL-MOUNTED SUPPORT BRACKET.
3. PROVIDE WALL MOUNTED THERMOSTAT.
4. PROVIDE NEMA 7 ENCLOSURE.

NOTES:

1. ALL EQUIPMENT SHALL BE SUPPORTED BY STRUCTURAL FRAME. DO NOT SUPPORT FROM TRAILER ROOF/WALL UNLESS RATED FOR LOAD.
2. EF–1 IS A DIRECT DRIVE EXHAUST FAN. SET BALANCE DAMPER TO DELIVER 850 CFM. SET QUADRANT LOCK AND PIN TO THIS SETTING.
3. ADJUST VARIABLE SHEAVE ON SUPPLY FAN TO MAINTAIN –0.10" W.G. ROOM STATIC PRESSURE WITH ALL DOORS CLOSED.
4. INSTALL PER MANUFACTURER'S INSTRUCTIONS FOR CLEARANCES REQUIRED.
5. BALANCE OUTSIDE AIR, RETURN AIR AND BAROMETRIC RELIEF TO MAINTAIN ROOM PRESSURE OF +0.10" W.G.


6" HIGH CONCRETE EQUIPMENT PAD
AC–1
3/4" PVC CONDENSATE DRAIN. SPILL TO GRADE.
B.D.
OUTSIDE AIR INTAKE WITH MERV–8 FILTER. 300 CFM +/–
5
16"X12" SUPPLY DUCT.
16"X12" RETURN DUCT.
PROVIDE 2" THICK EXTERIOR DUCT INSULATION WITH ALUMINUM JACKETING FOR ALL DUCTWORK.
PROVIDE MITERED ELBOW WITH TURNING VANES. TRANSITION TO 16"ø IN RISE (TYP FOR SUPPLY AND RETURN DUCTS).
B.D.
20"WX24"HX24"DEEP PLENUM
16"ø GALV.
16"ø GALV.
20"WX24"HX24"DEEP PLENUM
BOTTOM OF HEATER ELEVATION AT 6'–6" ABOVE FINISHED FLOOR MINIMUM (TYP).
HTR–101
4
T
HTR–102
4
5
20"X24" RETURN GRILLE. TITUS MODEL 3FS. 900 CFM +/–
BOTTOM OF GRILLE AT 6'–4" ABOVE FINISHED FLOOR (TYP).
20"X24" SUPPLY GRILLE TITUS AEROBLADE MODEL 272FS ADJUSTABLE VANE WITH OPPOSED BLADE DAMPER. 1200 CFM.
PROVIDE 10" DEEP PLENUM WITH COUNTERBALANCED BACKDRAFT DAMPER RUSKIN MODEL CBD2.
MESH SCREEN
BOTTOM OF DUCT AT 7'–0" ABOVE FINISHED FLOOR
12"X12" EXHAUST DUCT 10" DEEP WITH MESH INLET SCREEN AND OBD BALANCING DAMPER WITH QUADRANT LOCK.
PROVIDE STRUCTURAL SUPPORT MOUNTED TO FLOOR.
PROVIDE STRUCTURAL SUPPORT MOUNTED TO FLOOR.
SF–1
3
FLEXIBLE CONNECTION
5
T
EF–1
2
PROVIDE FULL WEATHER HOOD WITH BIRD SCREEN
12"X12" EXHAUST LOUVER RUSKIN MODEL L375D. BOTTOM OF LOUVER AT 7'–0" ABOVE FINISHED FLOOR.

HVAC PLAN

1/2" = 1'–0"

1/2" = 1'– 0"
1 0 1 2

REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: DHL
DRAWN BY: ALP
SHEET CHK'D BY: GJS
CROSS CHK'D BY: CC
APPROVED BY: GJS
DATE: AUGUST 2012

LINE IS 1 INCH
AT FULL SIZE
(34X22)
SCALE ACCORDINGLY

CDM

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1218 3rd Avenue, Suite 100
Seattle, CA 98101
Phone: 206-336-4900
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Renewable Energy Production from DoD Installation Solid Waste by Anaerobic Digestion

PILOT EQUIPMENT
HVAC PLAN

PROJECT NO. 50957–73968
FILE NAME: H001
DRAWING NO.
H-1
SHEET NO.

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PLAN OR SECTIONS	SINGLE LINE DIAGRAM	CONTROL SCHEM DIAGRAM	DESCRIPTION
CB	AF AT		MOLDED CASE OR INSULATED CASE CIRCUIT BREAKER (3 POLE UNLESS OTHERWISE NOTED). "AF" INDICATES CIRCUIT BREAKER FRAME SIZE "AT" INDICATES CONTINOUS AMP TRIP SETTING
	ST		STUNT TRIP
			FUSE
	_A		600 VOLT. 3 POLE NON-FUSED DISCONNECT (30A AND HORSEPOWER RATED UNLESS OTHERWISE SPECIFIED)
F			600 VOLT. 3 POLE FUSED DISCONNECT (30A AND HORSEPOWER RATED UNLESS OTHERWISE SPECIFIED)
	* _A MCP **	M #	MOTOR STARTER: WALL MOUNTED COMBINATION MOTOR CIRCUIT PROTECTOR AND MAGNETIC FULL VOLTAGE STARTER # CONTROL CIRCUIT ID NUMBER * MAGNETIC TRIP MOTOR CIRCUIT PROTECTOR TRIP RATING ** NEMA CONTACTOR SIZE FVNR = FULL VOLTAGE NON-REVERSING
C		C #	WALL MOUNTED COMBINATION BREAKER AND CONTACTOR
VFD-*	VFD		VARIABLE FREQENCY DRIVE (* = LETTER DESIGNATES SPECIFIC VFD)
	SSS		SOLID STATE REDUCED VOLTAGE MOTOR CONTROLLER
	ATS NO.1 _AMPS #-POLE N S		AUTOMATIC TRANSFER SWITCH #1 (ATS 1): "N" INDICATES NORMAL SOURCE. "S"INDICATES STANDBY SOURCE. 100A INDICATES CONTINUOUS CURRENT RATING.
	K		KEY INTERLOCK
XFMR-#			POWER TRANSFORMER – RATING AS SHOWN
		OR	CURRENT TRANSFORMER (C.T.) – RATING, NUMBER, AND CONNECTION AS SHOWN
			POTENTIAL TRANSFORMER (P.T.) – RATING AND NUMBER AS SHOWN
	*		CAPACITOR = * REPRESENTS: "SC" = SURGE CAPACITOR "PF" = POWER FACTOR CORRECTION CAPACITOR
	DMM		DIGITAL DISPLAY METERING DEVICE.
	TVSS		TRANSIENT VOLTAGE SURGE SUPRESSOR
			GROUND
			GROUNDING ROD
MCC*	MCC *		MOTOR CONTROL CENTER * (* = LETTER DESIGNATING SPECIFIC MCC)
MSB	MSB		MAIN SWITCHBOARD (# DESIGNATES SPECIFIC PANEL)
LP-#	LP-*** PP-***		LIGHTING PANELBOARD LP# (# DESIGNATES SPECIFIC PANEL)
DP-#			DISTRIBUTION POWER PANELBOARD DP
IPB#			INSTRUMENTATION PULL BOX #
PSCP			PUMP STATION CONTROL PANEL (PSCP)
IMH#			INSTRUMENT MANHOLE (IMH) OR HANDHOLE (IHH) # OR ELECTRICAL MANHOLE (EMH) OR HANDHOLE (EHH) #
M P-101	15	1/3	MOTOR, NUMBER INSIDE CIRCLE = HP (P-101=MECHANICAL EQUIPMENT IDENTIFICATION NUMBER)
H	15 KW	H	UNIT HEATER, NUMBER INSIDE SYMBOL = HEATER LOAD
G			GENERATOR
SV	S		SOLENOID VALVE
MOV	MOV		MOTORIZED VALVE OR GATE WITH INTEGRAL STARTER. (HP AS RECOMMENDED BY VALVE SUPPLIER)

PLAN OR SECTIONS	SINGLE LINE DIAGRAM	CONTROL SCHEM DIAGRAM	DESCRIPTION
			LIGHTING NOTES 1) FIRST LETTER OR LETTER & SUBSCRIPT INDICATES FIXTURE TYPE. REFER TO LIGHTING FIXTURE SCHEDULE. 2) NUMBER INDICATES CIRCUIT 3) LETTER INDICATES SWITCH CONTROLLING FIXTURE 4) "LP-2" INDICATES THE PANEL THAT POWER IS DERIVED FROM
A 1b,LP-2			FLUORESCENT LIGHTING FIXTURE (TUBE TYPE) SEE LIGHTING NOTES ABOVE
A 1b,LP-2			INCANDESCENT, COMPACT FLUORESCENT OR HID LIGHTING FIXTURE SEE LIGHTING NOTES ABOVE
1b,LP-2			EMERGENCY LIGHTING UNITS WITH INTEGRAL BATTERY -TWO LIGHTING HEADS SHOWN. SEE LIGHTING NOTES ABOVE
PE		PE	PHOTOELECTRIC EYE (PHOTOCELL)
$\$_{1b}\ \$^2\ \$^3$			SWITCH CONTROLLING CIRCUIT 1B. (2 INDICATES 2 POLE, 3 OR 4 INDICATES 3 WAY OR 4 WAY SWITCH)
$\$^M$			MOMENTARY CONTACT SWITCH, CENTER OFF
4,LP-6 P 2			FRACTIONAL HORSEPOWER MOTOR STARTING SWITCH W/OVERLOADS UNLESS INDICATED OTHERWISE. "P" INDICATES WITH PILOT LIGHT. "2" INDICATES 2 POLE. "4.LP-6" INDICATES CIRCUIT AND PANEL POWERING THE SWITCH.
CKT#			DUPLEX 20 AMP GROUNDING TYPE CONVENIENCE OUTLET GFCI INDICATES GROUND FAULT CIRCUIT INTERRUPTER TYPE
(OR)			SPECIAL PURPOSE RECEPTACLE.
			EQUIPMENT LOCATION KEY (NOTE 2)
		▲	DEVICE LOCATED IN FIELD.
		●	DEVICE LOCATED IN PANEL NOTED
PB		OFF ON	ON – OFF SELECTOR SWITCH
PB			MOMENTARY TYPE PUSHBUTTON CONTROL (FUNCTION AS LABELED)
PB		LOS	STOP PUSHBUTTON CONTROL STATION MOMENTARY TYPE W/LOCK-OUT DEVICE
PB		H O A	3 POSITION SELECTOR SWITCH HAND-OFF-AUTOMATIC SHOWN
PB		L R	2 POSITION SELECTOR SWITCH LOCAL-REMOTE SHOWN
		*CR #	CONTROL RELAY #DESIGNATES CONTROL CIRCUIT *SEQUENTIAL PREFIX FOR CIRCUIT IN WHICH DEVICE USED MORE THAN ONCE
		X#	NORMALLY OPEN – RELAY CONTACT COIL
		X#	NORMALLY CLOSED – RELAY CONTACT COIL
		R	PUSH TO TEST PILOT LIGHT A = AMBER, G = GREEN, R = RED, ETC.
		R	PILOT LIGHT, NON-PUSH TO TEST. COLORS SAME AS ABOVE

PLAN OR SECTIONS	SINGLE LINE DIAGRAM	CONTROL SCHEM DIAGRAM	DESCRIPTION
	Timing range	TDD # R#	TIME DELAY RELAY TDE INDICATES ON DELAY TYPE (TIME DELAY ON ENERGIZATION)
	Timing set point	S#	TDO INDICATES OFF DELAY TYPE (TIME DELAY ON DE-ENERGIZATION)
			ON DELAY TIMING CONTACT-NORMALLY CLOSED, TIME OPEN (NCTO)
			ON DELAY TIMING CONTACT-NORMALLY OPEN, TIME CLOSE (NOTC)
			OFF DELAY TIMING CONTACT-NORMALLY CLOSED, TIME CLOSE (NCTC)
			OFF DELAY TIMING CONTACT-NORMALLY OPEN, TIME OPEN (NOTO)
		XX-###	DESIGNATES INSTRUMENT-NOTE 4 & 5 (REFER TO INSTRUMENT LIST & P& ID LEGEND SHEETFOR ADDITIONAL DETAILS)
⊗		PS-#	PRESSURE SWITCH # (NO CLOSES ON RISING PRESSURE)
⊗		PS-#	PRESSURE SWITCH # (NC OPENS ON RISING PRESSURE)
⊗		TS-#	TEMPERATURE SWITCH # (NO CLOSES ON RISING TEMP)
⊗		TS-#	TEMPERATURE SWITCH # (NC OPENS ON RISING TEMP)
SD			SMOKE DETECTOR
J			JUNCTION BOX (PULL BOX OR CONDUIT FITTING) IN GENERAL, UNLESS SPECIFICALLY NOTED, A PULL FITTING (CONDUIT BODY, IE "T", "X", ETC) MAY BE USED WHERE CONDUIT CONFIGURATION AND NUMBER OF WIRES ALLOWS.
			EXPOSED CONDUIT RUN
			CONCEALED CONDUIT OR GROUND WIRE RUN. (FLOOR, CEILING, WALLS OR UNDERGROUND)
G			120, 208, OR 240V CONDUIT RUN. CROSS-HATCHES INDICATES NUMBER OF CONDUCTORS (HOT, NEUTRAL, AND GROUND SHOWN) NO CROSSHATCHES INDICATES 3#12 AWG IN 3/4" CONDUIT. WIRE IS #12 UNLESS NOTED OTHERWISE.
			CONDUIT TURNING UP
			CONDUIT STUBBED OUT AND CAPPED
			CONDUIT TURNING DOWN
1,3.LP-# 1"C			HOME RUN TO LIGHT PANEL LP# WITH CIRCUITS 1 AND 3 IN 1" CONDUIT. CONDUIT IS 3/4"UNLESS NOTED OTHERWISE.
B2	B2		ELECTRICAL CONDUIT IDENTIFICATION: CONDUIT NUMBER PREFIX INDICATES PANEL FROM WHICH CONDUIT RECEIVES POWER. HOME RUN TO MCC B WITH EXPOSED CONDUIT #2 SHOWN. REFER TO CONDUIT SCHEDULE FOR CONDUIT SIZE AND FILL.
I# J#			INSTRUMENTATION CONDUIT IDENTIFICATION: I OR J PREFIX REPRESENTS INSTRUMENT CONDUIT. REFER TO CONDUIT SCHEDULE FOR CONDUIT SIZE AND FILL. I –TYPICALLY REPRESENTS A CONDUIT CONTAINING A LOW LEVEL SIGNAL SUCH AS 4-20MA ANALOG, DATA HIGHWAY, ETC. J –TYPICALLY REPRESENTS A CONDUIT CONTAINING 120VAC PLC DIGITAL INPUTS OR OUTPUTS, MISC 120VAC CONTROL ETC. # –TYPICALLY REPRESENTS INSTRUMENT LOOP WITH WHICH CONDUIT IS ASSOCIATED.
▨	▨	▨	CROSS HATCHING INDICATES REMOVAL OF EXISTING EQUIPMENT
			SHADED LINES INDICATE EXISTING EQUIPMENT
NEMA#			ALL PANELS, STARTERS, DISCONNECTS, WIRING DEVICES ETC. WITHIN THE ROOM NOTED TO HAVE ENCLOSURES WITH NEMA TYPE # ENCLOSURES (EXCEPT AS SPECIFICALLY NOTED)
ALR		ALR	ALARM INDICATING FIXTURE
ALR		ALR	COMBINATION LIGHT/SOUND ALARM FIXTURE

NOTES:

1. THIS SHEET IS A GENERAL ELECTRICAL LEGENDS; ALL SYMBOLS INCLUDED HERE MAY NOT NECESSARILY BE USED ON THE CONTRACT DRAWINGS.
2. THE SYMBOLS ARE USED ON THE CONTROL SCHEMATIC DRAWINGS TO INDICATE THE PHYSICAL LOCATION OF DEVICES. REFER TO THE CONTROL SCHEMATICS FOR SPECIFIC DETAILS.
3. ⊗ SYMBOL DENOTES AN INSTRUMENTATION DEVICE
4. XX-### INSTRUMENT IDENTIFICATION TAG NUMBER.
   XX DENOTES FUNCTIONAL IDENTIFICATION. (REFER TO P & ID LEGEND FOR INSTRUMENT TAGGING ABBREVIATIONS).
   ## DENOTES LOOP NUMBER.

PLC INPUT/OUTPUT DEVICES–

AS SHOWN ON CONTROL SCHEMATICS

	NORMALLY OPEN CONTROL OUTPUT
	NORMALLY CLOSED CONTROL OUTPUT
AO + –	ANALOG OUTPUT 4-20MA UNLESS NOTED
AI + –	ANALOG INPUT 4-20ma UNLESS NOTED
DI	DIGITAL INPUT

30% SUBMITTAL - NOT FOR CONSTRUCTION

REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: RRR
DRAWN BY: WKT
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: APRIL 2011

LINE IS 1 INCH
AT FULL SIZE
(34X22)
SCALE ACCORDINGLY

CDM
Camp Dresser & McKee Inc.
1218 3rd Avenue, Suite 100
Seattle, CA 98101
Phone: 206-336-4900
consulting • engineering • construction • operations

Renewable Energy Production from
DoD Installation Solid Waste by
Anaerobic Digestion

ELECTRICAL LEGEND

PROJECT NO. 50957-73968
FILE NAME: E001
DRAWING NO.
E-1
SHEET NO.
OF 30

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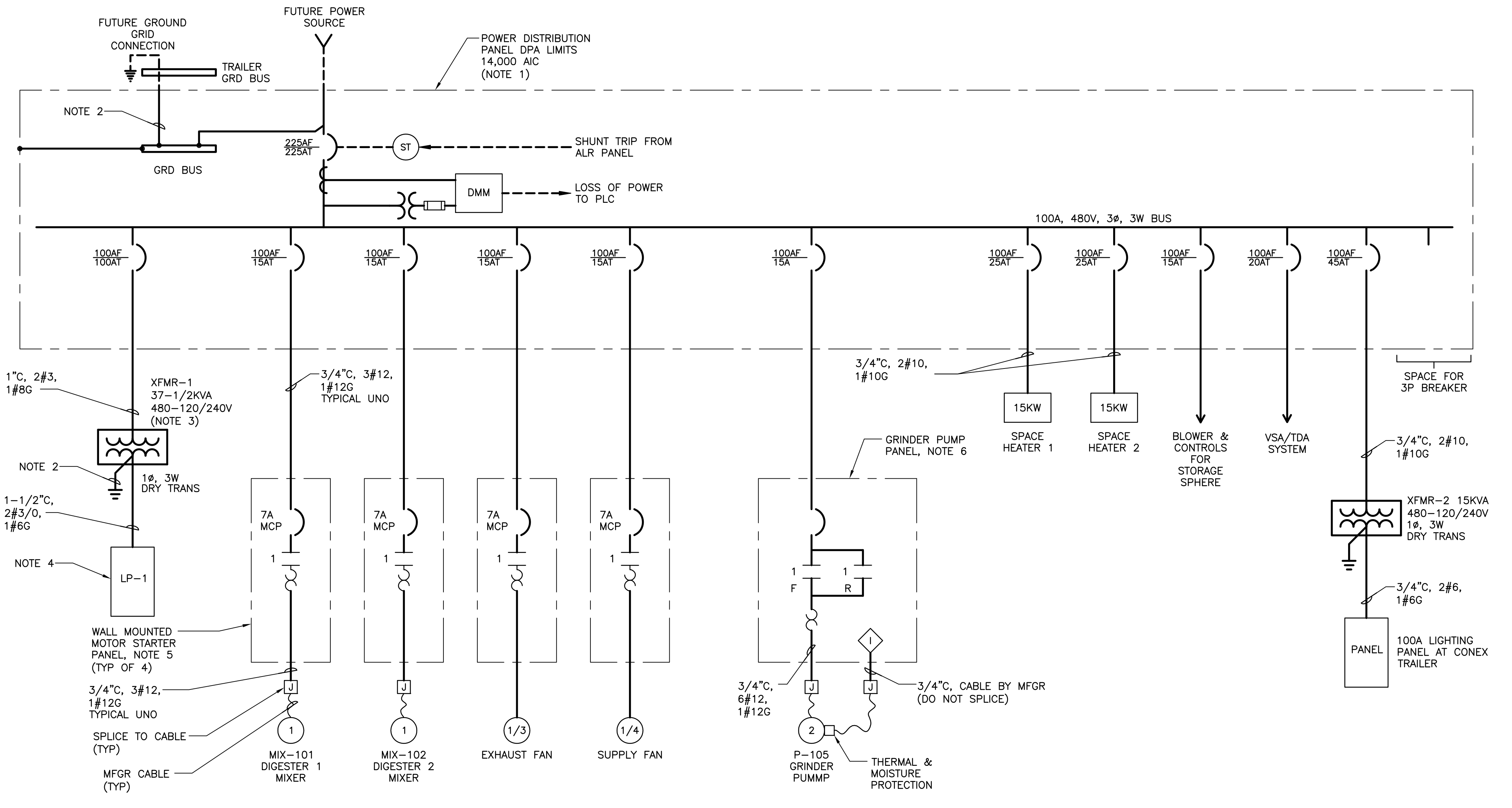
FUTURE GROUND GRID CONNECTION
FUTURE POWER SOURCE
TRAILER GRD BUS
POWER DISTRIBUTION PANEL DPA LIMITS 14,000 AIC (NOTE 1)
NOTE 2
GRD BUS
225AF
225AT
ST
SHUNT TRIP FROM ALR PANEL
DMM
LOSS OF POWER TO PLC
100A, 480V, 3Ø, 3W BUS
100AF 100AT
100AF 15AT
100AF 15AT
100AF 15AT
100AF 15AT
100AF 15A
100AF 25AT
100AF 25AT
100AF 15AT
100AF 20AT
100AF 45AT
1"C, 2#3, 1#8G
XFMR-1 37-1/2KVA 480-120/240V (NOTE 3)
NOTE 2
1Ø, 3W DRY TRANS
1-1/2"C, 2#3/0, 1#6G
NOTE 4
LP-1
WALL MOUNTED MOTOR STARTER PANEL, NOTE 5 (TYP OF 4)
3/4"C, 3#12, 1#12G TYPICAL UNO
7A MCP
1
3/4"C, 3#12, 1#12G TYPICAL UNO
SPLICE TO CABLE (TYP)
MFGR CABLE (TYP)
J
1
MIX-101 DIGESTER 1 MIXER
MIX-102 DIGESTER 2 MIXER
1/3
EXHAUST FAN
1/4
SUPPLY FAN
GRINDER PUMP PANEL, NOTE 6
F
R
3/4"C, 6#12, 1#12G
3/4"C, CABLE BY MFGR (DO NOT SPLICE)
2
P-105 GRINDER PUMMP
THERMAL & MOISTURE PROTECTION
3/4"C, 2#10, 1#10G
15KW
SPACE HEATER 1
15KW
SPACE HEATER 2
BLOWER & CONTROLS FOR STORAGE SPHERE
VSA/TDA SYSTEM
SPACE FOR 3P BREAKER
3/4"C, 2#10, 1#10G
XFMR-2 15KVA 480-120/240V 1Ø, 3W DRY TRANS
3/4"C, 2#6, 1#6G
PANEL
100A LIGHTING PANEL AT CONEX TRAILER

SINGLE LINE DIAGRAM

NOTES:

1. DP-A: NEMA 3R 480 VOLT DISTRIBUTION PANEL MOUNTED TO EXTERIOR OF TRAILER, WITH NEMA 3R ENCLOSURE, BOLT-ON MOLDED CASE BREAKERS, SHUNT TRIP ON MAIN BREAKER, OTHER FEATURES AS SHOWN. EATON-CUTLER HAMMER POW-R-LINE 2A OR EQUAL.
2. #6 BARE COPPER TO TRAILER GROUND BUS OR GROUND LUG.
3. XFMR-1: DRY-TYPE TWO-WINDING TRANSFORMER, VENTILATED, NEMA 2 DRIP-PROOF, WITH WEATHER SHIELD SUITABLE FOR OUTDOOR MOUNTING. NEMA TP-1 TYPE, COMPLIANT WITH THE DEPARTMENT OF ENERGY (DOE), 10 CFR PART 431, "ENERGY CONSERVATION PROGRAM FOR COMMERCIAL EQUIPMENT: DISTRIBUTION TRANSFORMERS ENERGY CONSERVATION STANDARDS; FINAL RULE" DATED OCT 2007. PROVIDE BRACKET MOUNTING TO BOLT TRANSFORMER TO EXTERIOR OF TRAILER. EATON-CUTLER HAMMER OR EQUAL.
4. LP-1: NEMA 3R 120-240 VOLT LIGHTING PANEL MOUNTED TO EXTERIOR OF TRAILER, WITH NEMA 3R ENCLOSURE, BOLT-ON MOLDED CASE BREAKERS, OTHER FEATURES AS SHOWN. EATON-CUTLER HAMMER POW-R-LINE 1A OR EQUAL.
5. INDIVIDUAL WALL MOUNTED FULL VOLTAGE NON-REVERSING COMBINATION MOTOR STARTER
    - A. MOTOR CIRCUIT PROTECTOR WITH DOOR MOUNTED, PADLOCKABLE OPERATING HANDLE INTERLOCKED WITH COVER
    - B. NEMA RATED CONDUCTOR
    - C. OVERLOAD HEATERS SIZED FOR MOTOR FURNISHED
    - D. AUXILIARY CONTACTS AS SHOWN ON THE CONTROL SCHEMATICS
    - E. APPLETON OR EQUAL
6. GRINDER PUMP PANEL FURNISHED WITH PUMP, INCLUDES CLASS I, DIV 1 RATED ENCLOSURE, REVERSING STARTER, PUMP CONTROLS AND PROTECTIONS.
7. DIGITAL ENERGY METER, LCD DISPLAY, WATT-HR METER WITH DEMAND, MONITORING VOLTAGE, CURRENT, PF & FREQUENCY: DRY ALARM CONTACT PROGRAMMED TO DETECT LOSS OF VOLTAGE (POWER FAIL ALARM TO AUTODIALER). EATON IQ 35M OR EQUAL.

100 AMP MAIN BREAKER — **PANELBOARD LP-1** — LOCATION: **outside trailer**
100 AMP BUS RATING **32** POLES — **10** KA SHORT CIRCUIT RATING — ENCLOSURE RATING: **NEMA 3R**
120/240 VOLTS **1** PHASE **3** WIRE **60 Hz.** — ELECTRONIC GRADE: **NO** — MOUNTING: **SURFACE**

CIRCUIT NO.	DESCRIPTION	LOAD KVA LINE 1	LOAD KVA LINE 2	BREAKER AMPS/ POLES	NOTES	CIRCUIT NO.	DESCRIPTION	LOAD KVA LINE 1	LOAD KVA LINE 2	BREAKER AMPS/ POLES	NOTES
1	Lighting	0.4	▨	15 /1	5	2	Receptacles	1.44	▨	15 /1	5
3	Alarm panel ALR PNL	▨	1	15 /1	1, 5	4	Tank Heater 2A	▨	0.22	15 /1	3, 5
5	Pilot Control panel PCP	0.5	▨	15 /1	5	6	Tank Heater 2B	0.22	▨	15 /1	3, 5
7	Tank Heater 1A	▨	0.22	15 /1	3, 5	8	AE/AIT-131A&B	▨	0.01	15 /1	
9	Tank Heater 1B	0.22	▨	15 /1	3, 5	10	Single Phase 120 volt Circuit		▨	15 /1	
11	Single Phase 120 volt Circuit	▨		15 /1		12	flow meter FIT-111	▨		15 /1	5
13	Single Phase 120 volt Circuit		▨	15 /1		14	flow meter FIT-112		▨	15 /1	5
15	Solenoid panel	▨	0.68	20 /1	5	16	Single Phase 120 volt Circuit	▨		15 /1	
17	compressor	1.8	▨	20 /2		18	Single Phase 120 volt Circuit		▨	15 /1	
19		▨	1.8			20	Single Phase 120 volt Circuit	▨		15 /1	
21	Single Phase 120 volt Circuit		▨	15 /1		22	Single Phase 120 volt Circuit		▨	15 /1	
23	Single Phase 120 volt Circuit	▨		15 /1		24	Single Phase 120 volt Circuit	▨		15 /1	
25	Single Phase 120 volt Circuit		▨	15 /1		26	Single Phase 120 volt Circuit		▨	15 /1	
27	Single Phase 120 volt Circuit	▨		15 /1		28	Single Phase 120 volt Circuit	▨		15 /1	
29	Single Phase 120 volt Circuit		▨	15 /1		30	Single Phase 120 volt Circuit		▨	15 /1	
31	Single Phase 120 volt Circuit	▨		15 /1		32	Single Phase 120 volt Circuit	▨		15 /1	
		▨						▨			
	TOTAL LINE KVA THIS SIDE	2.92	3.7				TOTAL LINE KVA THIS SIDE	1.66	0.23		
							TOTAL KVA PER LINE	4.58	3.93		
							TOTAL KVA	8.51			

NOTES:
1. PROVIDE LOCKING HARDWARE
3. 30 ma GFI CIRCUIT BREAKER FOR EQUIPMENT PROTECTION ONLY (HEAT TRACE)
5. BRANCH CIRCUIT WIRING: 3/4"C, 2#12 & 1#12G

NOTES CONT.:
2. 5 ma GROUND FAULT INTERRUPTER (GFI) CIRCUIT BREAKER
4. PROVIDE LOCKING HARDWARE & PAINT BREAKER HANDLE RED (FACP)
6.

SEE REVISED SCHEDULE ON FOLLOWING PAGE

LP-1 PANEL SCHEDULE

REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: RRR
DRAWN BY: JAW
SHEET CHK'D BY: GNM
CROSS CHK'D BY:
APPROVED BY:
DATE: AUGUST 2012

LINE IS 1 INCH
AT FULL SIZE
(34X22)
SCALE ACCORDINGLY

CDM
Camp Dresser & McKee Inc.
1218 3rd Avenue, Suite 100
Seattle, CA 98101
Phone: 206-336-4900
consulting • engineering • construction • operations

Renewable Energy Production from
DoD Installation Solid Waste by
Anaerobic Digestion

SINGLE LINE DIAGRAM
AND PANEL SCHEDULE

PROJECT NO. 50957-73968
FILE NAME: E002
DRAWING NO.
E-2
SHEET NO.
10 OF 28

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200 AMP MAIN BREAKER
200 AMP BUS RATING **32** POLES
120/240 VOLTS **1** PHASE **3** WIRE **60 Hz.**

PANELBOARD LP-1

10 KA SHORT CIRCUIT RATING
ELECTRONIC GRADE: **NO**

LOCATION: **outside trailer**
ENCLOSURE RATING: **NEMA 3R**
MOUNTING: **SURFACE**

CIRCUIT NO.	DESCRIPTION	LOAD KVA		BREAKER AMPS/ POLES	NOTES	CIRCUIT NO.	DESCRIPTION	LOAD KVA		BREAKER AMPS/ POLES	NOTES
		LINE 1	LINE 2					LINE 1	LINE 2		
1	Lighting	0.4	▨	15 /1	5	2	Receptacles	1.44	▨	15 /1	5
3	Alarm panel ALR PNL	▨	1	15 /1	1, 5	4	Tank Heater 2A	▨	0.22	15 /1	3, 5
5	Pilot Control/metering panel PCP	0.5	▨	15 /1	5	6	Tank Heater 2B	0.22	▨	15 /1	3, 5
7	Tank Heater 1A	▨	0.22	15 /1	3, 5	8	AE/AIT-151-A&B	▨	0.01	15 /1	
9	Tank Heater 1B	0.22	▨	15 /1	3, 5	10	Single Phase 120 volt Circuit	0	▨	15 /1	
11	Tank Heaters 1C, D, E, F	▨	0.88	15 /1	3, 5	12	flow meter FIT-111	▨	0.5	15 /1	5
13	Single Phase 120 volt Circuit		▨	15 /1		14	flow meter FIT-112	0.5	▨	15 /1	5
15	Solenoid panel	▨	0.68	20 /1	5	16	heat pump AC-1	▨	11.73	110 /2	6
17	compressor	1.8	▨	20 /2		18		11.73	▨		
19		▨	1.8			20	Tank Heaters 2C, D, E, F	▨	0.88	15 /1	3, 5
21	Single Phase 120 volt Circuit	0.11	▨	15 /1		22	Single Phase 120 volt Circuit		▨	15 /1	
23	Single Phase 120 volt Circuit	▨	0.11	15 /1		24	Single Phase 120 volt Circuit	▨		15 /1	
25	heat tracing	1.285	▨	20 /1	3, 5	26	Single Phase 120 volt Circuit		▨	15 /1	
27	heat tracing	▨	1.285	20 /1	3, 5	28	Single Phase 120 volt Circuit	▨		15 /1	
29	Single Phase 120 volt Circuit		▨	15 /1		30	Single Phase 120 volt Circuit		▨	15 /1	
31	Single Phase 120 volt Circuit	▨		15 /1		32	Single Phase 120 volt Circuit	▨		15 /1	
		▨						▨			
	TOTAL LINE KVA THIS SIDE	4.315	5.975				TOTAL LINE KVA THIS SIDE	13.89	13.34		
							TOTAL KVA PER LINE	18.205	19.315		
							TOTAL KVA	37.52			

NOTES:		NOTES CONT.:	
1.	PROVIDE LOCKING HARDWARE	2.	5 ma GROUND FAULT INTERRUPTER (GFI) CIRCUIT BREAKER
3.	30 ma GFI CIRCUIT BREAKER FOR EQUIPMENT PROTECTION ONLY (HEAT TRACE)	4.	PROVIDE LOCKING HARDWARE & PAINT BREAKER HANDLE RED (FACP)
5.	BRANCH CIRCUIT WIRING: 3/4"C, 2#12 & 1#12G	6.	BRANCH CIRCUIT WIRING: 1"C, 2#2, 1#6G
7.		8.	
9.		10.	
11.		12.	
13.		14.	
15.		16.	
17.		18.	
19.		20.	

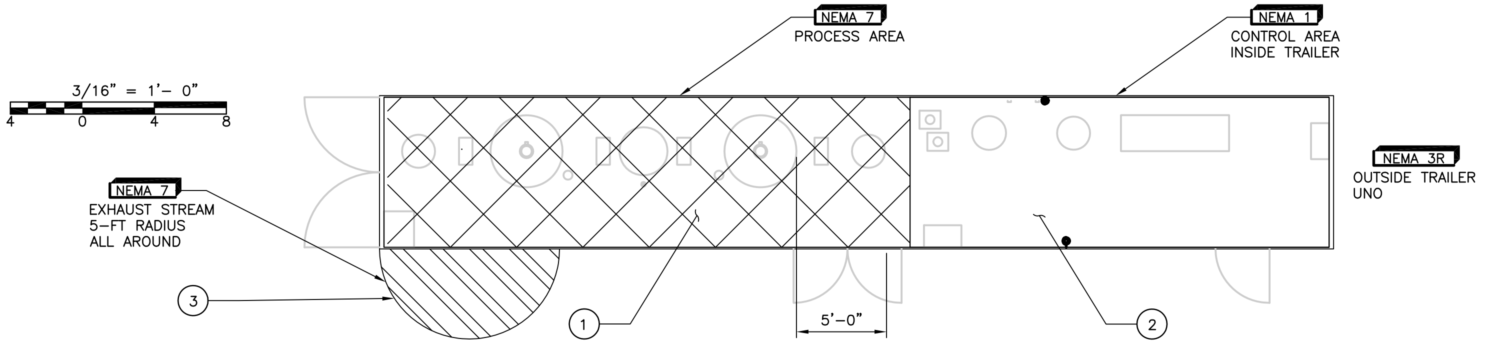
480 V DP-A at trailer

08/23/12

			LOAD			QUANTITY			FEEDER SIZING	DEM FAC	VOLT	CONN	OPER DEMAND	EMERG	FEEDER SIZING	FEEDER SIZING	FEEDER SIZING
NO.		DESCRIPTION	SIZE	UNIT	MOTOR RPM	CONN	OPER	EMER	FACTOR		KV	KVA	KVA	KVA	CONN. KVA	DEM. KVA	E. KVA
1	-	P-105 grinder pump	2	HP	1800 RPM @ 60Hz	1	1	0	1	1	0.48	2.8	2.8	0.0	2.8	2.8	0.0
2	-	space heater 1	15	KW	1800 RPM @ 60Hz	1	1	0	1.25	1	0.48	15.0	15.0	0.0	18.8	18.8	0.0
3	-	space heater 2	15	KW	1800 RPM @ 60Hz	1	1	0	1.25	1	0.48	15.0	15.0	0.0	18.8	18.8	0.0
4	-	37.5 kva XFMR	78	FLA	1800 RPM @ 60Hz	1	0.75	0	1.25	1	0.48	64.8	48.6	0.0	81.0	60.8	0.0
5	-	MIX-101	1	HP	1800 RPM @ 60Hz	1	1	0	1	1	0.48	1.7	1.7	0.0	1.7	1.7	0.0
6	-	MIX-102	1	HP	1800 RPM @ 60Hz	1	1	0	1	1	0.48	1.7	1.7	0.0	1.7	1.7	0.0
7	-	supply fan	0.25	HP	1800 RPM @ 60Hz	1	1	0	1	1	0.48	0.9	0.9	0.0	0.9	0.9	0.0
8	-	exhaust fan	0.33	HP	1800 RPM @ 60Hz	1	1	0	1	1	0.48	0.9	0.9	0.0	0.9	0.9	0.0
9	-	VSA/TDA system	2	HP	1800 RPM @ 60Hz	1	1	0	1	1	0.48	2.8	2.8	0.0	2.8	2.8	0.0
10	-	storage sphere blower + controls	10	FLA	1800 RPM @ 60Hz	1	1	0	1.25	1	0.48	8.3	8.3	0.0	10.4	10.4	0.0
11	-	15 kva XFMR for conex trailer	31	FLA	1800 RPM @ 60Hz	1	0.75	0	1.25	1	0.48	25.8	19.3	0.0	32.3	24.1	0.0
		SPARE CAPACITY	0	%								0.0	0.0	0.0	0.0	0.0	0.0
TOTAL		**DP-A at trailer**									**0.48**	**139.7**	**117.0**	**0.0**	**172.1**	**143.7**	**0.0**
		CONNECTED LOAD				STARTER		LARGEST MOTOR					MIN BREAKER TRIP =				218.6
		LARGEST MOTOR CONNECTED	2	HP		FV		MAX BREAKER TRIP =			15 A		MIN FEEDER AMPS =				207.9
		TOTAL MOTOR HP	7	HP				MAIN BREAKER		80 %		RATED	MAX BREAKER TRIP =				225.0
		TOTAL VFD LOAD	0	KVA													
		DEMAND LOAD				STARTER		LARGEST MOTOR					MIN BREAKER TRIP =				184.4
		LARGEST MOTOR CONNECTED	2	HP		FV		MAX BREAKER TRIP =			15 A		MIN FEEDER AMPS =				173.7
		TOTAL MOTOR HP	7	HP				MAIN BREAKER		80 %		RATED	MAX BREAKER TRIP =				200.0
		TOTAL VFD LOAD	0	KVA													
		EMERGENCY LOAD				STARTER		LARGEST MOTOR					MIN BREAKER TRIP =				0.0
		LARGEST MOTOR CONNECTED	0	HP		FV		MAX BREAKER TRIP =			0 A		MIN FEEDER AMPS =				0.0
		TOTAL MOTOR HP	0	HP				MAIN BREAKER		80 %		RATED	MAX BREAKER TRIP =				0.0
		TOTAL VFD LOAD	0	KVA													
		COMMENTS:															

NOTES:

1. SEE SHEET E-4 FOR GENERAL AND SHEET NOTES.


3/16" = 1'- 0"
4 0 4 8
NEMA 7
PROCESS AREA
NEMA 1
CONTROL AREA
INSIDE TRAILER
NEMA 3R
OUTSIDE TRAILER
UNO
NEMA 7
EXHAUST STREAM
5-FT RADIUS
ALL AROUND
3
1
5'-0"
2

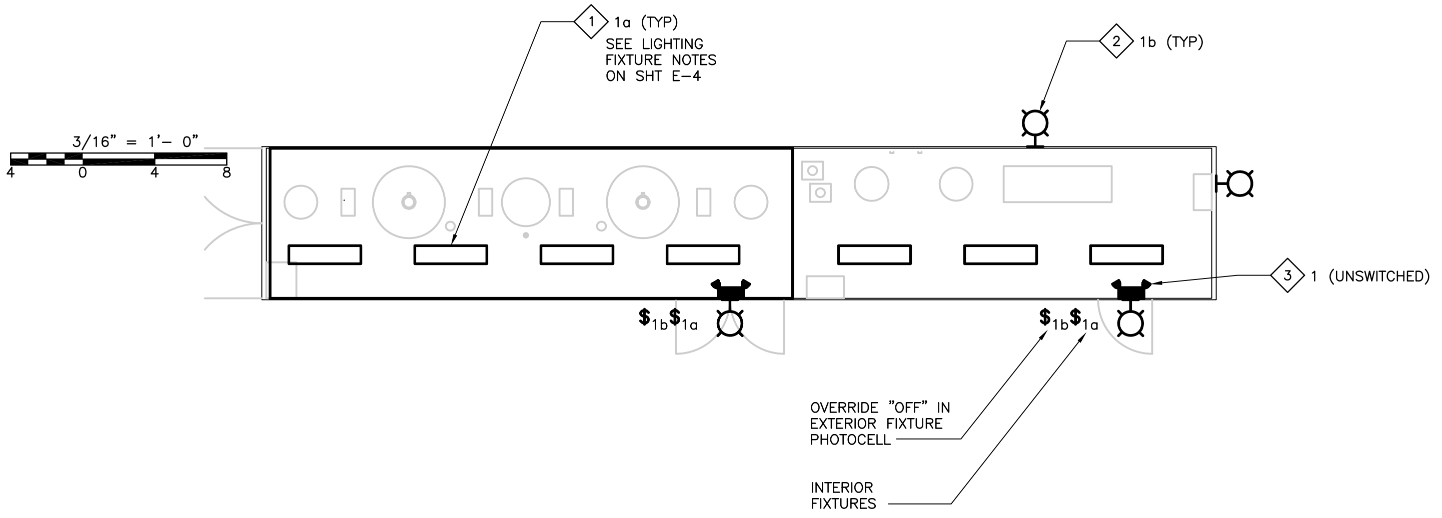
① CLASS I, DIV 1, GRP C&D: LEFT SIDE OF TRAILER FALSE WALL

② UNCLASSIFIED: REMAINDER OF TRAILER

③ CLASS I, DIV 2, GRP C&D: 5-FT RADIUS AROUND EXHAUST FAN OUTLET

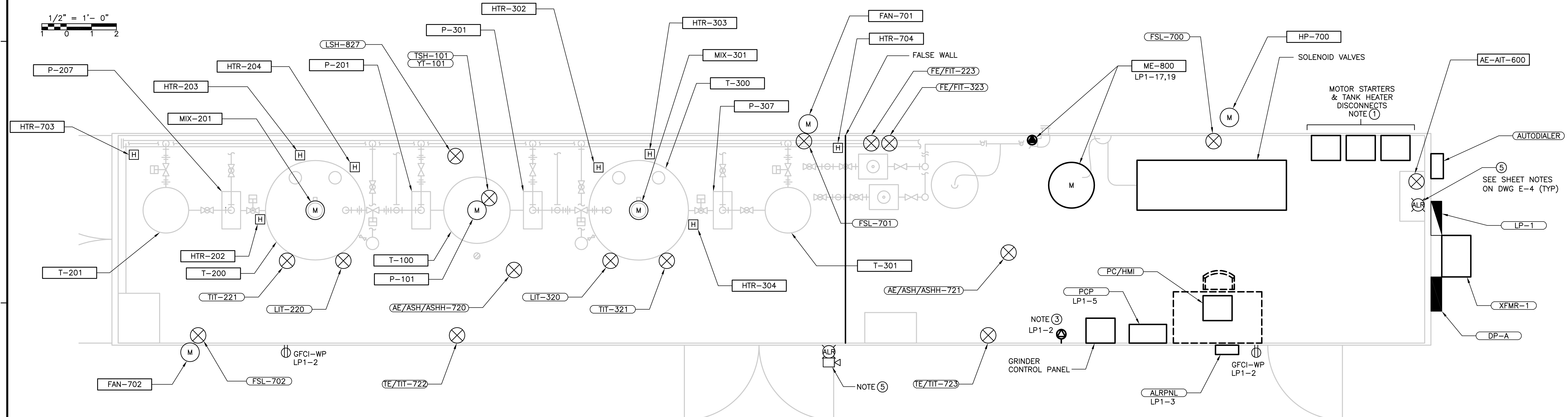
ELECTRICAL CLASSIFICATION PLAN

3/16" = 1'-0"


1 1a (TYP)
SEE LIGHTING
FIXTURE NOTES
ON SHT E-4
2 1b (TYP)
3/16" = 1'- 0"
4 0 4 8
3 1 (UNSWITCHED)
$1b$1a
$1b$1a
OVERRIDE "OFF" IN
EXTERIOR FIXTURE
PHOTOCELL
INTERIOR
FIXTURES

LIGHTING PLAN

3/16" = 1'-0"


1/2" = 1'- 0"
1 0 1 2
HTR-302
P-301
HTR-303
FAN-701
LSH-827
TSH-101
YT-101
MIX-301
HTR-704
P-207
HTR-204
P-201
T-300
FALSE WALL
FE/FIT-223
FE/FIT-323
FSL-700
HP-700
SOLENOID VALVES
ME-800
LP1-17,19
AE-AIT-600
HTR-203
P-307
MOTOR STARTERS
& TANK HEATER
DISCONNECTS
NOTE 1
MIX-201
HTR-703
AUTODIALER
5
SEE SHEET NOTES
ON DWG E-4 (TYP)
M
H
ALR
FSL-701
LP-1
HTR-202
T-100
T-301
T-200
P-101
HTR-304
T-201
PC/HMI
AE/ASH/ASHH-721
PCP
LP1-5
TIT-221
LIT-220
AE/ASH/ASHH-720
LIT-320
TIT-321
XFMR-1
NOTE 3
LP1-2
DP-A
GFCI-WP
LP1-2
GRINDER
CONTROL PANEL
GFCI-WP
LP1-2
FAN-702
FSL-702
TE/TIT-722
NOTE 5
TE/TIT-723
ALRPNL
LP1-3

POWER & INSTRUMENT PLAN

1/2" = 1'-0"

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REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: RRR
DRAWN BY: JAW
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: AUGUST 2012

LINE IS 1 INCH
AT FULL SIZE
(34X22)
SCALE ACCORDINGLY

CDM
Camp Dresser & McKee Inc.
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Seattle, CA 98101
Phone: 206-336-4900
consulting • engineering • construction • operations

Renewable Energy Production from
DoD Installation Solid Waste by
Anaerobic Digestion

PILOT EQUIPMENT
ELECTRICAL PLANS

PROJECT NO. 50957-73968
FILE NAME: E003
DRAWING NO.
E-3
SHEET NO.
OF 28

GENERAL NOTES

1. REMOVE ALL EXISTING ELECTRICAL ITEMS (NOT SHOWN) FROM THE TRAILER. EQUIPMENT REMOVED SHALL BECOME THE CONTRACTOR’S PROPERTY AND SHALL BE DISPOSED OF OFF THE SITE BY THE CONTRACTOR
2. PROVIDE ALL LABOR, MATERIALS, EQUIPMENT, TOOLS, APPURTENANCES, AND TESTING NECESSARY FOR COMPLETE AND PROPERLY OPERATING ELECTRICAL/INSTRUMENTATION SYSTEM AS INDICATED ON THE DRAWINGS. ALL MATERIAL THAT CAN REASONABLY INFERRED TO BE A PART OF THE ELECTRICAL AND INSTRUMENTATION SYSTEMS AND NECESSARY TO ITS PROPER OPERATION SHALL BE FURNISHED AND INSTALLED WHETHER OR NOT SPECIFICALLY CALLED OUT ON THE DRAWINGS.
3. MATERIALS AND EQUIPMENT FURNISHED UNDER THIS CONTRACT SHALL BE NEW. PROVIDE UL LABELED OR LISTED MATERIALS WHERE UL STANDARDS APPLY. WORK AND MATERIALS SHALL BE IN ACCORDANCE WITH NFPA AND NATIONAL ELECTRICAL CODE.
4. EQUIPMENT, MATERIALS AND INSTALLATION IN AREAS DESIGNATED AS HAZARDOUS ON THE DRAWINGS SHALL COMPLY WITH NEC ARTICLES 500, 501, AND 502. EQUIPMENT AND MATERIALS INSTALLED IN HAZARDOUS AREAS SHALL BE UL LISTED FOR THE APPROPRIATE HAZARDOUS AREA CLASSIFICATION
5. UNLESS SPECIFICALLY DIMENSIONED, THE DRAWINGS ARE NOT INTENDED TO SHOW THE EXACT INSTALLATION LOCATIONS OF CONDUIT OR EQUIPMENT. COORDINATE THE INSTALLATION WITH OTHER TRADES AND THE ACTUAL SUPPLIED EQUIPMENT.
6. TEST SYSTEMS AND EQUIPMENT AND REPAIR OR REPLACE ALL DEFECTIVE WORK AND EQUIPMENT AT NO ADDITIONAL COST TO THE OWNER. TESTS SHALL INCLUDE THE FOLLOWING:
    - a. CHECK AND RECORD THE FULL LOAD CURRENT DRAW OF EACH MOTOR. CHECK MOTOR NAMEPLATES FOR CORRECT PHASE AND VOLTAGE. CHECK ROTATION OF MOTORS PRIOR TO TESTING THE DRIVEN LOAD.
    - b. CHECK AMPERE RATING OF THERMAL OVERLOADS FOR MOTORS.
    - c. CHECK SETTINGS OF THE MOTOR CIRCUIT PROTECTORS. ADJUST SETTINGS TO LOWEST SETTING THAT WILL ALLOW THE MOTOR TO BE STARTED WHEN UNDER LOAD CONDITIONS’
    - d. CHECK INTERLOCKING, CONTROL AND INSTRUMENT WIRING FOR EACH SYSTEM AND/OR PART OF A SYSTEM TO PROVE THAT THE SYSTEM WILL FUNCTION PROPERLY AS INDICATED BY CONTROL SCHEMATIC AND WIRING DIAGRAMS.
    - e. MEGGER TEST ALL LOW VOLTAGE POWER SYSTEM CABLE. MINIMUM WIRE INSULATION RESISTANCE SHALL NOT BE LESS THAN 250 MEGOHMS.
    - f. CHECK OPERATION OF THE PCP UPS AND THE AUTO–DIALER BATTERY BACKUP FOR OPERATION UNDER POWER FAIL CONDITIONS.
    - g. SUBMIT WRITTEN TEST RESULTS
7. IDENTIFY MOTOR STARTERS, CONTROL STATIONS, ETC. WITH THE NAME OF THE EQUIPMENT IT SERVES. CONTROL PANELS, PANELBOARDS, ETC, SHALL HAVE NAMEPLATE DESIGNATIONS AS SHOWN ON THE DRAWINGS. PROVIDE ANSI Z535.4 COMPLIANT WARNING SIGNS FOR POWER EQUIPMENT.
8. CONDUIT AND CONDUIT FITTINGS NOTES:
    - a. CONDUIT SHALL BE GALVANIZED RIGID STEEL CONSISTING OF HEAVY WALL STEEL TUBING WITH A HOT–DIPPED GALVANIZED FINISH INSIDE AND OUT AFTER THREADING AND SHALL COMPLY WITH ANSI C 80.1 AND UL/6. LIQUID–TIGHT FLEXIBLE METAL CONDUIT SHALL BE USED FOR ALL MOTOR TERMINATIONS, THE PRIMARY AND SECONDARY OF TRANSFORMERS, AND OTHER EQUIPMENT WHERE VIBRATION IS PRESENT OR MAY REQUIRE REMOVAL. THE LENGTH OF LIQUID–TIGHT FLEXIBLE METAL CONDUIT SHALL NOT EXCEED 36”. LIQUID–TIGHT FLEXIBLE METAL CONDUIT SHALL BE SQUARE LOCKED, GALVANIZED STEEL FLEXIBLE CONDUIT WITH A MOISTURE PROOF, FLAME RESISTANT, POLYVINYL CHLORIDE JACKET, FOR USE WITH RIGID METAL CONDUIT SYSTEMS. SEALTITE, TYPE UA, OR EQUAL.
    - b. CONDUIT SEALING AND DRAIN FITTINGS SHALL BE INSTALLED IN THE HAZARDOUS (CLASSIFIED) AREAS DESIGNATED CLASS 1, DIVISION 1, AND CLASS 1, DIVISION 2 AS REQUIRED BY NEC ARTICLE 501 AND 502. CONDUITS TERMINATING AT BOXES ENCLOSING CIRCUIT OPENING EQUIPMENT SHALL BE SEALED AT THE ENTRANCE TO THE ENCLOSURE WITH APPROVED COMPOUND FILLED SEALING FITTINGS TO PREVENT PASSAGE OF EXPLOSIVE OR COMBUSTIBLE GASES THROUGH THE CONDUITS. ALL CONDUITS LEADING FROM OR ENTERING HAZARDOUS LOCATIONS SHALL BE SIMILARLY SEALED AT POINTS OF EXIT OR ENTRANCE. EXPOSED CONDUITS PASSING THROUGH HAZARDOUS LOCATIONS SHALL BE SEALED AT BOTH THE ENTRANCE TO AND THE EXIT FROM THE HAZARDOUS LOCATIONS. SEAL FITTINGS SHALL BE APPLETON “EYS” TYPE OR EQUAL WITH APPROVED SEALING COMPOUND.
    - c. DRAWINGS DO NOT SHOW CONDUIT RUNS. PROVIDE AS REQUIRED BY THE SINGLE LINES, INTERCONNECTION DIAGRAM, PANEL SCHEDULE AND GENERAL NOTES. COORDINATE CONDUIT INSTALLATION WITH OTHER TRADES AND THE ACTUAL SUPPLIED EQUIPMENT. PROVIDE ALL NECESSARY FITTINGS, SUPPORTS, AND BOXES FOR A COMPLETE RACEWAY INSTALLATION.
    - d. WALL OPENINGS SHALL BE SEALED WITH A UL APPROVED EXPENDING MATERIAL TO PROVIDE WEATHER TIGHT SEAL.
    - e. EXPLOSION PROOF BOXES SHALL BE DESIGNED FOR THE SPECIFIC HAZARDOUS LOCATIONS SHOWN ON THE DRAWINGS. THEY SHALL BE CAST IRON WITH CADMIUM ZINC OR HOT DIPPED GALVANIZED FINISH, STAINLESS STEEL OR HOT DIPPED GALVANIZED BOLTS; TYPE EJB OR EJB_N4 AS MANUFACTURED BY THE CROUSE HINDS COMPANY; APPLETON ELECTRIC CO,. OR EQUAL.
    - f. NO CONDUIT SMALLER THAN 3/4 INCH ELECTRICAL TRADE SIZE SHALL BE USED, NOR SHALL ANY HAVE MORE THAN THE EQUIVALENT OF THREE 90 DEGREE BENDS IN ANY ONE RUN.
9. WIRE AND CABLE NOTES:
    - a. ALL WIRE SHALL BE INSTALLED IN CONDUIT.
    - b. WIRES AND CABLES SHALL BE OF ANNEALED, 98 PERCENT CONDUCTIVITY, SOFT DRAWN COPPER. ALL CONDUCTORS SHALL BE STRANDED, EXCEPT THAT LIGHTING AND RECEPTACLE WIRING MAY BE SOLID. SHALL HAVE 600 VOLT INSULATION EXCEPT WHERE INDICATED OTHERWISE.
    - c. EXCEPT FOR CONTROL, SIGNAL AND INSTRUMENTATION CIRCUITS, WIRE SMALLER THAN NO. 12 AWG SHALL NOT BE USED.
    - d. POWER WIRE SHALL BE NEC TYPE XHHW OR XHHW–2.
    - e. CONTROL, STATUS AND ALARM WIRE SHALL BE NO.14 AWG NEC TYPE THWN.
    - f. WIRE FOR PROCESS INSTRUMENTATION SIGNALS (I.E. 1–5 VDC, 4–20 MADC), R.T.D., POTENTIOMETER AND SIMILAR SIGNALS SHALL BE SINGLE PAIR CABLE: 2 NO. 16 STRANDED AND TWISTED CONDUCTORS ON 2 IN LAY, 100% ALUMINUM/POLYESTER FOIL SHIELD WITH DRAIN WIRE, PVC JACKET. BELDEN NO. 1030A OR EQUAL.
    - g. WIRE SHALL BE COLOR CODED OR CODED USING ELECTRICAL TAPE, FOLLOWING UL COLOR CODING SCHEME.
    - h. SHIELDED INSTRUMENTATION WIRE AND CONTROL CONDUCTORS SHALL BE RUN WITHOUT SPLICES BETWEEN INSTRUMENTS, TERMINAL BOXES, OR PANELS. TERMINAL BLOCKS SHALL BE PROVIDED FOR ALL INSTRUMENT AND CONTROL CABLE TERMINATIONS. GROUND SHIELD ON INSTRUMENTATION WIRES AT ONE END ONLY AS RECOMMENDED BY THE INSTRUMENT MANUFACTURER AND ISOLATED AT ALL OTHER LOCATIONS. TERMINAL BLOCKS SHALL BE PROVIDED FOR INTER_CONNECTING SHIELD DRAIN WIRES AT ALL JUNCTION BOXES. WHERE INDIVIDUAL CIRCUIT SHIELDING IS REQUIRED, EACH SHIELD CIRCUIT SHALL BE PROVIDED WITH ITS OWN BLOCK.
    - i. INSTALL EACH 480 VOLT FEED IN ITS OWN CONDUIT.
    - j. 120 VOLT CONDUCTORS MAY BE GROUPED INTO MULTI WIRE HOMERUNS OF UP TO 3 CIRCUITS.
    - k. CONTROL WIRES MAY BE GROUPED INTO MULTI WIRE HOMERUNS BUT MAY NOT BE MIXED WITH OTHER SIGNAL OR POWER CONDUCTORS.
    - l. INSTRUMENTATION LOW VOLTAGE SIGNAL CABLES MAY BE GROUPED INTO MULTI CIRCUIT HOMERUNS BUT MAY NOT BE MIXED WITH OTHER CONTROL OR POWER CONDUCTORS.

GENERAL NOTES (CONTD)

10. CONTROL PANEL NOTES:
    - a. EACH CONTROL PANEL SHALL BEAR THE UL LABEL. THE UL LABEL SHALL APPLY TO THE ENCLOSURE, THE SPECIFIC EQUIPMENT SUPPLIED WITH THE ENCLOSURE, AND THE INSTALLATION AND WIRING OF THE EQUIPMENT WITHIN AND ON THE ENCLOSURE.
    - b. ALL COMPONENTS SHALL BE MOUNTED IN A MANNER THAT SHALL PERMIT SERVICING, ADJUSTMENT, TESTING, AND REMOVAL WITHOUT DISCONNECTING, MOVING, OR REMOVING ANY OTHER COMPONENT. COMPONENTS MOUNTED ON THE INSIDE OF PANELS SHALL BE MOUNTED ON REMOVABLE PLATES UNLESS NOTED. COMPONENT MOUNTING SHALL BE ORIENTED IN ACCORDANCE WITH MANUFACTURER’S RECOMMENDATIONS. THE INTERNAL COMPONENTS SHALL BE IDENTIFIED WITH SUITABLE PLASTIC OR METAL ENGRAVED NAMETAGS MOUNTED ADJACENT TO EACH COMPONENT IDENTIFYING THE COMPONENT IN ACCORDANCE WITH THE DRAWINGS.
    - c. ALL PANELS IN OUTDOOR ENVIRONMENTS SHALL BE NEMA 4X UNLESS OTHERWISE NOTED. ALL PANELS LOCATED IN A HAZARDOUS LOCATION SHALL BE RATED FOR THE TYPE OF HAZARD (E.G., NEMA 7 FOR CLASS 1, DIVISION 2). ENCLOSURES SHALL BE SIZED AS REQUIRED FOR THE COMPONENTS INSTALLED.
    - d. EXPLOSION PROOF PANELS SHALL BE GASKETED CAST ALUMINUM CONTROL CENTERS, FACTORY INSTALLED COVER MOUNTED CONTROL DEVICES AND FACTORY TAPPED FOR THE CONDUIT ENTRIES REQUIRED. APPLETON ACSEW OR EQUAL.
    - e. POWER DISTRIBUTION WIRING ON THE LINE SIDE OF FUSES OR BREAKERS SHALL BE 12 AWG MINIMUM. CONTROL WIRING ON THE SECONDARY SIDE OF FUSES SHALL BE 16 AWG MINIMUM. ELECTRONIC ANALOG CIRCUITS SHALL UTILIZE 18 AWG SHIELDED, TWISTED PAIR, CABLE INSULATED FOR NOT LESS THAN 600 VOLTS.
    - f. POWER AND LOW VOLTAGE DC WIRING SYSTEMS SHALL BE ROUTED IN SEPARATE WIREWAYS. WIRING TROUGHS SHALL NOT BE FILLED TO MORE THAN 60 PERCENT VISIBLE FILL.
    - g. DIFFERENT WIRING SYSTEMS SHALL TERMINATE ON SEPARATE TERMINAL BLOCK.TERMINAL BLOCKS SHALL BE ARRANGED IN VERTICAL ROWS AND SEPARATED INTO GROUPS (POWER, AC CONTROL, DC SIGNAL). ONLY ONE SIDE OF A TERMINAL BLOCK ROW SHALL BE USED FOR INTERNAL WIRING.
    - h. EACH PANEL SHALL BE PROVIDED WITH A CIRCUIT BREAKER TO INTERRUPT INCOMING POWER.
    - i. PILOT TYPE INDICATING LIGHTS SHALL BE PUSH TO TEST TYPE, PROVIDED WITH LOW VOLTAGE LED LAMPS SUITABLE FOR THE VOLTAGE SUPPLIED, NEMA RATING TO MAINTAIN OVERALL PANEL RATING.PROVIDE NAMEPLATES AS SHOWN ON THE DRAWINGS.
    - j. SELECTOR SWITCHES AND PUSHBUTTONS: HEAVY–DUTY, FULL SIZE TYPE WITH CONTACT ARRANGEMENT AND SWITCHING ACTION AS REQUIRED, NEMA RATING TO MAINTAIN OVERALL PANEL RATING. PROVIDE NAMEPLATES AS SHOWN ON THE DRAWINGS
    - k. GENERAL PURPOSE RELAYS AND TIME DELAY RELAYS: PLUG_IN TYPE, VOLTAGE RATING AND CONTACT ARRANGEMENT/FUNCTION AS REQUIRED, RATED FOR CONTINUOUS OPERATION. IDEC OR EQUAL.
    - l. PROVIDE CORROSION INHIBITORS IN ALL OUTDOOR PANELS AND ENCLOSURES

SHEET NOTES (DRAWING E–3)

① BOLTED COMBINATION MOTOR STARTERS AND TANK HEATER DISCONNECTS AS SHOWN ON THE SINGLE LINE. MOUNT IN 2 ROWS SO THAT THE OPERATING HANDLES ARE NOT HIGHER THAN 6 FT ABOVE FLOOR. STARTERS SHALL BE EXPLOSION PROOF, CAST ALUMINUM, WITH MOTOR CIRCUIT PROTECTOR UTILIZING A COVER MOUNTED, PAD LOCKABLE BREAKER OPERATOR INTERLOCKED WITH THE COVER DOOR. SEPARATE FUSED 120 VOLT CONTROL CIRCUIT IN PANEL PCP WILL BE USED. NO PILOT DEVICES REQUIRED. APPLETON AEB SERIES OR EQUAL. TANK HEATER DISCONNECTS ARE DESCRIBED ON DWG E–5.

② TEMPORARY LOCATION FOR COMPRESSOR AND COMPRESSOR RECEPTACLE INSIDE TRAILER FOR TRANSPORT AND TESTING. COMPRESSOR AND RECEPTACLE TO BE RELOCATED OUTSIDE TRAILER BEFORE PILOT PLANT OPERATION. RECEPTACLE TO BE SIMPLEX, 20A, 2W3P, 250 VOLT, NON–HAZARDOUS, HEAVY DUTY, NEMA 4X WATER TIGHT, MECHANICALLY INTERLOCKED, WITH BACK BOX. COOPER–CROUSE HINDS GH320MI6W OR EQUAL.

③ RECEPTACLE FOR INSIDE TRAILER: SIMPLEX, CLASS I DIV 2 GRP D RATED, DEAD FRONT, SPRING DOOR, INTERLOCKED CIRCUIT BREAKING TYPE, 15A, 125 V, COOPER–CROUSE HINDS ENR5151 OR EQUAL WITH BACK BOX AND MATCHING PLUG.

④ OUTDOOR RECEPTACLES: SPECIFICATION GRADE, WEATHER RESISTANT, DUPLEX, 15A, 125V, GFCI TYPE WITH HEAVY DUTY, DIE CAST ALUMINUM WP WHILE IN USE COVER, T&B RED DOT CODE KEEPER WET LOCATION COVER AND BACK BOX, OR EQUAL.

⑤ ALARM BEACONS AND HORN FOR COMBUSTIBLE GAS LEAK/VENTILATION FAILURE NOTIFICATION. INDOOR UNIT SHALL BE EXPLOSION PROOF BEACON ONLY, CLASS I DIV 2 GRP D RATED, WITH STROBE TUBE; FEDERAL SIGNAL FIREBALL 2 OR EQUAL. PROVIDE A NAMEPLATE ON WALL BELOW: “ALARM LIGHT INDICATES COMBUSTIBLE GAS LEAK/VENTILATION FAILURE”. OUTDOOR UNIT SHALL BE COMBINATION STROBE BEACON AND HORN UNIT, NEMA 4X, FEDERAL SIGNAL STREAMLINE LOW PROFILE OR EQUAL. : “ALARM LIGHT INDICATES COMBUSTIBLE GAS LEAK/VENTILATION FAILURE. DO NOT ENTER”. BOTH UNITS SHALL BE WALL MOUNT TYPE, 12 VDC, WITH AMBER LENS.

⑥ PILOT CONTROL PANEL “PCP”: COMPLY WITH CONTROL PANEL SPECIFICATIONS UNDER “GENERAL NOTES”. COVER MOUNTED PILOT DEVICES ARE SHOWN ON THE PIDS AND CONTROL SCHEMATIC DIAGRAMS. INTERIOR DEVICES, INCLUDING RELAYS AND THE PLC, SHALL BE AS SHOWN ON THE INTERCONNECT AND CONTROL SCHEMATIC DIAGRAMS AND AS REQUIRED BY THE SPECIFICATION NOTES. EXPLOSION PROOF ENCLOSURE SHALL BE APPROXIMATELY 48”HX24”WX12”D, AS REQUIRED.

⑦ COMBUSTIBLE GAS LEAK/VENTILATION FAILURE ALARM PANEL “ALR PNL”: COMPLY WITH CONTROL PANEL SPECIFICATIONS UNDER “GENERAL NOTES”. COVER MOUNTED PILOT DEVICES AND INTERIOR DEVICES, INCLUDING RELAYS AND UPS FOR POWER BACKUP, SHALL BE AS SHOWN ON CONTROL SCHEMATIC DIAGRAM AND AS REQUIRED BY THE SPECIFICATION NOTES. ARRANGE INTERNAL DEVICES TO MINIMIZE PANEL DEPTH. HINGE COVER, STEEL NEMA 3R ENCLOSURE SHALL BE APPROXIMATELY 24”HX20”WX8”D, AS REQUIRED. HOFFMAN OR EQUAL.

LIGHTING FIXTURE NOTES (DRAWING E–3)

1. EXPLOSION PROOF FLUORESCENT FIXTURE, CLASS I DIV 1GRP D RATED, 120 V, NOMINAL 12”X48”, 2–32 WATT LAMPS, ELECTRONIC BALLAST, COOPER–CROUSE HINDS EVF SERIES OR EQUAL.
2. CUTOFF WALLPACK FIXTURE, 120 V, 70W MH, PHOTOCELL, DIE CAST HOUSING GLASS REFRACTOR, RAB WP1C OR EQUAL.
3. COMBINATION EXIT AND EMERGENCY LIGHT, , CLASS I DIV 2GRP D RATED, 120 V, LED EXIT LIGHT WITH RED LETTERING, 2–6W HALOGEN EMERGENCY LIGHT HEADS, LEAD CALCIUM BATTERY AND SOLID STATE CHARGING SYSTEM. THE EXIT LIGHT COMPANY “COMBO–C1D2” OR EQUAL.

30% SUBMITTAL - NOT FOR CONSTRUCTION

REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: RRR
DRAWN BY: JAW
SHEET CHK’D BY:
CROSS CHK’D BY:
APPROVED BY:
DATE: APRIL 2011

LINE IS 1 INCH
AT FULL SIZE
(34X22)
SCALE ACCORDINGLY

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Renewable Energy Production from
DoD Installation Solid Waste by
Anaerobic Digestion

ELECTRICAL NOTES

PROJECT NO. 50957–73968
FILE NAME: E004
DRAWING NO.
E-4
SHEET NO.
OF 30

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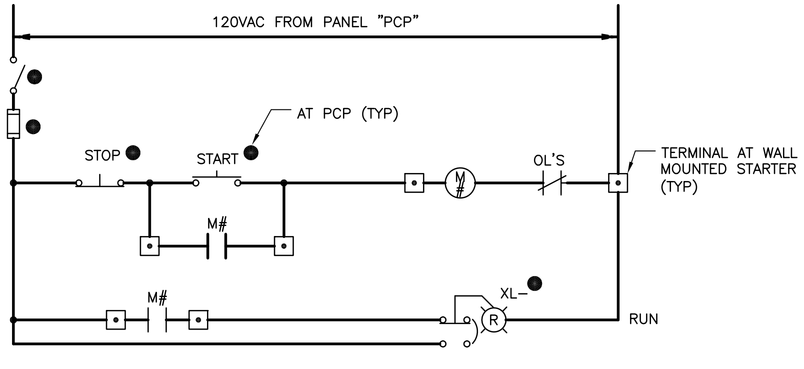
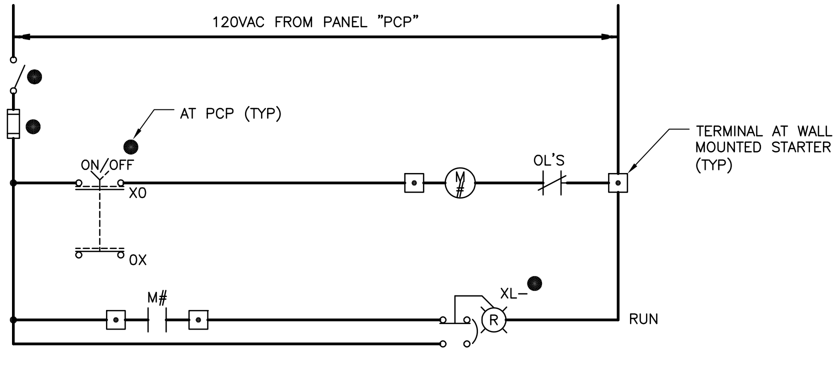

120VAC FROM PANEL "PCP"
AT PCP (TYP)
STOP
START
M#
OL'S
TERMINAL AT WALL MOUNTED STARTER (TYP)
M#
XL-
R
RUN

NOTES:

1. DEVICES WITHOUT LOCATION SYMBOL LOCATED AT WALL MOUNTED STARTER

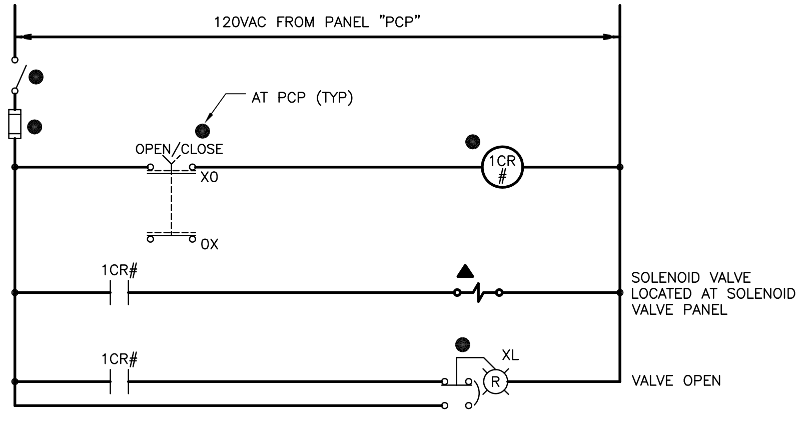
MIX–201 & 301 DIGESTER MIXERS


120VAC FROM PANEL "PCP"
AT PCP (TYP)
ON/OFF
XO
OX
M#
OL'S
TERMINAL AT WALL MOUNTED STARTER (TYP)
M#
XL-
R
RUN

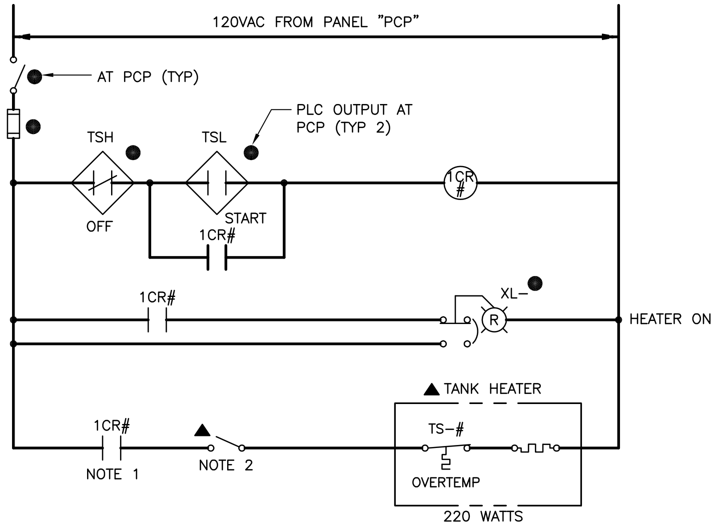
NOTES:

1. DEVICES WITHOUT LOCATION SYMBOL LOCATED AT WALL MOUNTED STARTER

EXHAUST & SUPPLY FANS


120VAC FROM PANEL "PCP"
AT PCP (TYP)
OPEN/CLOSE
XO
OX
1CR #
1CR#
SOLENOID VALVE LOCATED AT SOLENOID VALVE PANEL
1CR#
XL
R
VALVE OPEN

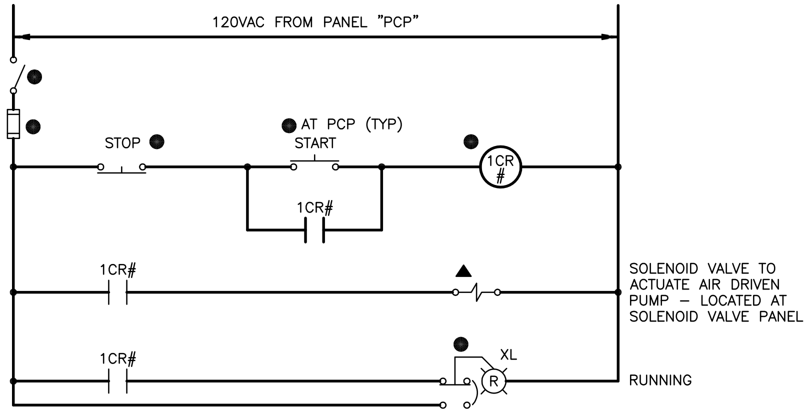
TYPICAL SOLENOID VALVE


120VAC FROM PANEL "PCP"
AT PCP (TYP)
PLC OUTPUT AT PCP (TYP 2)
TSH
TSL
OFF
START
1CR#
1CR #
1CR#
XL-
R
HEATER ON
TANK HEATER
1CR#
NOTE 1
NOTE 2
TS-#
OVERTEMP
220 WATTS

DIGESTER TANK HEATERS HTR–202,203,204,302,303&304

NOTES:

1. RELAY CONTACTS RATED FOR CONTINUOUS LOAD.
2. WALL MOUNTED LOCKABLE DISCONNECT, FRONT OPERATED, FACTORY SEALED, CLASS I, DIV 2, 20 AMP, APPLETON EDS OR EQUAL.


120VAC FROM PANEL "PCP"
STOP
AT PCP (TYP)
START
1CR #
1CR#
1CR#
SOLENOID VALVE TO ACTUATE AIR DRIVEN PUMP – LOCATED AT SOLENOID VALVE PANEL
1CR#
XL
R
RUNNING

METERING PUMP P–201,207,301,307&803

REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: RRR
DRAWN BY: WKT
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: AUGUST 2012

LINE IS 1 INCH
AT FULL SIZE
(34X22)
SCALE ACCORDINGLY

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Renewable Energy Production from
DoD Installation Solid Waste by
Anaerobic Digestion

CONTROL DIAGRAMS
1 OF 2

PROJECT NO. 50957–73968
FILE NAME: E005
DRAWING NO.
E-5
SHEET NO.
OF 28

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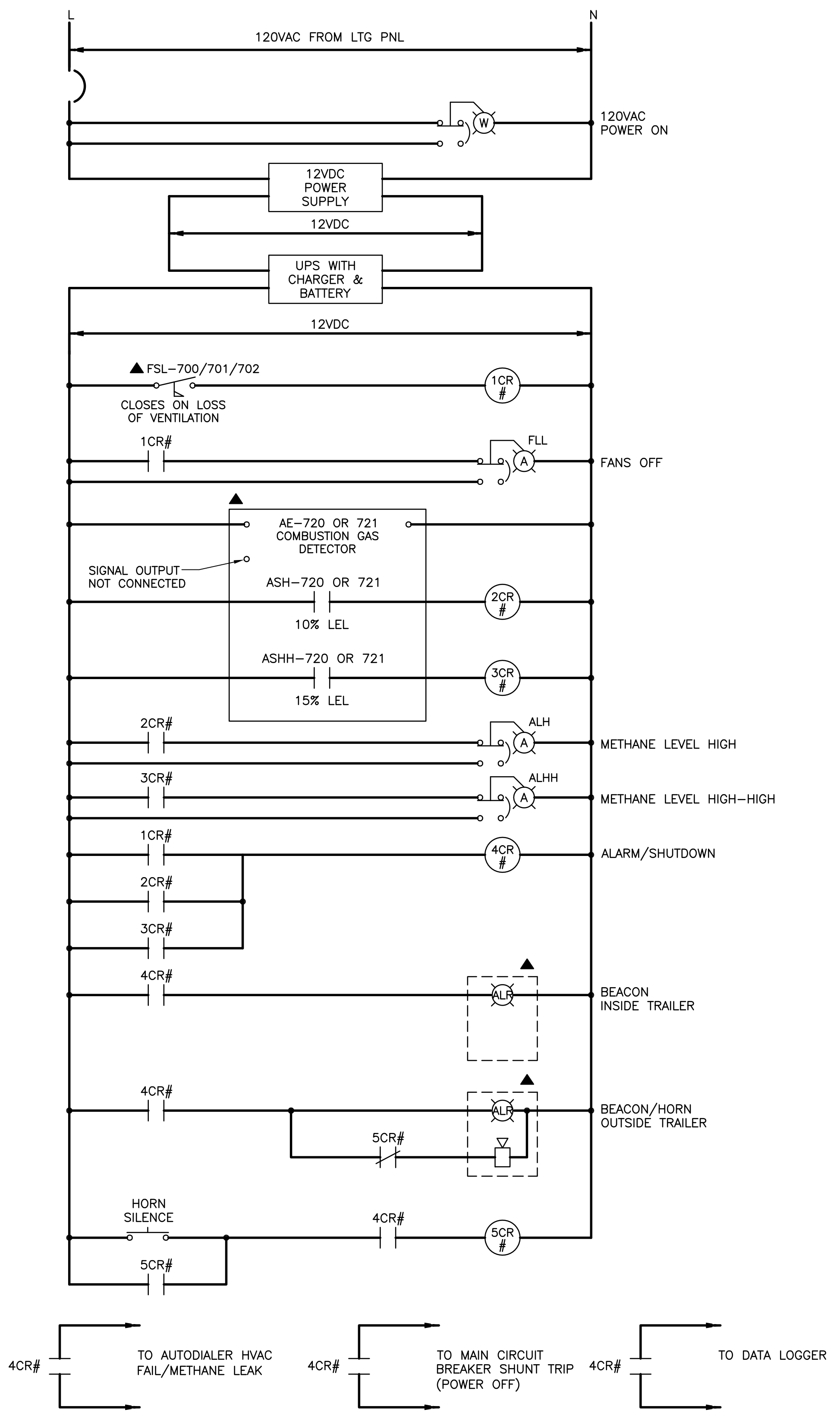
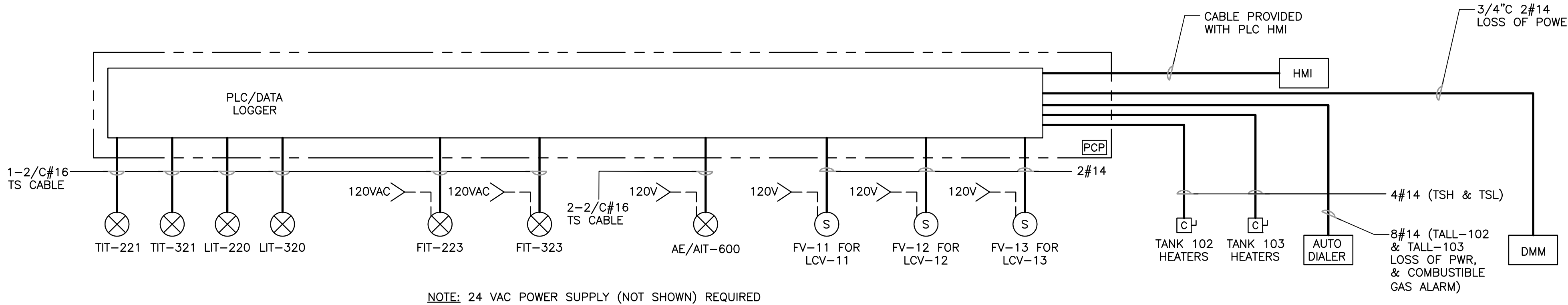

L
N
120VAC FROM LTG PNL
W
120VAC POWER ON
12VDC POWER SUPPLY
12VDC
UPS WITH CHARGER & BATTERY
12VDC
FSL-700/701/702
CLOSES ON LOSS OF VENTILATION
1CR#
1CR#
FLL
A
FANS OFF
AE-720 OR 721 COMBUSTION GAS DETECTOR
SIGNAL OUTPUT NOT CONNECTED
ASH-720 OR 721
10% LEL
2CR#
ASHH-720 OR 721
15% LEL
3CR#
2CR#
ALH
A
METHANE LEVEL HIGH
3CR#
ALHH
A
METHANE LEVEL HIGH-HIGH
1CR#
4CR#
ALARM/SHUTDOWN
2CR#
3CR#
4CR#
ALR
BEACON INSIDE TRAILER
4CR#
ALR
5CR#
BEACON/HORN OUTSIDE TRAILER
HORN SILENCE
4CR#
5CR#
5CR#
4CR#
TO AUTODIALER HVAC FAIL/METHANE LEAK
4CR#
TO MAIN CIRCUIT BREAKER SHUNT TRIP (POWER OFF)
4CR#
TO DATA LOGGER

NOTE: UNLESS OTHERWISE INDICATED, ALL DEVICES ARE LOCATED IN ALR PNL.

HVAC & COMBUSTIBLE GAS ALARM PANEL "ALR PNL"


CABLE PROVIDED WITH PLC HMI
3/4"C 2#14 LOSS OF POWER
HMI
PLC/DATA LOGGER
PCP
1-2/C#16 TS CABLE
2#14
120VAC
120VAC
2-2/C#16 TS CABLE
120V
120V
120V
120V
4#14 (TSH & TSL)
8#14 (TALL-102 & TALL-103 LOSS OF PWR, & COMBUSTIBLE GAS ALARM)
TIT-221
TIT-321
LIT-220
LIT-320
FIT-223
FIT-323
AE/AIT-600
S
FV-11 FOR LCV-11
S
FV-12 FOR LCV-12
S
FV-13 FOR LCV-13
C
TANK 102 HEATERS
C
TANK 103 HEATERS
AUTO DIALER
DMM

NOTE: 24 VAC POWER SUPPLY (NOT SHOWN) REQUIRED FOR PLC, HMI & LOOP POWERED INSTRUMENTS.

PLC INTERCONNECTION DIAGRAM

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REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: RRR
DRAWN BY: WKT
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: AUGUST 2012

LINE IS 1 INCH AT FULL SIZE (34X22) SCALE ACCORDINGLY

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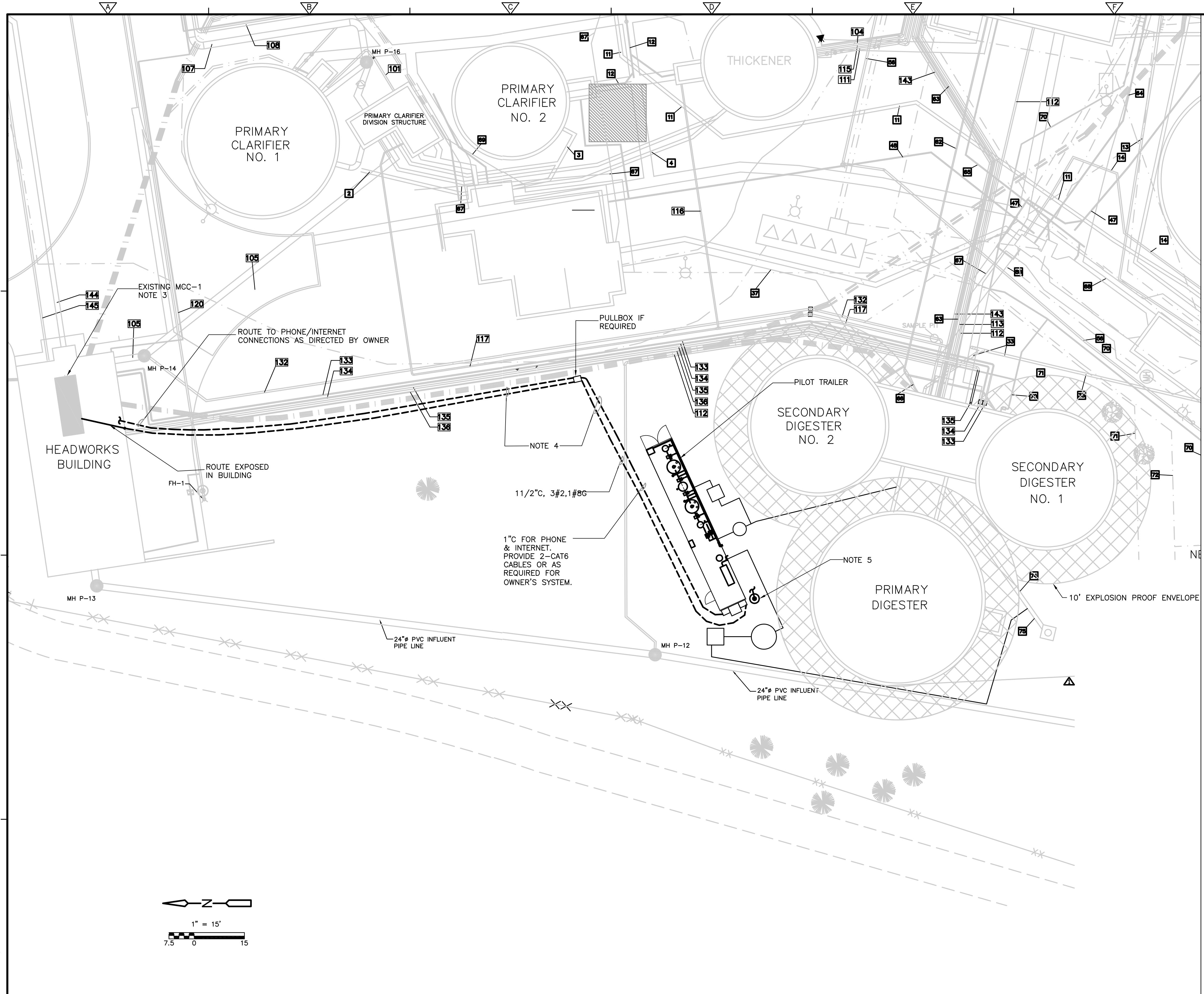
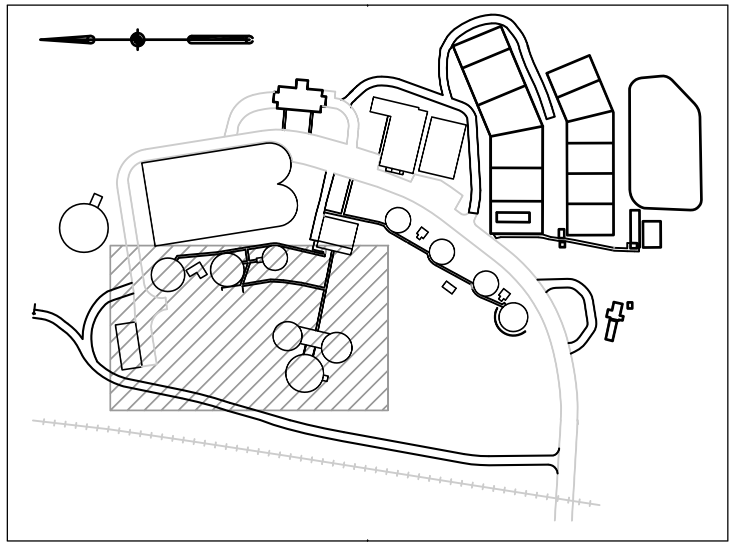
Renewable Energy Production from DoD Installation Solid Waste by Anaerobic Digestion

CONTROL DIAGRAMS
2 OF 2

PROJECT NO. 50957-73968
FILE NAME: E006
DRAWING NO.
E-6
SHEET NO.
OF 28


A
B
C
D
E
F
G
H
1
2
3
4
PRIMARY CLARIFIER NO. 1
PRIMARY CLARIFIER DIVISION STRUCTURE
PRIMARY CLARIFIER NO. 2
THICKENER
MH P-16
MH P-14
MH P-13
MH P-12
FH-1
107
108
101
104
115
111
143
112
116
105
144
145
120
117
132
133
134
135
136
137
EXISTING MCC-1 NOTE 3
ROUTE TO PHONE/INTERNET CONNECTIONS AS DIRECTED BY OWNER
PULLBOX IF REQUIRED
HEADWORKS BUILDING
ROUTE EXPOSED IN BUILDING
NOTE 4
11/2"C, 3#2,1#8G
1"C FOR PHONE & INTERNET. PROVIDE 2-CAT6 CABLES OR AS REQUIRED FOR OWNER'S SYSTEM.
PILOT TRAILER
SECONDARY DIGESTER NO. 2
SECONDARY DIGESTER NO. 1
PRIMARY DIGESTER
NOTE 5
10' EXPLOSION PROOF ENVELOPE
SAMPLE PI
24"ø PVC INFLUENT PIPE LINE
24"ø PVC INFLUENT PIPE LINE
NE
Z
1" = 15'
7.5
0
15



KEY MAP

NOTES:

1. UNDERGROUND UTILITIES ARE SHOWN BASED ON PLANT RECORD DRAWINGS WHICH REPRESENT THE BEST INFORMATION AVAILABLE. THE TYPE, SIZE, LOCATION, AND NUMBER ARE APPROXIMATE AS SHOWN BY THESE DRAWINGS.
2. PRIOR TO COMMENCEMENT OF ANY EXCAVATION, CONTRACTOR SHALL LOCATE AND MARK THE ACTUAL LOCATION OF UNDERGROUND UTILITIES.
3. PROVIDE 3 PHASE, 100AT BREAKER IN EXISTING "SPACE" AT MCC-1 FOR POWER TO PANEL DPA AT PILOT TRAILER. BREAKER TYPE & BRAND TO BE COMPATIBLE WITH EXISTING MCC.
4. SCHEDULE 40 PVC DB CONDUITS, MINIMUM 24" BELOW GRADE, SAND ENCASED. SPACE 9" APART. EXACT ROUTING TO BE DETERMINED IN FIELD. NO MORE THAN 3-90 DEGREE BENDS ALLOWED. IF ADDITINAL BENDS ARE REQUIRED, PROVIDE PULL BOX.
5. PROVIDE 3/4" X 10' COPPER GROUND ROD. EXOTHERMICALLY WELD TO #2 BARE GROUND WIRE. EXTEND GROUND WIRE TO TRAILER GROUND BUS.

LEGEND:

72 EXISTING PIPELINE LABEL
117 NEW PIPELINE LABEL
EXISTING UNDERGROUND ELECTRICAL LINES
═ EXISTING PIPELINE TO BE ABANDONED
═ EXISTING PIPELINE TO BE REUSED
═ NEW PIPELINE
▨ LIMITS OF CONCRETE PIPE ENCASEMENT
☒ ANCHORS (TYP)

REV. NO.	DATE	DRWN	CHKD	REMARKS

DESIGNED BY: RRR
DRAWN BY:
SHEET CHK'D BY:
CROSS CHK'D BY:
APPROVED BY:
DATE: APRIL 2011

LINE IS 1 INCH
AT FULL SIZE
(34X22)
SCALE ACCORDINGLY

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Renewable Energy Production from
DoD Installation Solid Waste by
Anaerobic Digestion

ELECTRICAL SITE PLAN

PROJECT NO. 50957-73968
FILE NAME: E101
DRAWING NO.
E101
SHEET NO.
OF 28

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Appendix H: Supporting Data

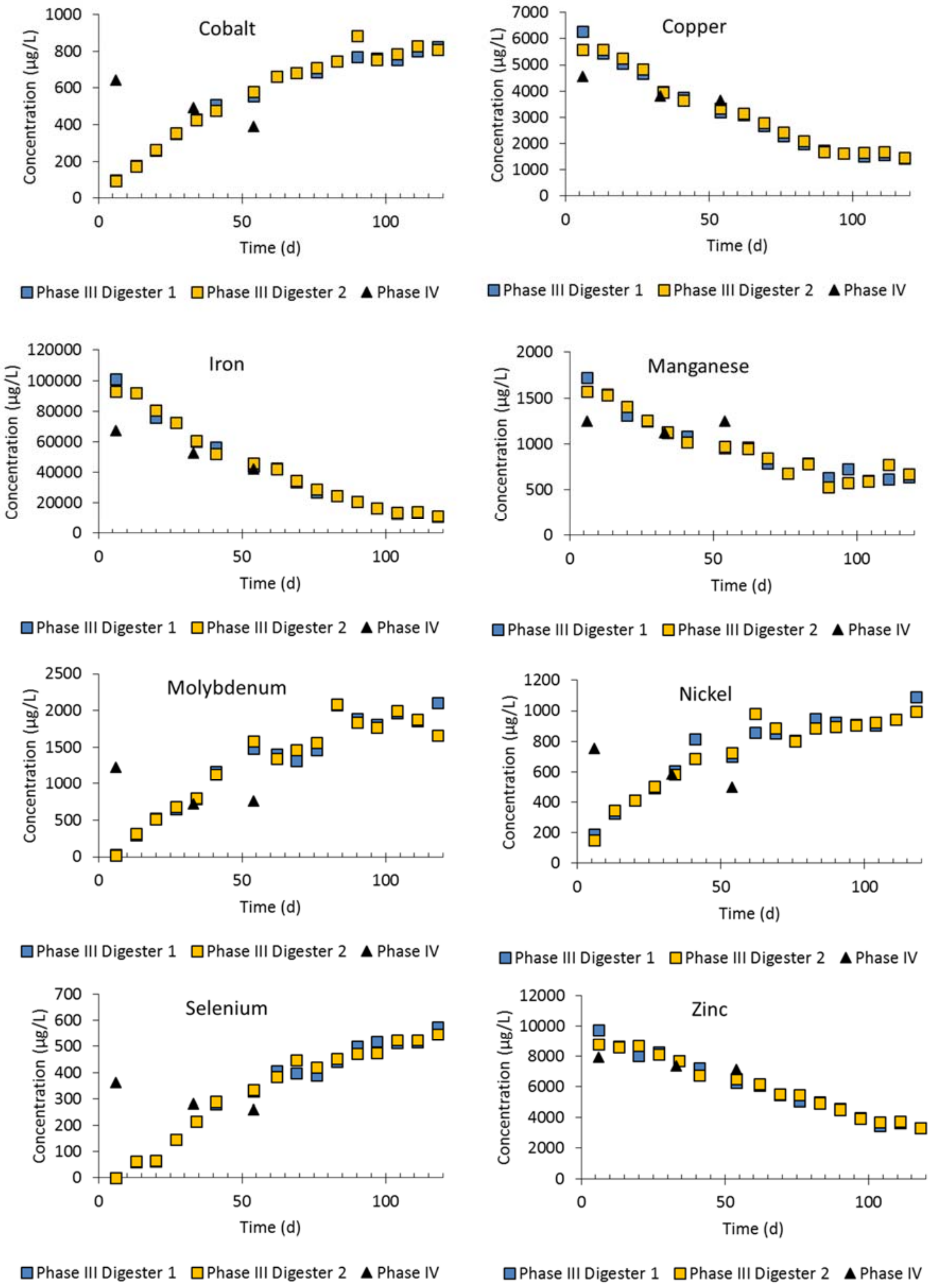


Figure 1. Measured concentrations of metals in the digestate.

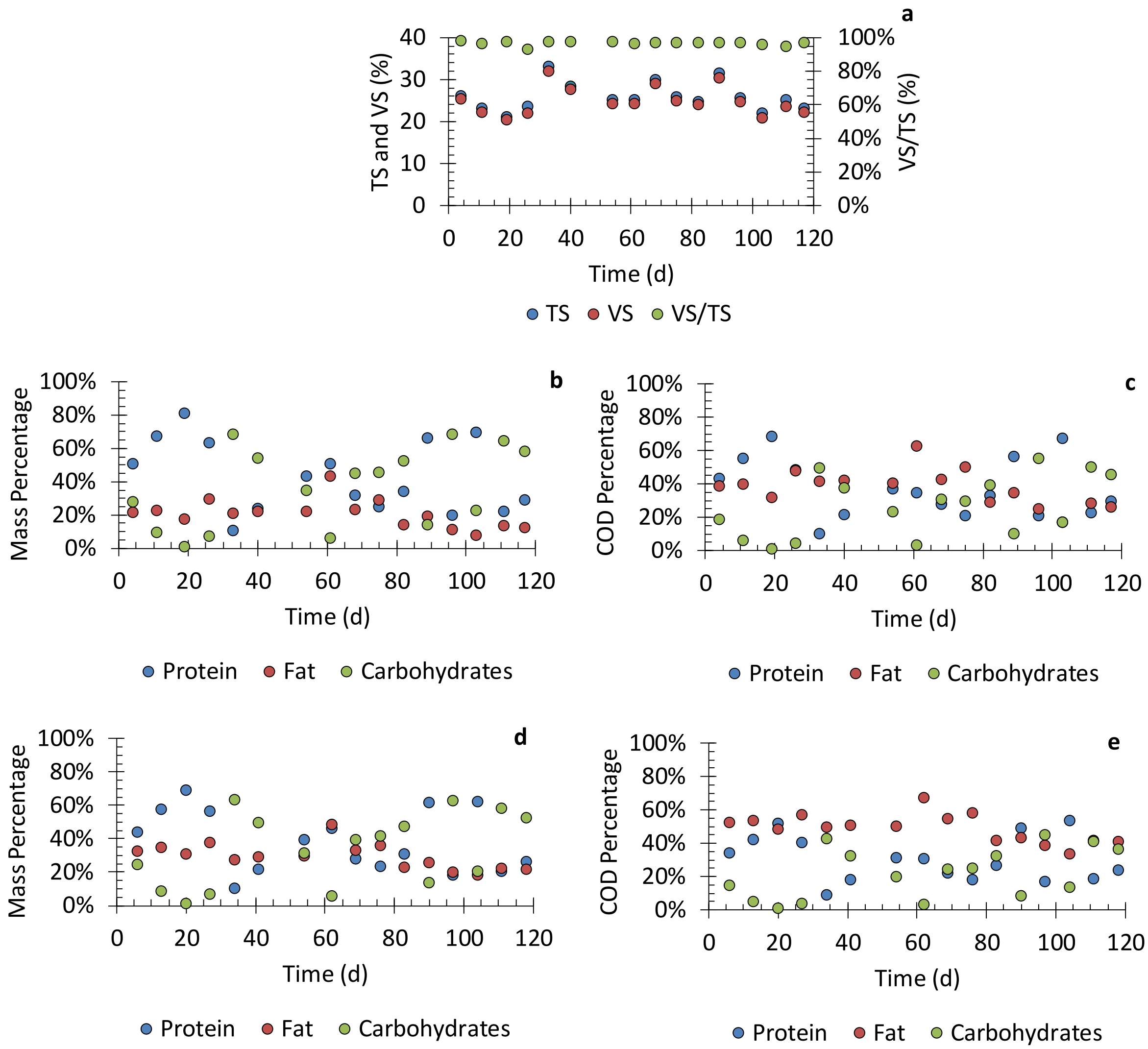


Figure 2. Food waste composition during Phases II and III after removal of foreign debris. Temporal trends are shown for total and volatile solids (a); and fat, protein, and carbohydrates in the organic fraction of food waste alone (b and c) and the food waste/canola oil mixture (d and e) on a mass basis (b and d) and a COD basis (c and e).

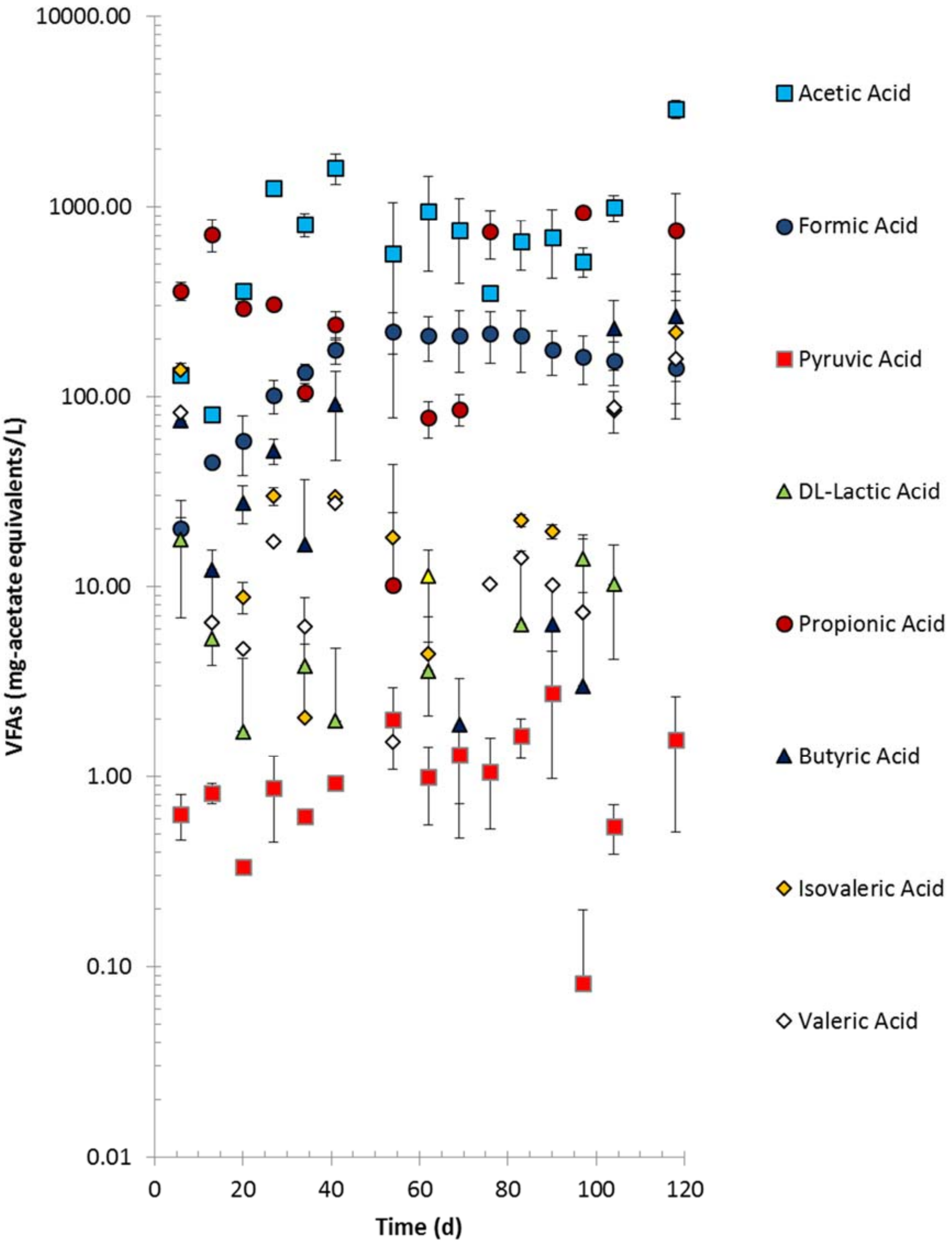


Figure 3. VFA trends during Phases II and III. Propionate data may be suspect because of matrix interferences resulting in inconsistent detections.

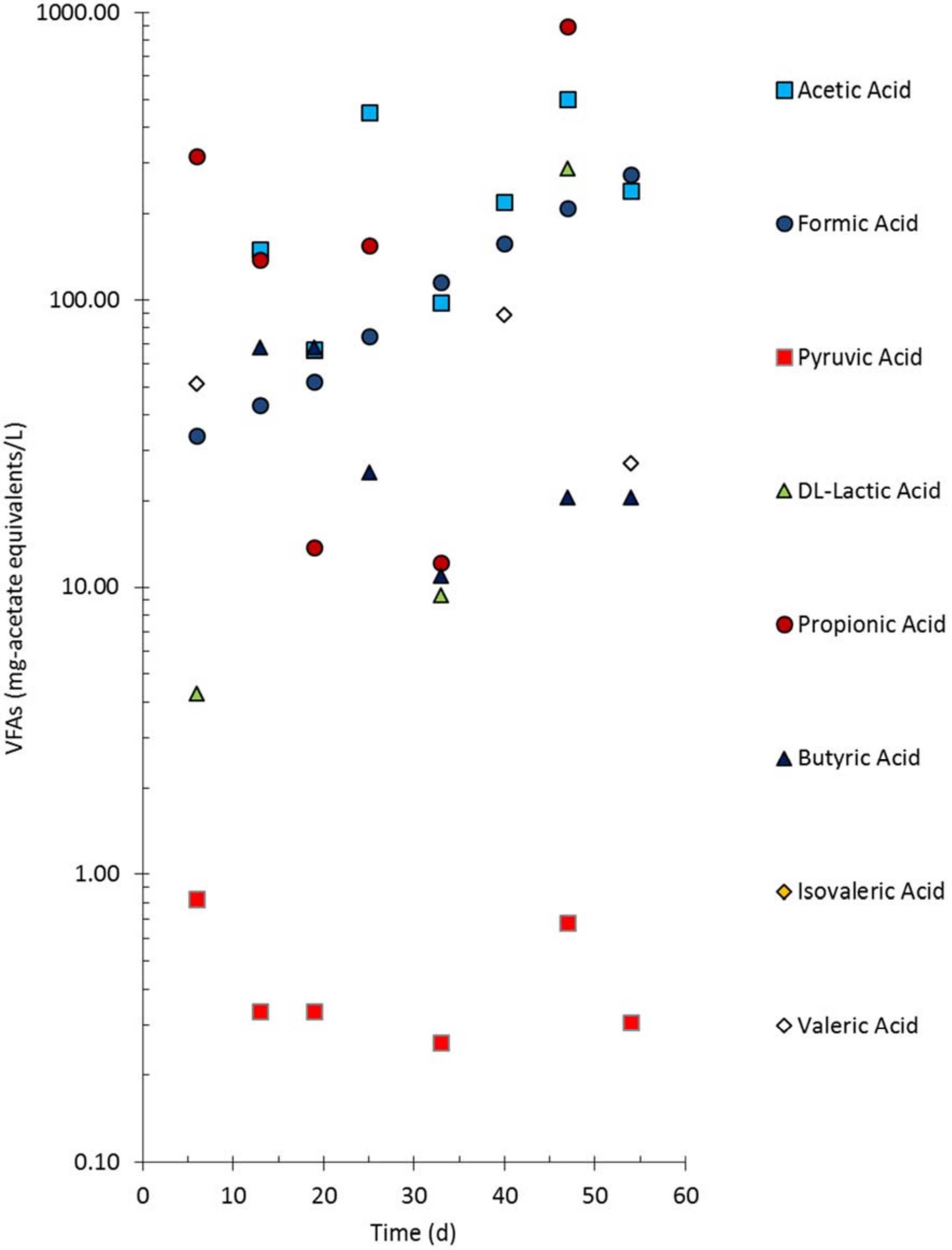


Figure 4. VFA trends during Phase IV. Propionate data may be suspect because of matrix interferences resulting in inconsistent detections.

Appendix I: Digester Feeding Details

Digester Feeding – Procedures, Time Line, and Observations during Phases II and III

Segregation of Food Waste

All of the food waste was segregated by hand. The primary items separated consisted of wrappers, plastic, foil, plastic Saran wrap, Styrofoam, and occasionally glass. I also removed food substances that would not digest or would cause mechanical failures such as bones and various seeds or pits. I removed as much non-biodegradable material as I could, being careful to make sure all larger items were removed. Small shredded wrappers and other small pieces of trash were not always completely removed, but they were not a threat to digester upset or mechanical failure. I also removed any remaining trash found in the feed mixture after the batch was prepared. I was careful to remove only trash from the feed mixture in the mix tank to make sure no food waste would be removed.

Procedure for Preparing the Digester Feed Mixture (Same for both diaphragm and hand pump feed methods):

All of the ingredients for the digester feed were weighed and added to the feed mixture tank. Water was added to the mix tank before all other components. The diaphragm pump was then turned on and the pressure was adjusted to provide enough force to circulate the water without causing any splashing. In the following order, the food waste, oil and nutrients were added to the water. The food waste was carefully added stepwise with handful sized amounts to prevent splashing and to allow for effective mixing without overloading the diaphragm pump with solids. While mixing, any trash or wrappings that floated to the top was carefully removed. The air supply to the diaphragm pump was limited, and mixing would significantly slow over the first 10 – 15 min. of preparing the feed. Depending on the volume of the feed mixture and the characteristics of the food waste, the diaphragm pump's reduced ability to provide effective circulation there were instances where solids would clump and/or settle. The feed would require a significant amount of mixing by hand with a paddle to break up the clumps and prevent settling. As soon as mixing stopped, the waste would quickly settle regardless of how broken up it was. This was mostly the case for thick or dense food waste, but the preparation of every feed mixture required some extent of manual mixing to assist the diaphragm pump. Oil added to the feed mixture presented an issue since its hydrophobic properties. Oil would quickly rise to the surface of the feed mixture and remain there regardless of how effective the diaphragm pump was mixing and homogenizing the feed. The only way to keep the oil suspended in the feed was to repetitively use the hand paddle to force the oil back into the mixture. Once the feed mixture was prepared and mixed as thoroughly as possible, a sample of the digester feed was collected. With the diaphragm pump continuing to circulate the feed, a 2-L measuring cup was used to scoop up a sample. The measuring cup was used to agitate the mixture by swirling the cup around in the feed and repetitively filling and dumping feed back into the mixture. This was done to avoid settling and oil separation to ensure a representative sample could be collected. When the feed appeared to be as thoroughly mixed as possible from the agitation, the measuring cup was used to scoop up the feed one last time to transfer to a sample container.

Digester Feeding: Diaphragm Pump (12/20/2013 – 1/3/2014).

After the feed mixture was prepared and the sample was collect, the diaphragm pump was shut off to allow time for the air compressor to regenerate. During this time, the digesters were drained to the appropriate volume using a manual ball valve located at the bottom of each digester. Once the digesters were drained, a hose was connected to the outlet of the mix tank and to the inlet of a digester. The feed inlet on both digesters was located near the bottom, so the digesters were always bottom fed. Draining the digesters and setting up the feeding assembly generally took 15 – 20 min. Once set up, the diaphragm pump was turned back on, and the feed mixture was circulated for 5-10 minutes, or until the mixture appeared to be evenly mixed. This step usually required manual mixing with a paddle to assist the diaphragm pump. The diaphragm pump was plumbed to direct the feed mixture to both the mix tank and to the hose for digester feeding in a manner that both paths could be simultaneously used. When the feed was ready, it was directed into the hose toward the digester. To fill the hose with feed, the ball valve on the feed end of the hose was cracked open to the atmosphere to displace air in the hose with the feed mixture. This was to prevent air from entering the digester. Due to the difficulty in removing all air from the hose, it was inevitable for a small volume of air to enter the digester (1 L or so). The valve on the digester inlet and the valve at the end of the hose was opened to allow the feed to flow into the digester. The flow rate was very difficult to control because the diaphragm pump could only be controlled by the amount of air being supplied to it. The valve allowing the feed mixture to circulate in the mix tank had to either be closed or restricted to create enough pressure from the diaphragm pump to feed the digester. Once the digester was fed, the feed hose was disconnected transferred to the second digester. The entire process was then repeated.

Observations and Comments:

- Pressure loss from the diaphragm pump due to lack of compressed air supply resulted in poor ability to effectively mix the digester feed. This caused solids settling and oil separation to occur.
- Hand mixing with a paddle was used to assist the diaphragm pump, but it was not possible to maintain hand mixing while feeding the digester. This led to variability in the consistency of the feed mixture delivered to each digester.
- The only way to effectively control the rate of filling the digesters, various ball valves had to be adjusted, which meant there may have been instances where larger solids were prevented from entering the digester by restricted valves. Valve adjustment while feeding was done carefully to prevent this as much as possible.
- Missed pieces of trash or plastic from food waste separation would sometimes get stuck in the ball valves, which may have hindered some solids from entering the digester.
- Depending on the characteristics of the food waste, it was common for residual food waste to remain in the mix tank after feeding. This was prevented as much as possible with hand mixing, but it is suspected that there were a few occasions when less food waste was fed to the digesters than desired. (Feed mixture entering the digester was diluted due settled solids in the mix tank that were left behind)

- The canola oil would separate and remain at the surface of the digester feed in the mix tank during feed cycles. This was prevented as much as possible by brief opportunities for hand mixing, but it is suspected that the second digester fed received more oil than the first.
- Air was introduced to the digesters during feeding due to residual air in the feed hose prior to feeding the digester. An air pocket would occasionally accumulate in the feed hose while feeding, which was overcome by controlling the feed rate as best as possible so that the pocket would not be forced into the digester.
- Feed would be delivered to the digesters in small "bursts" to prevent filling a greater volume than planned. This required constantly checking the digester volume by moving back and forth between the operation and control room, but the surges from filling the digester caused the pressure transmitter to spike multiple gallons above the actual volume. These spikes took a long time to equilibrate, and the digester volume would occasionally stabilize hours later, indicating up to 2-3 gallons of extra feed was added. Due to the limited volume of feed that was prepared and the observed volume of feed remaining in the mix tank after a feed cycle, the stabilized volume after stabilization could not have been always been completely accurate. This decreased confidence in the actual volume the digesters were fed and presented. It also caused wide fluctuations in the actual digester volume, so the volumes reported from many feed cycles were approximations based on the average value of the fluctuations. Drifting in the volumes over time after each feed created a challenge in determining the most appropriate time to record the actual volumes that were fed, which was typically done between 15 and 30 minutes after the feed cycle was completed.

Digester Feeding: Hand pump (1/6/2014 – 4/25/2014)

All steps involved with using the hand pump remained exactly the same as the diaphragm pump procedure with a few exceptions. Once the feed mixture was prepared, the hand pump assembly was set up. This required a hose between the outlet of the mix tank to the inlet of the hand pump and a hose between the outlet of the hand pump and the inlet of the digester. Once the digester feed was prepared using the method explained above, the diaphragm pump was used to direct the feed to the hand pump while still allowing for decent circulation of the feed in the mix tank. The hand pump would not allow the feed mixture to pass through unless it was manually pumped, so it was easier to control the feeding rate. The air existing in the hose between the hand pump and the digester inlet was displaced in the same manner as previously described, but the process was more effective with the hand pump since it was possible to displace the air by incrementally filling the hose with feed. Once the air was displaced, the all valves in the feed path were opened, and the feed was introduced to the digester in 0.25 gallon increments. Once the digester was fed, the valves were closed, and the mix tank, hoses and pumps were drained and cleaned. Cleaning did not interfere with the digester feeding process.

Observations and Procedural Comments:

- Greater control of feeding the digester allowed for increased confidence in the actual volume delivered to the digester (1 gallon for every 4 pumps).

- It became possible to manually stir the digester feed in the mix tank after every 1-2 gallons of feed delivered to the digester. As a result, both digesters received feed of improved consistency. Though improved, maintaining an evenly mixed feed without settling or oil separation was still difficult.
- Beginning 1/20/2014, the digester feeding process was adjusted so that the order in which the digesters were fed was alternated each feed day to counteract the uneven distribution of solids delivered to each digester.
- By increased hand mixing, settle solids were broken up and mixed often. The actual amount of food waste delivered to the digesters was closer to the planned amount than what was attained when feeding with the diaphragm pump.

Time Line

12/30/2013:

Severe foaming clogged the digester gas lines, the flow meter was plugged and the digesters were over flowing into the foam pots. The gas lines were opened in order to clean the lines and flow meter by flushing with water. The digesters continued to foam out of the gas line where it was disconnected.

12/30/2013 Foaming Event-Digester 1 Foam Pot

The foaming and cleaning process was not fully resolved until 1/3/2014.

1/6/2014:

Feeding the digesters with the hand pump permanently replaced using the diaphragm to feed the digesters. The diaphragm pump was still used for circulating and mixing the feed mixture, and it was used to pump the feed into the influent hose of the hand pump. The consistency of the food waste mixture when being prepared was not affected since the mixture depended solely on the characteristics of the food waste. The primary two differences between feeding methods were:

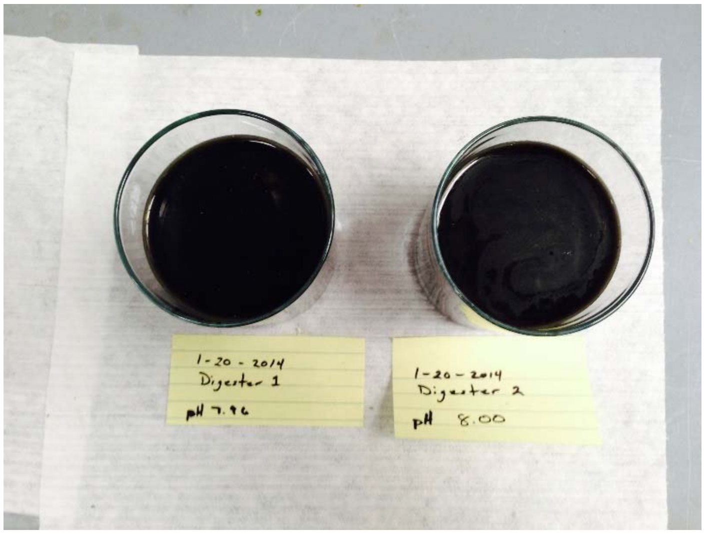
1) Better control over feeding the digesters with the hand pump increased the accuracy of reported volumes delivered to the digesters.
2) Better feeding control allowed the ability to mix the feed by hand in the mix tank more frequently and thoroughly, which improved the consistency of the feed added to each digesters and minimized the amount of food waste remaining in the mix tank after a feed cycle.

1/10/2014:

A thin oily film is present on the surface of the digester sludge when taking samples.

- Digester sludge samples were collected by filling a clean 5 gallon bucket with sludge using the feed inlet at the bottom of each digester. 1-2 gallons of sludge was collected to clear the path length of the feed inlet, the bucket was dumped, and then another 2-3 gallons of sludge was collected. A thin oily film existed at the surface of the sludge in the bucket. This was likely oil that still existed in the digester. The sludge in the bucket was thoroughly mixed by repetitively filling a measuring cup and dumping it back into the bucket in addition to swirling the sludge around with the cup. Once the sludge was adequately mixed, a sample was scooped up with the measuring cup and poured into the sample container. The mixing was carried out between every sample that was collected. When duplicate samples were collected, the process was repeated starting at clearing the digester inlet path length.
- The oil film in the bucket and measuring cup was thin and difficult to see. Samples were taken quickly after agitating the sludge in attempt to collect the sample while the oil remained suspended in the sludge.
- A film can be seen at the surface of the sludge sample on the right side in the picture below. The sample was not from 1/10, but it is easy to see in the picture.
- **The film has been referred to as an 'oil film', but it was only a descriptive observation since the film was not characterized.*

Digester sludge picture taken 1/20/2014. Digester 2 on the right side of the figure offers a good representation of the film that was observed during sample collection.



1/13/2014:

D1 and D2 sludge waste is beginning to become a little thicker. Small solid food pieces are present in the waste sludge for both digesters. Mostly rice and lettuce pieces, approximately 5-10 pieces/gallon. There is not as much oil on the surface of the sludge as 1/10/2014.

- There are not any pictures of sludge samples available between 12/20/2013 and 1/13/2014, but the solids will be observable in many pictures provided in this document.
- It is unknown why the samples from 1/13 appeared to contain less film.

1/14/2014:

Digester 1: Brown solid specs are suspended in the sludge waste. The sludge still appears to be a very dark brownish black, but it may be due to small solid brown specs and thicker consistency. Digester 2: Sludge has the same thickness as digester 1, but there are not any brown specs present. D2 sludge seems slightly lighter in color than D1 sludge.

1/14/2014 Digester 1&2 samples

1/14
D1
1/14
D2

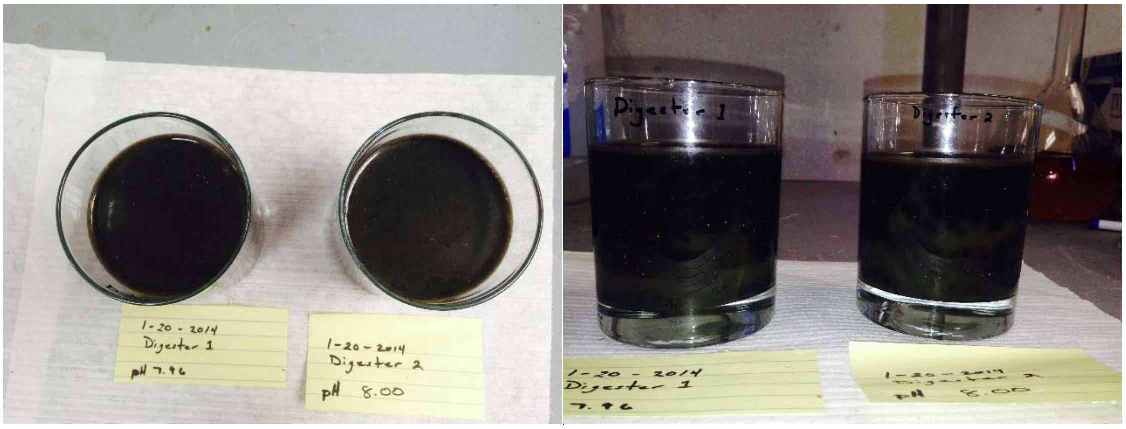
1/17/2014:

No noticeable changes in the consistency and color for the sludge in both digesters since last described on 1/14/2014.

- No picture available, sludge similar pictures above.

1/20/2014:

Digester 1: Brown solid specs are suspended in the sludge waste. The sludge still appears to be a very dark brownish black. It does not seem quite as thick as on 1/17. Digester 2: Now has brown solid specs and looks exactly like D1

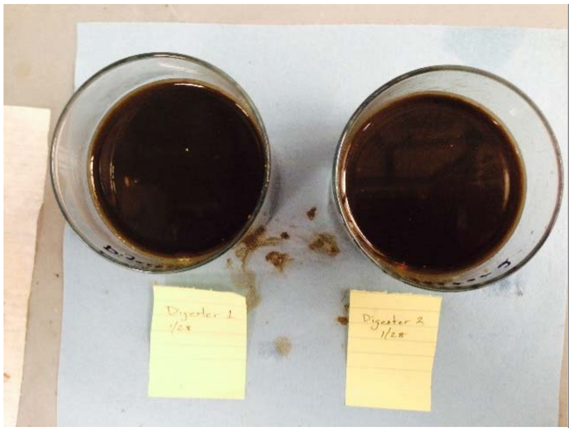

1-20-2014
Digester 1
pH 7.96
1-20-2014
Digester 2
pH 8.00
Digester 1
Digester 2
1-20-2014
Digester 1
7.96
1-20-2014
pH 8.00

- This was the beginning of alternating the order in which the digesters were fed.

1/28/2014:

D1: Sludge looks a little darker than previous week. Still quite a few brown solid specs, though the sludge looks like it is getting better.

- Lighting conditions when pictures were taken varied, and the actual color of the sludge is not well represented in many of the pictures.

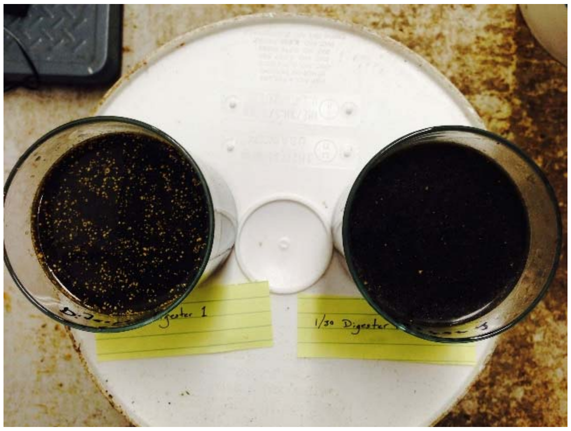

Digester 1
1/28
Digester 2
1/28

Digester 1
Digester 2
Digester 1
1/28
Digester 2
1/28

1/30/2014:

D1:Sludge is becoming browner and there are more brown solid specs than any point in the past. The brown specs are about the size of a grain of sand on average. They have a solid texture, but can be smashed easily; similar to the texture of cooked rice. An oily film appears at the surface of the sludge as well. D2: Slude appears more brown, but not quite as much as D1. There isn't nearly as many brown specs as D1 (D2 has 5-10% of the number of brown specs that D1 has). There is more oil on the surface of the D2 sludge than on the D1 sludge.

Digester 1
Digester 2
1/30 Digester 1
1/30 Digester 2


Digester 1
1/30 Digester

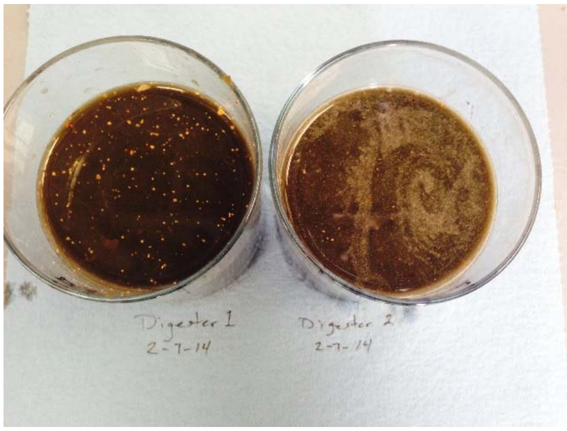
1/31/2014:

D1: Sludge looks better than the previous day. Less Brown solid specs. No noticable change in color or consistency. D2: No noticable changes.

- No picture available.

2/7/2014

1) D1: Brown Specs still present. Number of specs have decreased. No other noticable changes. D2: Tiny specs appeat in sludge. Unlike D1 the specs appear to be tiny slivers of paritcles. Increased oily film on sludge surface.

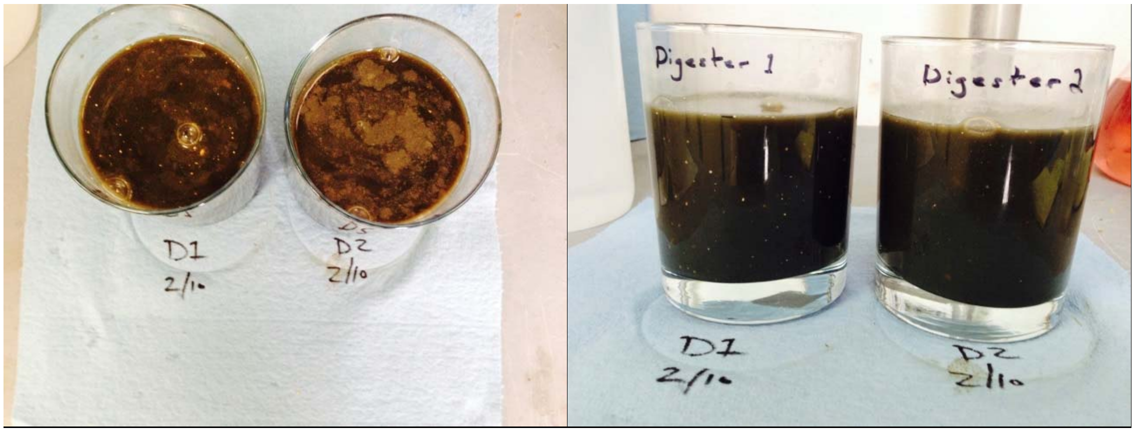


2) Digester Feed Mixture was difficult to keep thoroughly mixed during feeding. Food waste settled in mixture. Digester 2 was fed first and Digester 1 may have received more solids than digester 2 from settling.

- Food Collected from 2/5/2014 used for 2/7/2014 feed: Consisted entirely of eggs, which does not mix well. It forms clumps through entire process that must constantly be broken up and mixed.

2/10/2014:

No change in sludge description for both digesters, except D1 has less solid brown specs than on 2/7


D1
2/10
D2
2/10
Digester 1
Digester 2
D1
2/10
D2
2/10

2/17/2014:

Digester waste sludge for both digesters has not changed in appearance or consistency since last description and seems to be stable, The amount of brown specs and oil film at the surface of the sludge fluctuates; increasing after feeding and decreasing slowly until next the feed.

Digester 1
Digester 2
D1
2/17
D2
2/17
D1
2/17
D2
2/17

3/10/2014:

- D1: Has small solid brown specs, becoming slightly lighter in color- Dark Brown. D2: Becoming slightly lighter in color-dark brown. Very small solid specs 1/4 the size of specs in D1 exist.
- Pictures from 3/10/14 are not recorded, pictures below were taken 3/11/2014.

3/11
D1
3/11
D2
Digester 1
Digester 2
3/11
D1
3/11
D2

4/9/2014:

Used grinder when making digester feed mixture. It did not work great, but food solids were much smaller, and the pump circulated better. There was less food settling as well.

- This was the only time a modification to the feeding process was made. The food waste did not have a large amount of trash, but had a few larger clumps to break up. The grinder was placed in the mix tank to see if it would effectively break up the food waste. The grinder circulated the mixture in the mix tank during feed preparation to supplement the circulation from the diaphragm pump, but the grinder did not have enough force to improve actual mixing speed. This did not significantly impact the feed mixture other than helping break up larger chunks of food more effectively than doing it by hand. The smaller solids did appear to distribute and remain suspended in the feed mixture better than what would have been done by hand. The grinder was removed from the mix tank before feeding the digesters. Removing the grinder was done such that it did not remove any of the feed mixture from the mix tank.
- The consistency of the feed mixture delivered to each digester may have been more consistent, but it was difficult to determine because there were not any unique observations or noticeable differences compared to a normal feed cycle other than the smaller solids.

Appendix J: Standard Operating Procedure for COD Analysis

Standard Operating Procedure for Digester Feed and Digester Sludge COD Analysis.

ESTCP Project ER-200933

Authored by: Pat Evans and Tyler Miller on 5/30/14

Approved by: Shawn Oliviera

Scope and Applicability

This SOP details procedures and safety considerations for analyzing the Chemical Oxygen Demand (COD) of Digester Feed and Digester Sludge samples collected at the pilot-scale anaerobic digestion facility at the US Air Force Academy (ESTCP). The procedure is based on use of the Hach COD test kit. Instructions for the Hach test kit should also be followed. The below procedure covers all steps including sample preparation, reaction, analysis and calculations. The procedure also addresses specific safety hazards that will be encountered upon executing various steps in the process such as safe lab practices, handling hazardous chemicals and being aware of hot surfaces.

Safety/Hazards

Chemical Oxygen Demand vials contain potentially dangerous chemicals including potassium dichromate, sulfuric acid and mercury. The vials must be handled very carefully and held over the bench and close to the bench surface at all times. Potassium dichromate is a strong oxidizer, causing an exothermic reaction upon the addition of any sample containing organic matter. This causes the vial to become extremely hot almost immediately when mixing the sample in the vial. Once a sample is added to a vial, screw the cap back on quickly and tightly, and then gently mix the contents of the vial. Do not touch the vial except for the cap while reacting. The COD solution is composed of 50% sulfuric acid and is damaging to the skin and eyes. Mercury is a very toxic heavy metal and is also damaging to the body and the environment. Always wear gloves, safety glasses and have access to an eyewash station. An acid spill kit can be used in the event a COD vial is spilled or broken and can be disposed in a designated, marked COD waste bucket.

The COD sample preparation in this procedure involves using a blender. Make sure the blender is always on the lowest speed before turning it on to prevent splashing. Splashing can also occur when the samples and DI water are poured into the blender pitchers. Aliquots of each sample will be taken directly from the blender pitcher while the blender blade is spinning. The pipette tip needs to be held closely to the wall of the blender pitcher when drawing the sample and hands should not be placed inside the pitcher. It is important to keep the pitchers clean in between each sample batch and get disinfected at the end of every test. The digester feed and digester sludge samples may contain hydrogen sulfide, dissolved methane, and potentially pathogenic bacteria. Precautions must be taken to avoid dermal and eye contact as well as ingestion of the samples. Personal protective equipment to be used shall include safety glasses, gloves and a 4-gas meter. These items are discussed further in the Health and Safety Plan (HASP). Specific use of these items is discussed in the procedures below.

Equipment

1. VitaMix Blender
2. Blender pitchers (3) w/ lids, Labeled: Sample Blend (SB), Dilution 1 (D1), Dilution 2 (D2)
3. Balance (Make/Model)
4. Hach COD reactor
5. DR 900 Colorimeter COD Vials 50-1500 mg/L Range- 2 per sample
6. 5 ml Eppendorf pipette w/ pipette tips
7. 1000 mg/L COD Standard
8. COD vial cooling rack.
9. Deionized (DI) water
10. Sink w/ potable water
11. Kim Wipes
12. Paper Towels/Rags
13. Alconox/Water Mixture
14. Sponge Scrubber
15. PPE described in HASP
16. Acid spill kit
17. COD waste container

Procedure for COD analysis of Digester Feed Samples

1. Remove sample from the refrigerator and let thaw if necessary
2. Once thawed, carefully pour the sample into the pitcher labeled sample blend. If the sample is still frozen, partially frozen or is poured into the pitcher too quickly, splashing will occur. *Important!*- Secure the lid tightly onto the pitcher before blending to prevent splashing. During this step and the following steps, conduct atmospheric monitoring using the 4-gas meter.
3. Blend the sample vigorously. Make sure the blender is on the variable setting and start on the lowest speed. Slowly increase the speed of the blender until it is at its highest point and then switch the blend setting to high. Blend the sample for approximately 30 seconds on high or until it the sample is thoroughly homogenized. Bring the blending speed back down to low (2-3).
4. While the sample is still mixing, tare the pitcher labeled Dilution 1. Stop the blender, remove the lid, and pour 25 g of the sample into the D1 Pitcher. This should be done quickly to minimize sample separation, but carefully to prevent splashing. Dilute the sample to 250 g using DI water. Record the actual mass of the sample added and the total mass of the diluted mixture as M1 and M2, respectively.
5. Begin blending the D1 Pitcher on a low setting (2-3). During this time, tare the pitcher labeled Dilution 2 on the balance. Stop the blender and quickly pour 20 g of the first dilution into the D2 Pitcher. Dilute to 500 g using DI water. Record the actual mass of the 1st diluted sample added

and the total mass of the diluted mixture M3 and M4, respectively. Begin blending D2 on the lowest setting

6. Prepare 2 COD vials by labeling them with the sample collection date and sample type (i.e. DF for Digester Feed and DS for digester sludge). Remove the caps and place them in the cooling rack.
7. Adjust the 5 mL pipette to draw 2 ml of solution and connect a pipette tip. While blending on the lowest setting, place the pipette tip into the D2 Pitcher along one of the walls of the pitcher. Rinse the pipette 3 times by drawing and dispensing the diluted solution in the blender, being careful not to hit the blade. Do not place your hand in the blender vessel.
8. Once the pipette tip has been rinsed, draw 2 ml of the diluted sample and dispense it into a COD vial. Hold the COD vial at a 45 deg. angle and slowly dispense the sample down the wall of the vial. Try not to touch the pipette tip to the vial. If this occurs, wipe the tip with a kim wipe.
9. Screw the cap tightly back onto the COD vial and gently invert several times to mix the sample into the vial solution. Set in the vial cooling rack until all samples are prepped and ready to be placed into the reactor.
10. Repeat steps 7-9 for the second vial and then dispose the pipette tip.
11. Empty, rinse and thoroughly scrub all three pitchers using the Alconox solution and scrubber. Rinse each pitcher with DI water and wipe dry. Pitchers need to be cleaned and dried after every sample is prepared.
12. Fill one COD vial with 2 ml of the DI water used for diluting the samples. This will serve as a sample blank.
13. Fill two COD vials with 2 ml of 1000 mg/L COD standard in each vial for a sample reference.
14. Turn the reactor on and set for COD. It will take about 15 min. to heat up to temperature (150°C). Once the reactor has reached temperature, open the shield, and place all of the sample vials into the vial slots. Invert each vial 3-4 times before putting in the reactor. Close the reactor shield and press start. The reaction time is two hours. Once 2 hours has passed, the reactor automatically begins cooling. Do not take the vials out of the reactor until the temperature has cooled to at least 120 °C. Take the vials out of the reactor touching only the cap and place them in the vial cooling rack until they reach room temperature.
15. Use the Hach colorimeter to measure the samples. Change the colorimeter program to measure 50-1500 mg/L COD. Place the sample blank vial in the colorimeter and press zero.
16. Read each 1000 mg/L standard. Record the values.
17. Read each sample vial. Vials may be gently wiped clean with a Kim wipe before placing them into the colorimeter if there are any noticeable marks or particles that could interfere with the measurement.
18. Once finished, put COD vials in the designated hazardous waste bucket and clean up area. Discard digester feed samples in the sink and wash out sample containers with soap and water.

Procedure for COD Analysis of Digester Sludge Samples

1. Digester Sludge COD analysis is done using the same method for Digester Feed COD analysis with only one modification: Digester Sludge is only diluted 1 time.

2. Use the Dilution 2 pitcher and weigh 5 g of Digester Sludge. Dilute to 500 g with DI water. Record the actual mass of the digester sludge (M1) and the total mass of the dilution (M2).
3. Blend on the lowest setting, and use the pipette to draw 2 ml of the diluted sample.
4. Dispense 2 ml into the COD vial and invert gently several times before placing it in the vial cooling rack where it will remain until all samples are ready for the reactor.
5. Repeat Steps 3 & 4 for a second COD vial for each Digester Sludge sample.
6. Follow steps 11-20 in the Digester Feed COD analysis procedure.

Calculations

Digester Feed:

Multiply the measured COD value by the dilution factors (M1, M2, M3, M4) to calculate the COD of the original sample (equation 1).

$$\left[Measured\ COD\ \left(\frac{mg}{L}\right)\right] * \frac{M2}{M1} * \frac{M4}{M3} = \left[Digester\ Feed\ COD\ \left(\frac{mg}{L}\right)\right] \tag{1}$$

Digester Sludge:

Calculating COD for digester sludge samples is shown in equation 2.

$$\left[Measured\ COD\ \left(\frac{mg}{L}\right)\right] * \frac{M2}{M1} = \left[Digester\ Sludge\ COD\ \left(\frac{mg}{L}\right)\right] \tag{2}$$

Appendix K: Quality Assurance Summary

Quality Assurance Summary

Deviations from the QAPP

As this technology demonstration plan was a research project, the analysis plan and schedule changed was varied based on the preliminary results and information necessary for decision factors. Several deviations were made from the sample schedule and analytical methods outlined in the Technology Demonstration Plan, both increasing and decreasing the frequency of sampling.

Due to the nature of digester samples matrix, metals analysis were performed under United States Environmental Protection Agency (USEPA) methods 6010C (cobalt, copper, iron, manganese, zinc) and USEPA 6020A (molybdenum, nickel, selenium). Results were reported in mg/L due to the liquid matrix.

Evaluation of Data Quality

Data evaluation was performed by an independent quality assurance reviewer for completeness and compliance with the Technology Demonstration Plan. Activities performed by both CDM Smith and subcontracted laboratories (ALS Environmental, Simi Valley, CA; ALS Environmental, Kelso, WA) were compared against the goals and procedures set forth in this document.

Chemical data quality indicators (DQIs) are quantitative and qualitative goals and limits established for laboratory data that provide the means by which data reviewers can assess whether the goals of an investigation have been met. Quality Assurance (QA) indicators for measuring the study data are expressed in terms of precision, accuracy, representativeness, comparability, completeness, and sensitivity (PARCCS). The QA indicators provide a mechanism for ongoing control and evaluation of data quality throughout the project. The treatability QA/QC was assessed by internal QC checks, calibration checks, method blanks, surrogate spikes, adherence to holding times, and laboratory duplicates in accordance with the project plan. Both the pilot and the subcontracted laboratory data are assessed here.

Precision

The precision of a measurement is an expression of mutual agreement among individual measurements taken under prescribed similar conditions. Precision is quantitative and most often expressed in terms of relative percent difference (RPD). Precision of reported results is a function of inherent field-related variability plus laboratory analytical variability. Field duplicates were collected at a frequency of 5% of the total samples. For sample pairs where the concentration of the analyte is greater than 10x the PQL limit, the precision goal is <35%. For sample pairs where one or both of the samples are less than 10x the PQL limit, the precision goal is <50%. Sample pairs where one or both values were less than the PQL did not have RPDs calculated. All field samples met the precision goals set forth in the QAPP.

The contribution of laboratory-related sources to overall variability was measured by calculating the RPD between the matrix spike/matrix spike duplicate results, laboratory duplicate results, and laboratory control sample/control sample duplicate results. The subcontracted laboratory completed replicate analysis in accordance with the method and laboratory SOPs. In general, laboratory analyses met the precision goals, however several samples (Table 1) were outside of the laboratory established control limit (20%) but below the project precision goal of 35%.

Variability was attributed to the heterogeneity of the digester samples, and standard laboratory mixing techniques were not sufficient to homogenize the samples. This was anticipated based on the nature of anaerobic digestion sludge, thus the project precision goals were broader than the typical laboratory standards and thus meet the precision goals of the project.

Table 1. Precision excursions.

Sample Date	Parameter	Sample Name
1/29/2014	Copper	Undiluted Food Waste
2/12/2014	Volatile and Total suspended solids	Digester 1, Digester 2
2/12/2014	Molybdenum	Undiluted Food Waste
2/19/2014	Ash, Copper	Undiluted Food Waste
3/13/2014	Total suspended solids	Digester 2
3/27/2014	Total suspended solids	Digester 1
4/2/2014	Manganese	Undiluted Food Waste

Accuracy

Accuracy is defined as the degree of agreement between a measurement and an accepted reference or true value and is a measure of bias in a system. Accuracy is quantitative and usually expressed as the percent recovery (%R) of a sample result. Accuracy DQIs are calibrations and the recoveries of spiked analytes in LCS, MS, and surrogate compounds. Other indicators of analytical accuracy include the use of the EPA accepted analytical methods, evaluation of blank contamination, acceptable instrument calibrations, and adherence to the required sample preservation and holding times and chain-of custody procedures. The accuracy goals for method defined surrogates, laboratory control samples, and calibration standards are defined by the laboratory's quality assurance plan and standard operating procedure. There were several samples where the concentration of analytes significantly exceeded the matrix spike concentrations preventing accurate spike recoveries or where the digester matrix interfered with spiked recoveries. Table 2 documents summarizes the sample excursions. No excursions were observed in the gas samples or field analyses. Propionic acid results were inconsistent and the HPLC chromatograms indicated peak interference with an unidentified compound. Therefore, propionic acid data are considered suspect. Nevertheless, the contract laboratory (ALS Environmental) applied its SOPs to accept or reject data. The accepted data were used in calculation of ratios of VFA/TALK. All other indicators were acceptable other than the exceptions noted below.

Table 2. Accuracy excursions.

Sample Collection Date	Parameter	Sample Name	Notes
1/30/2014	Iron, molybdenum	Digester 1	MS/MSD Not Applicable: Concentration of sample was significantly higher than the added spike concentration preventing accurate recovery.
1/30/2014	Acetic acid	Digester 1	
2/12/2014	Iron	Digester 1	
2/12/2014	Acetic acid, formic acid	Digester 1	
2/20/2014	Iron, molybdenum	Digester 1	
2/27/2014	Molybdenum, nickel	Digester 1	
2/27/2014	Acetic acid	Digester 2	
3/5/2014	Molybdenum, acetic acid	Digester 1	
4/3/2014	Molybdenum	Digester 1	
2/12/2014	Lactic acid	Digester 1	MS/MSD Not Applicable: Matrix interference in the parent sample prevented accurate recovery of the spiked compound.
2/27/2014	Lactic acid, butyric acid, isovaleric acid, valeric acid	Digester 2	
3/13/2014	Isocaproic acid, butyric acid, propionic acid	Digester 1	
1/30/2014	Nickel	Digester 1	MS/MSD outside range: Matrix spike recovery was outside of the control criteria, suggesting a potential low bias in the sample results.
2/12/2014	Propionic acid, valeric acid	Digester 1	MS/MSD outside range: Matrix spike recovery was outside of the control criteria, suggesting results are potentially biased high.
3/27/2014	Lactic acid, isovaleric acid	Digester 1	

Field and laboratory calibrations were performed in accordance with manufacturers' recommendations and laboratory procedures. Field calibrations were documented in calibration logs. Method blanks were evaluated in the laboratory analyses, no detections exceeded the laboratory quality standards.

Completeness

Completeness is a measure of the amount of usable data that are obtained compared to the amount that was expected to be obtained during project planning. Data that were evaluated and needed no qualification, or were qualified as estimated "J" or "UJ," are considered usable. Completeness is assessed in terms of both sampling and analytical completeness. The completeness requirement, as stated in the QAPP and the demonstration plan, was 90 percent. Analysis were performed at a varied frequency than outlined demonstration plan, with some schedule variations due to the pilot schedule. The results were useable for the intended purpose with the exception of the above temperature liquid shipments and sulfur samples that exceeded the sample hold time (refer to Sensitivity, Representativeness, and Comparability section below for further details). Of the samples analyzed, there was a greater than 98% useable data.

Sensitivity, Representativeness and Comparability

Sensitivity is related to the ability to compare analytical results with project-specific levels of interest, such as regulatory limits. Analytical practical quantitation limits (PQLs) for the various sample analytes were sufficient for the purposes of the demonstration. Laboratory and field analyses methods used for this project were performed in accordance with the demonstration plan, and thus sufficient for the screening and definitive data collected to support the project decisions. ALS Laboratories reported results under the reporting limit but at or above the method detection limit.

Field samples collected and analyzed immediately on site. Acquisition, collection, and handling of samples was performed using appropriate sample preservatives per the analytical methods to ensure representativeness and comparability of results with other analyses that are performed in a similar manner. In addition, multiple lines of evidence were used to ensure that the data was sufficient to meet the decision inputs for this study.

There were a few analyses over the course of the demonstration that exceeded the laboratory hold times. The parameters and impact are summarized below:

- One TS/VS sample (Digester 2, 02/12/2014) that had to be reanalyzed due to a broken crucible. The laboratory hold time was exceeded in the re-analysis. The solids content may not be representative of the digester conditions.
- Ten liquid/solid sample shipments arrived at ALS laboratories below the target temperature range of 4±2°C, ranging from 0.6 to 1.9 °C. This is not expected to impact the data quality for the targeted analysis (VFAs, TS/VS, metals).
- The cooler from the 11/26/13, 9/19/13, and 4/10/14 sampling events were delayed during shipment, and were above the target temperatures upon arrival at the ALS Laboratory (15.2, 14.3, and 8.2 °C, respectively). Increased temperature may not have been sufficient to impede biological activity, thus solids and metals samples may be underestimated. Temperature highly impacts the biological conversion of fatty acids in anaerobic digestion sludge, thus samples from this shipment are not considered representative of the digester concentrations and should be flagged accordingly.
- One cooler from the 10/02/2013 sample event arrived on time at the ALS Laboratory at 14.0°C, above the preservation target. Increased temperature may not have been sufficient to impede biological activity, thus solids and metals samples may be underestimated. Temperature highly impacts the biological conversion of fatty acids in anaerobic digestion sludge. This sample was from Phase 1 which was not used in the data analysis.
- Two shipments of sulfur samples were delayed in shipping and arrived at the ALS laboratory past the recommended hold times. The sulfur content in the Biogas and Sweetened Biogas samples from 04/03/14 and 07/01/14 may be underestimated due to loss from the sample containers.

- The ALS Laboratory exceeded the sample hold time on two sulfur samples, 07/23/14 Biogas and the 10:57 Post-VSA Biogas sample from 07/31/14. The sulfur content may be underestimated in these samples.
- The VSA sample collected on day 47 of Phase IV were not included in the data analysis because of contamination with desorption gas.

Conclusions

The data for the pilot study was reviewed, and all data in the data set, with the exception of the noted hold time exceedances noted above, are considered useable. Overall, the data were determined to be of acceptable quality for meeting the Data Quality Objectives and are representative of the reactor conditions at the time of collection.

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Appendix L: Engineering Calculations for Energy Efficiency

Engergy Demand in 1 MG Digester

$$\text{Mixing} := \frac{\frac{1\cdot \text{Mgal}}{40\cdot \text{min}}\cdot 8.34\cdot \frac{\text{lbf}}{\text{gal}}\cdot .1\cdot \text{ft}}{80\%\cdot 93\%} = 0.633\cdot \text{kW}$$

Use 40 min turnover time, 0.1 ft headloss, no static head, 80% pump efficiency, 93% motor efficiency

$$\text{Recirc}_{\text{pump}} := \frac{500\cdot \text{gpm}\cdot 40\cdot \text{ft}\cdot 8.34\cdot \frac{\text{lbf}}{\text{gal}}}{65\%\cdot 93\%} = 6.235\cdot \text{kW}$$

Use sludge recirc pump at 500 gpm 40ft head (including HEX loss), no static head, 65% pump efficiency, 93% motor efficiency

$$\text{water}_{\text{pump}} := \frac{500\cdot \text{gpm}\cdot 25\cdot \text{ft}\cdot 8.34\cdot \frac{\text{lbf}}{\text{gal}}}{80\%\cdot 93\%} = 3.166\cdot \text{kW}$$

Use water recirc pump at 500 gpm, 25ft head (including HEX loss), no static head, 80% pump efficiency, 93% motor efficiency

$$\text{feed}_{\text{pump}} := \frac{\frac{1\cdot \text{Mgal}}{40\cdot \text{day}}\cdot 40\cdot \text{psi}}{50\%\cdot 93\%} = 0.65\cdot \text{kW}$$

Use feed pump at 40 day SRT, 40 psi discharge pressure, 50% pump efficiency, 93% motor efficiency

withdrawal by gravity - no power

Boiler secondary and hot water loops - not included as part of other plant systems

Energy for CNG

$$Q := 120000\cdot \frac{\text{mg}}{\text{L}}\cdot \frac{1\cdot \text{Mgal}}{40\cdot \text{day}}\cdot 377\cdot \frac{\text{L}}{\text{kg}} = 0.05\frac{\text{m}^3}{\text{s}}$$

$$P_{\text{compr}} := \frac{1\cdot \text{atm}\cdot Q\cdot \ln\left(\frac{3600\cdot \text{psi}}{1\cdot \text{atm}}\right)}{55\%\cdot 93\%} = 53.999\cdot \text{kW}$$

Assumes water cooling

$$P_{\text{water.cooling}} := 25\cdot \text{hp}$$

(assumed to include pumping energy and radiator energy)

$$P_{\text{water.scrubber.pump}} := \frac{50\cdot \text{gpm}\cdot 6.5\cdot \text{bar}}{80\%\cdot 93\%} = 2.756\cdot \text{kW}$$

Assumes CO2 removal with water scrubber at 6.5 bar operating pressure

$$\text{CNG}_{\text{energy}} := P_{\text{compr}} + P_{\text{water.cooling}} + P_{\text{water.scrubber.pump}} = 75.397\cdot \text{kW}$$

$$\text{Boiler}_{\text{heating}} := \frac{\frac{1\cdot\text{Mgal}}{40\cdot\text{day}}\cdot 8.34\cdot\frac{\text{lb}}{\text{gal}}\cdot 1\cdot\frac{\text{BTU}}{\text{lb}\cdot\text{R}}\cdot(95-60)\cdot\text{R}}{94\%}\cdot 115\% = 109.02\cdot\text{kW}$$

Assumes 40 day SRT, 60 degree raw FW temp, 95 degree operational temp, 94% boiler efficiency, 15% of heating energy for tank shell losses

$$\text{para}_{\text{elec}} := \text{Mixing} + \text{Recirc}_{\text{pump}} + \text{water}_{\text{pump}} + \text{feed}_{\text{pump}} + \text{CNG}_{\text{energy}} = 86.082\cdot\text{kW}$$

$$\text{para}_{\text{total}} := \text{para}_{\text{elec}} + \text{Boiler}_{\text{heating}} = 195.102\cdot\text{kW}$$

$$\text{Phase3}_{\text{In}} := 120000\cdot\frac{\text{mg}}{\text{L}}\cdot\frac{1\cdot\text{Mgal}}{40\cdot\text{day}}\cdot 1.47\cdot 10^{7}\cdot\frac{\text{J}}{\text{kg}} = 1.932\times 10^{3}\cdot\text{kW}$$

1.47 x 10^7 J/kg is for methane-COD?

$$\text{Phase3}_{\text{conver}} := 73\%\cdot\text{Phase3}_{\text{In}} = 1.41\times 10^{3}\cdot\text{kW}$$

73% is energy conversion not including parasitic demands

$$\text{Phase3}_{\text{adjust.elec}} := \text{Phase3}_{\text{conver}} - \text{para}_{\text{elec}}$$

$$\text{Phase3}_{\text{adjust.total}} := \text{Phase3}_{\text{conver}} - \text{para}_{\text{total}}$$

$$\text{Adj}_{\text{eff.elec}} := \frac{\text{Phase3}_{\text{adjust.elec}}}{\text{Phase3}_{\text{In}}} = 68.545\cdot\%$$

$$\text{Adj}_{\text{eff.total}} := \frac{\text{Phase3}_{\text{adjust.total}}}{\text{Phase3}_{\text{In}}} = 62.902\cdot\%$$

This is the result taking into account parasitic demands. Includes electrical and heating.

Appendix M: ADM1 Modeling of Field Demonstration

ESTCP food digester modeling study summary

Urv Patel, EIT

July 20, 2015

Introduction

The ADM1 model MATHCAD set up by Donnie Stallman from the earlier study on bench scale digesters treating U.S. Air Force Academy (USAFA) food waste was investigated for its ability to predict the measured performance of the pilot scale anaerobic digesters at the USAFA for the period from December 2013 to April 2014. The model investigation work was started in February 2015 by Urv Patel with i issues regarding various approaches to the model inputs and model coefficient assumptions and the initial conditions using the municipal digester seed sludge. Problems were encountered on the choice of the influent feed parameter, as the reported VS and COD data were not in agreement; the COD/VS ratio was too low. The purpose of this summary memo is to document the reason for electing to use the influent COD data for the model application and to provide an analysis of the model simulation using the influent COD data.

Prior to the model simulations using COD preliminary, results indicated difficulty fitting the dramatic decrease in digester VSS concentration after late February 2014. It seemed that the fast and slow fractions used in Stallman's model simulations were not providing reasonable model fits to these observations. Analysis of the remaining solids in the digester model output showed that in order to obtain a fit closer to the observed digester VSS data, it was necessary to have little inert VSS and digestable VSS remaining. The fat plus protein COD faction was also very high for this application (averaged 78%). For this reasons it was decided to use one hydrolysis rate for all the feed as is done in the ADM1 model. A hydrolysis rate of 1.5 d^{-1} was used and the results of this simulation are presented here.

The model fitting success was evaluated by comparing the model predicted versus measured data for the following parameters over the course of the digester Dec 2013 to April 2014 operation: 1) total methane production for each feed interval, 2) digester VSS concentration, and 3) digester ammonia-N and alkalinity concentrations. In addition the model versus the measured methane production rates after feeding profile was compared.

Determining initial conditions for ESTCP food digester simulations

The seed sludge used in the food waste digester was taken from an adjacent municipal wastewater treatment plant sludge digester. Thus, all the influent parameters determined by D. Stallman for municipal digester feed were used. The step by step derivation of the initial condition is as follows:

1. Change all the influent feed characteristics table to the one given below

ADM1 composition and kinetic parameters used to simulate municipal sludge digestion from Straub (2008)

Parameter	Value	Units
$f_{sI,xc}$	0.01	gS_I/gX_c
$f_{xI,xc}$	0.23	gX_I/gX_c
$f_{ch,xc}$	0.20	gX_{ch}/gX_c
$f_{pr,xc}$	0.40	gX_{pr}/gX_c
$f_{li,xc}$	0.16	gX_{li}/gX_c
$f_{rh,xc}$	0.33	gX_{rh}/gX_c
$f_{sh,xc}$	0.43	gX_{sh}/gX_c
$k_{hyd,rh}$	2.2	d^{-1}
$k_{hyd,sh}$	0.25	d^{-1}

2. The flowrate was made continuous (Q) and tank volume was changed to give a 30 day SRT when divided by flowrate
3. The temperature was changed to 36 Celsius
4. All other parameters were same as in D. Stallman
5. The simulation was ran for 200 day period to get a steady state
6. The digester VSS, Ammonia was compared with measured initial values of the food waste digester
7. The influent COD and percent protein was changed until the VSS and the Ammonia were very close to the measured initial conditions

The final initial conditions are tabulated in Appendix-3

SECTION-1

Model application using the influent measured VS concentration data

Assumptions and Inputs

1. The influent VS concentration data was converted to influent COD by using the proximate analyses results for protein (P), lipids (L), and carbs (C) to get their VS fractions and then using factors of COD/VS for these general substrates to get the feed total COD and COD of P, L, and C

2. The hydrolysis rate coefficients and fraction of slowly and rapidly biodegradable solids used were from D. Stallman thesis based on the bench-scale digester calibrations

Coefficient	Fast hydrolysis	Slow hydrolysis
Fraction	0.45	0.55
Hydrolysis rate coefficient, d^{-1}	1.50	0.15

3. Used the same coefficient values as per Stallman fermentation and Methanogenesis equations

4. Stallman's moles N/g protein COD coefficient of 0.009414 was changed to 0.008403 based on literature reference

5. 15% of biomass is assumed as inert

Poor model fit with VS influent data (See Appendix-1 for plots)

1. The methane production predicted by the model was 2 times the measured values.

2. The VSS predicted by the model was very high and never near the measured VSS.

3. The ammonia and alkalinity concentrations predicted by the model were 25-30 % greater than the measured values. We considered the measured ammonia and alkalinity data to be very reliable because they agreed with each other well based on the fact that most of the alkalinity in the digesters had to be derived from deamination of protein to ammonia.

Conclusion and next step

Thus, it was concluded that influent VS data is not reliable and over predicts all the parameters. Now, in SECTION-2 we show the model simulation results using measured COD data.

SECTION-2

Model application using influent measured COD data and coefficient determined by Stallman, et al

Assumptions and Inputs

1. The influent COD concentration data was used as model input

2. Measured proximate analysis was used after some unit conversions (elaborated in Appendix-B)

3. Percentage influent inert was assumed to be 1% in concentration

4. The hydrolysis rate coefficients and fraction of slowly and rapidly biodegradable solids used were from D. Stallman thesis based on the bench-scale digester calibrations

Coefficient	Fast hydrolysis	Slow hydrolysis
Fraction	0.45	0.55
Hydrolysis rate coefficient, d^{-1}	1.50	0.15

5. All other fermentation, methanogenesis etc. were used as per D.Stallman

6. Stallman's moles N/g protein COD coefficient of 0.009414 remained the same

Poor model fit with influent COD data and using coefficient determined by Stallman, et al.

(See Appendix-2 for plots)

1. The methane production predicted by the model has a poor match due to the slowly and rapidly hydrolysable fractions of solids

2. The VSS predicted by the model was very high and never near the measured VSS, because less fraction of the influent was digested resulting in higher undigested solids

3. The ammonia and alkalinity concentrations predicted by the model were close to measured values

Conclusion and next step

From this section, it is clear that using influent COD gives us reasonable fit in case Ammonia and Alkalinity but the predicted VSS was much higher. The primary reason for the higher VSS can be hypothesized to be the high fraction of undigested solids (shown in fig-XX, Appendix-2); this leaves us to the conclusion of using a higher hydrolysis rate of increasing the rapidly hydrolysable fraction of influent COD. After several iteration a particular set of coefficients were determined to have most reasonable fit, these coefficients and the final iteration using them is discussed in detailed.

SECTION-3

Model Simulation using the measured influent COD concentration data and coefficients determined through model iterations

Assumptions and Inputs

1. The influent COD concentration data was used as model input

2. Measured proximate analysis was used after some unit conversions (elaborated in Appendix-B)

3. Percentage influent inert was assumed to be 1% in concentration

4. Hydrolysis rate coefficient for both slowly and rapidly degradable fraction was 1.5 day^{-1}

5. Decay rate was changed from 0.02 (D.Stallman thesis) to 0.04 day^{-1} to lower the VSS in late February, 2014

6. Stallman's moles N/g protein COD coefficient of 0.009414 was changed to 0.008403 based on literature reference

7. Other coefficients were same as the model simulation using VS data (described in SECTION-1)

Model simulation predictions and comparisons with measured data

Figure 8 Predicted VSS in the digester (total, inert, undigested, biomass)

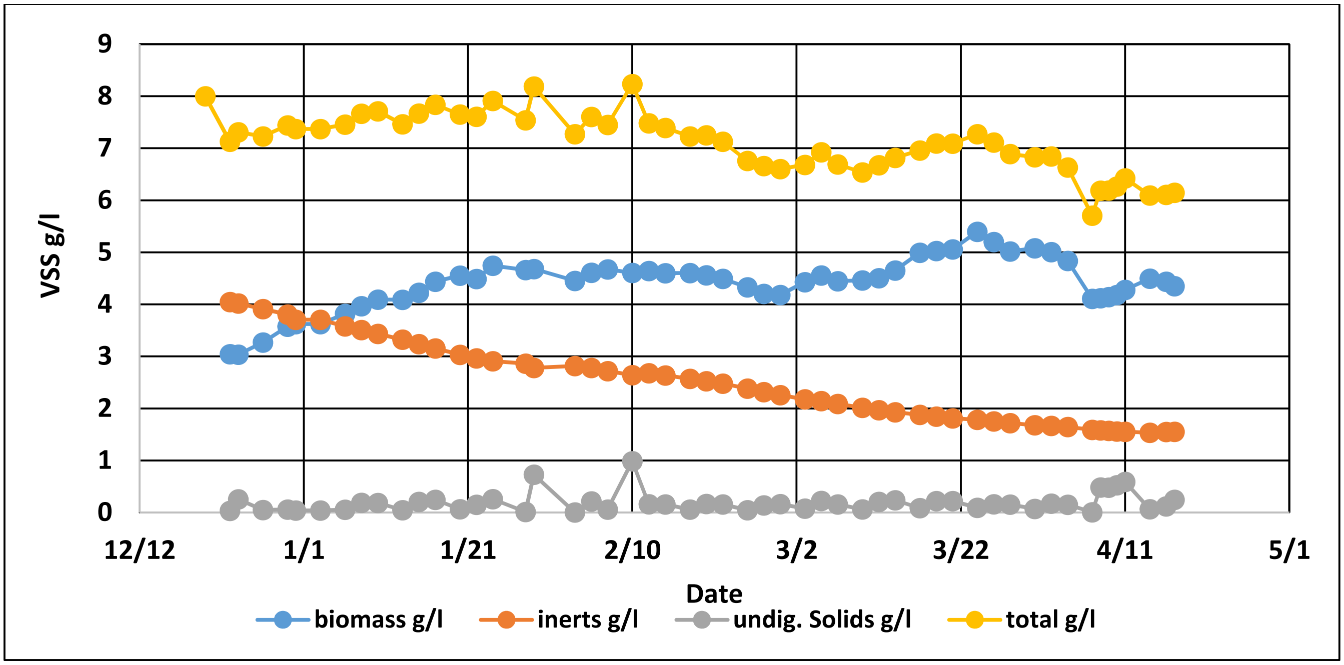
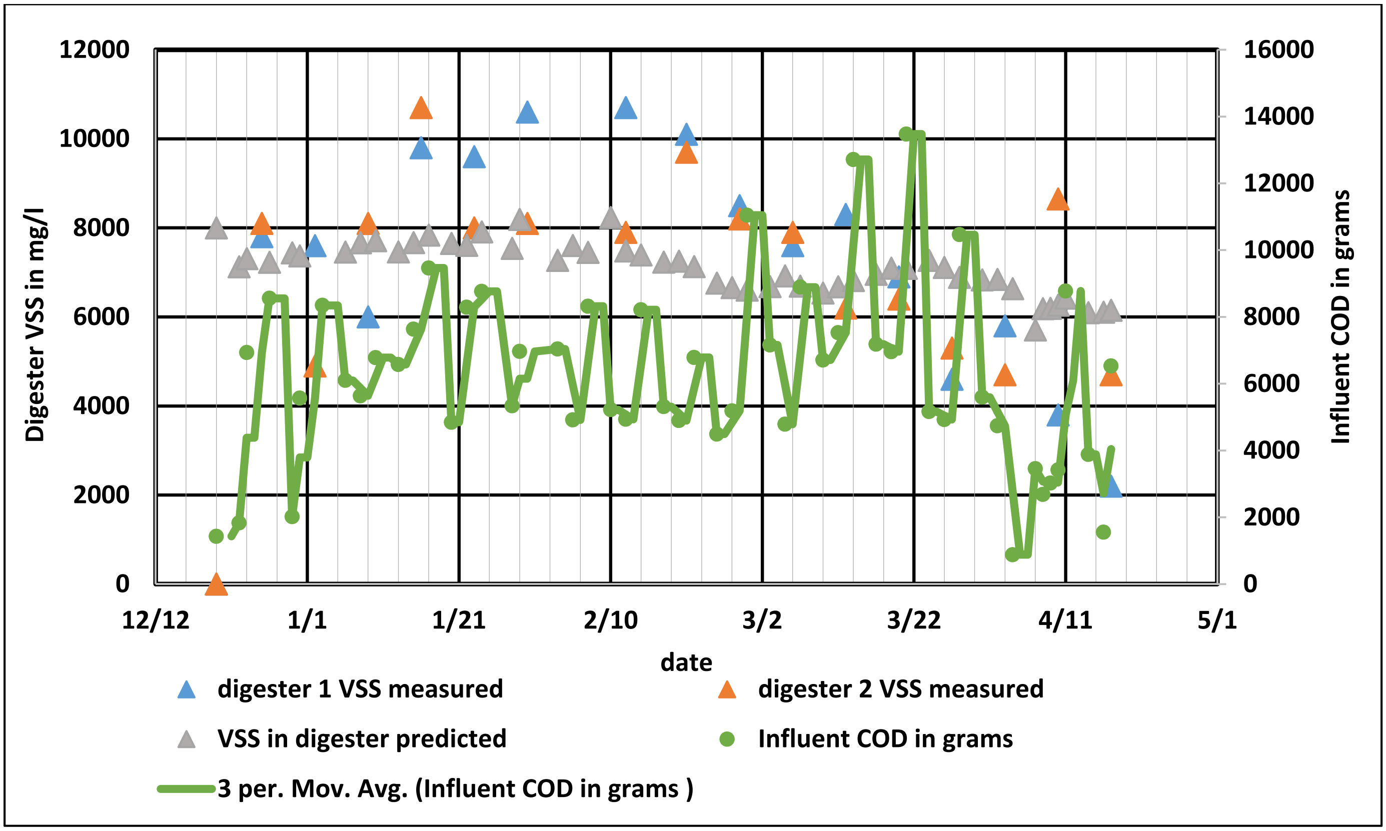


Fig-1 shows that due to the high hydrolysis rate used almost all the solids are digested (grey). The biomass is maintained between 3-5 g/l. The total predicted digester VSS concentration is compared to the measured digester VSS concentration in Fig-2.

Figure 2 VSS in digester predicted and measured; influent COD



*(3 per. Mov. Avg. is 3 Period Moving Average)

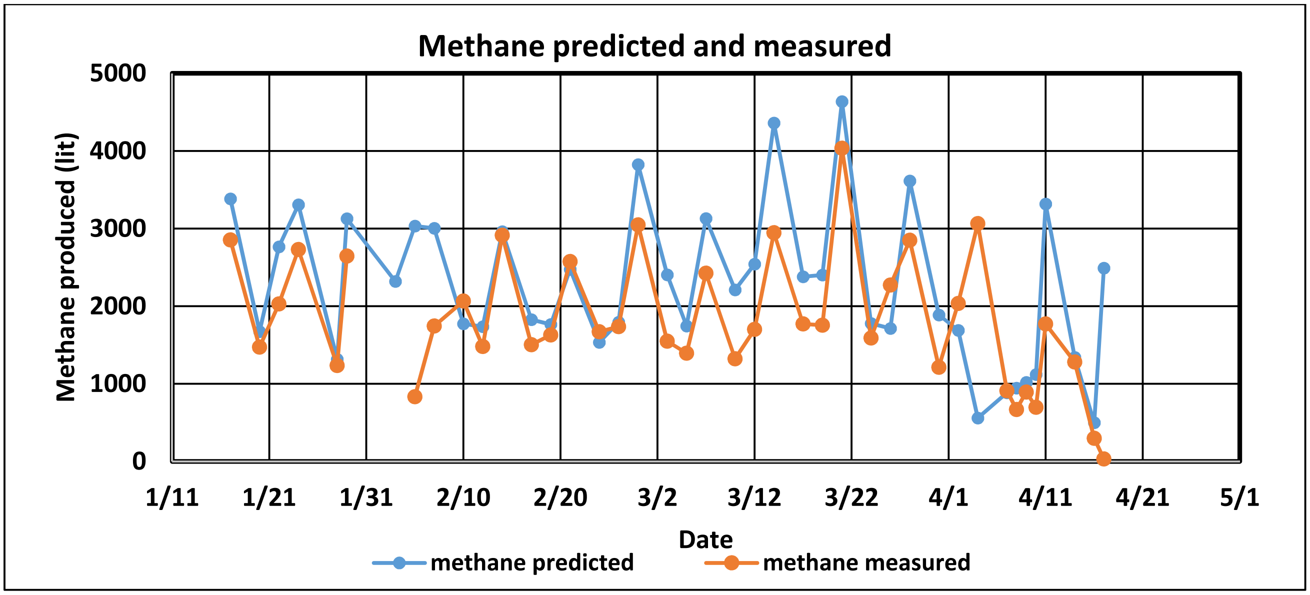
Observations from Fig-2

- The predicted digester VSS concentration (grey) is not able to match the measured digester VSS concentration trend in the digester 1 and 2 (blue and orange).
- The measured VSS in the digester 1 and 2 shows some drastic change in the VSS concentration for example: between 1/9 and 1/16 there is a jump of 2600 mg/l in the digester 2 VSS with no corresponding increase in the influent COD
- There is consistent increasing trend in the VSS from startup till 2/20 despite no corresponding increase in influent COD (grams)
- There is a decrease in the digester VSS concentration after late Feb despite an increase in the average influent COD which self-contradicts

Conclusions from Fig-2

- The mostly likely conclusion is that the measured VSS concentration data is not reliable

Figure 3 Total Methane predicted over feed interval (liter)



From the fig-3 we can observe that the predicted methane is slightly over predicted at several places but has a good correlation to measured data overall.

Figure 4 Correlation between predicted and measured total methane generation per feed interval (liters)

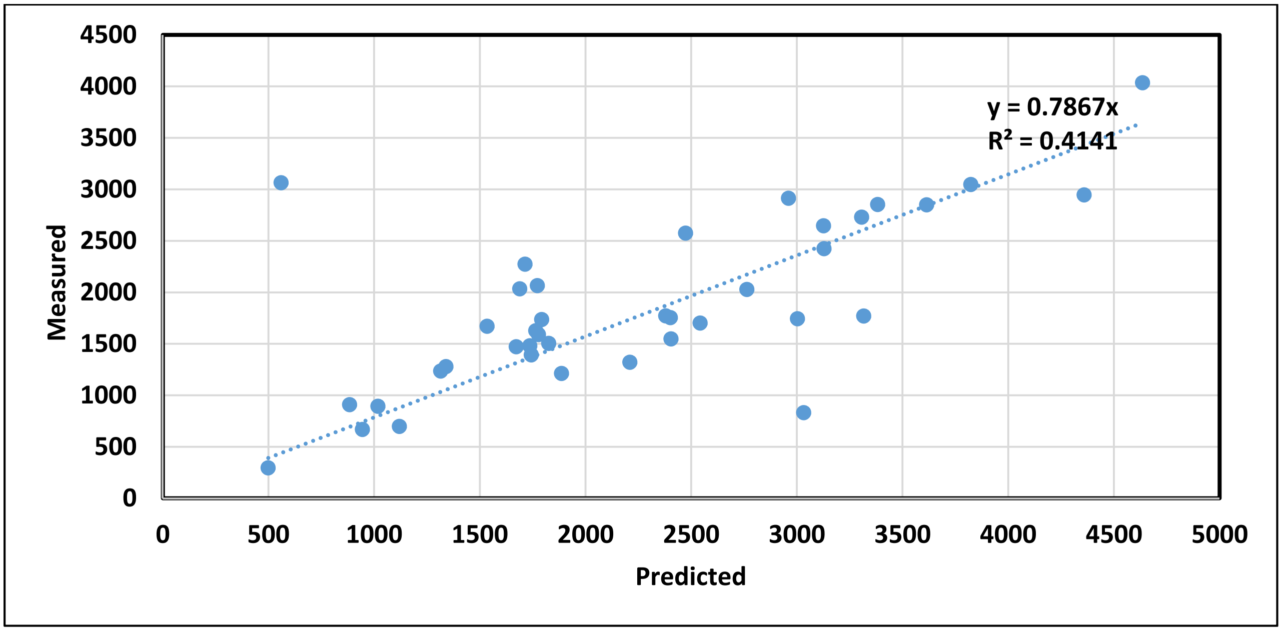


Figure 5 Methane generation rate in liter per hour on January17-19, 2014 (72 hour interval)
* (total methane measured is 2853 liter and total methane predicted is 3383 liter in fig 5)

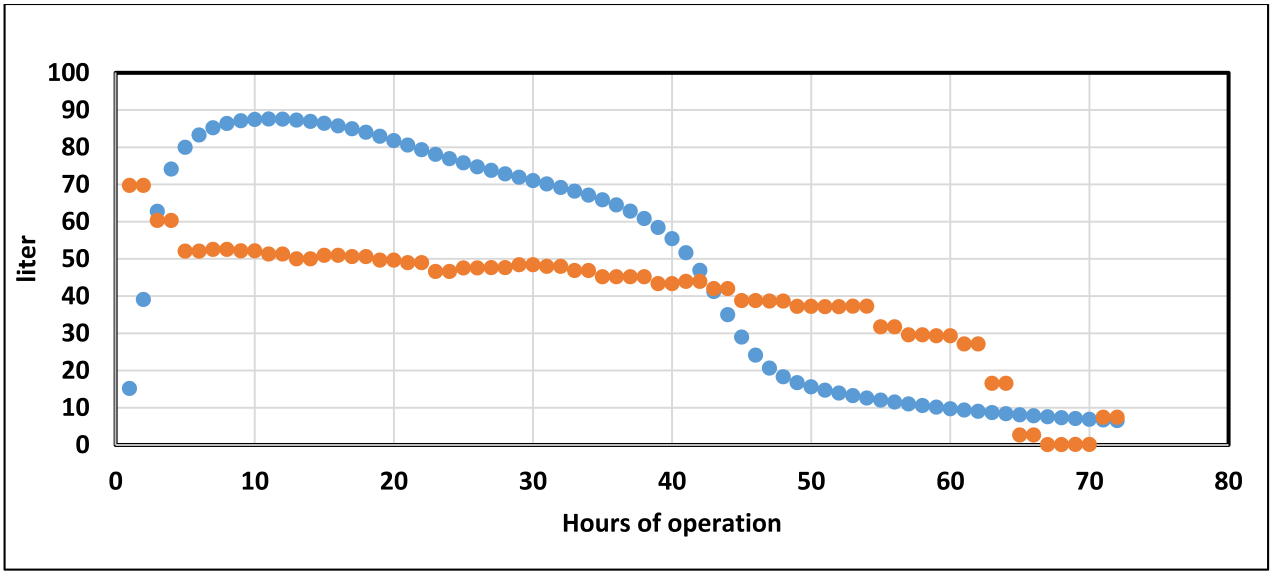


Figure 6 Methane generation rate in liter per hour on January20-21, 2014 (48 hour interval)

* (total methane measured is 1471 liter and total methane predicted is 1600 liter in fig 6)

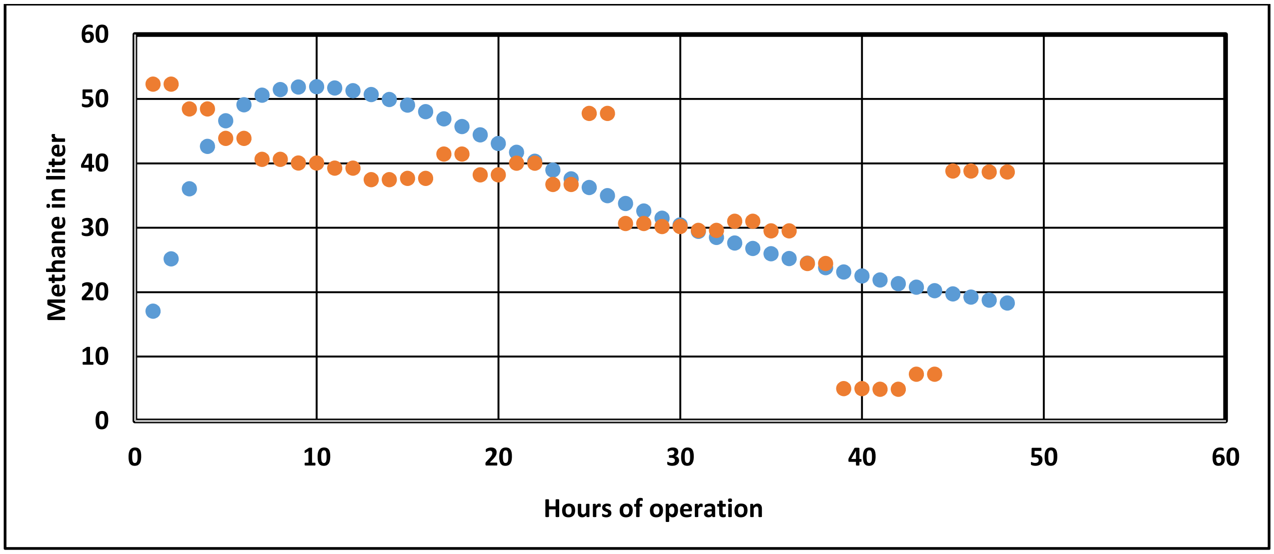


Fig-5 suggest that the hydrolysis rate chosen i.e. 1.5 per day is too high and Fig-6 suggests that the measured and predicted generation closely matches to some degree. This suggests that food waste composition may be changing drastically over the period of operation. Thus we face a limitation of inaccurately predicting the hydrolysis of food waste as the hydrolysis rate and fractions are fixed.

Very good Ammonia and Alkalinity fit was seen when we used the measured influent COD data.

Figure 6 Ammonia in digester predicted and measured

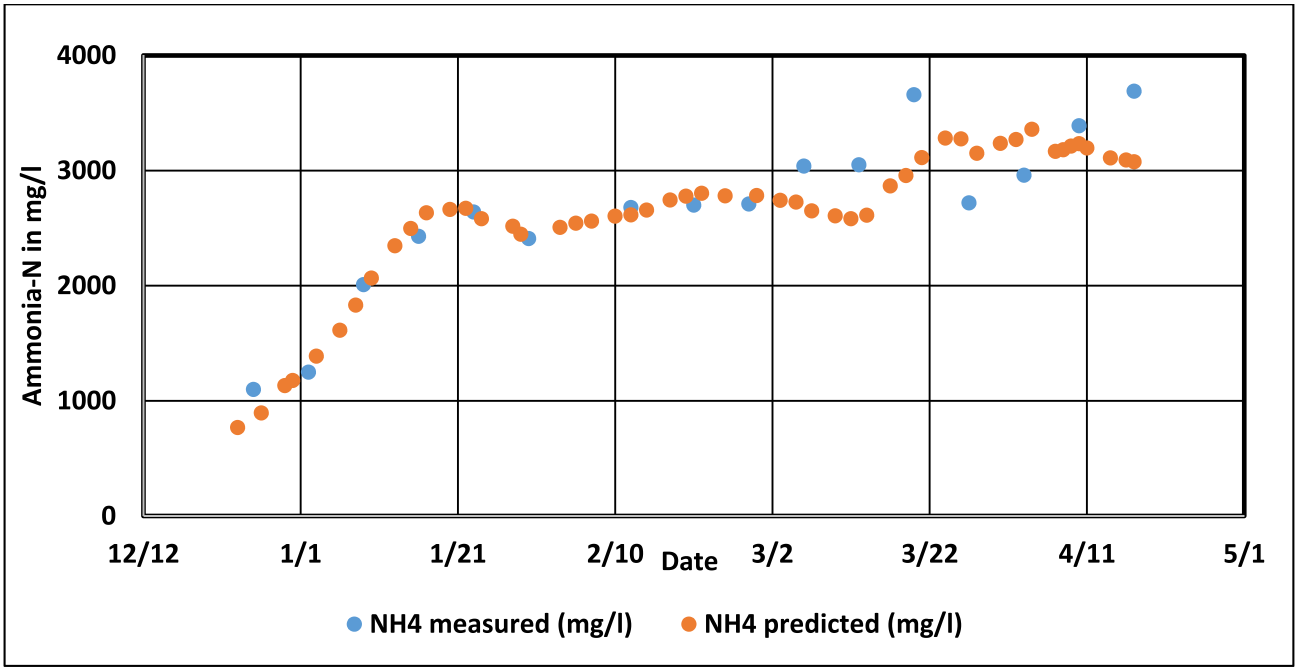
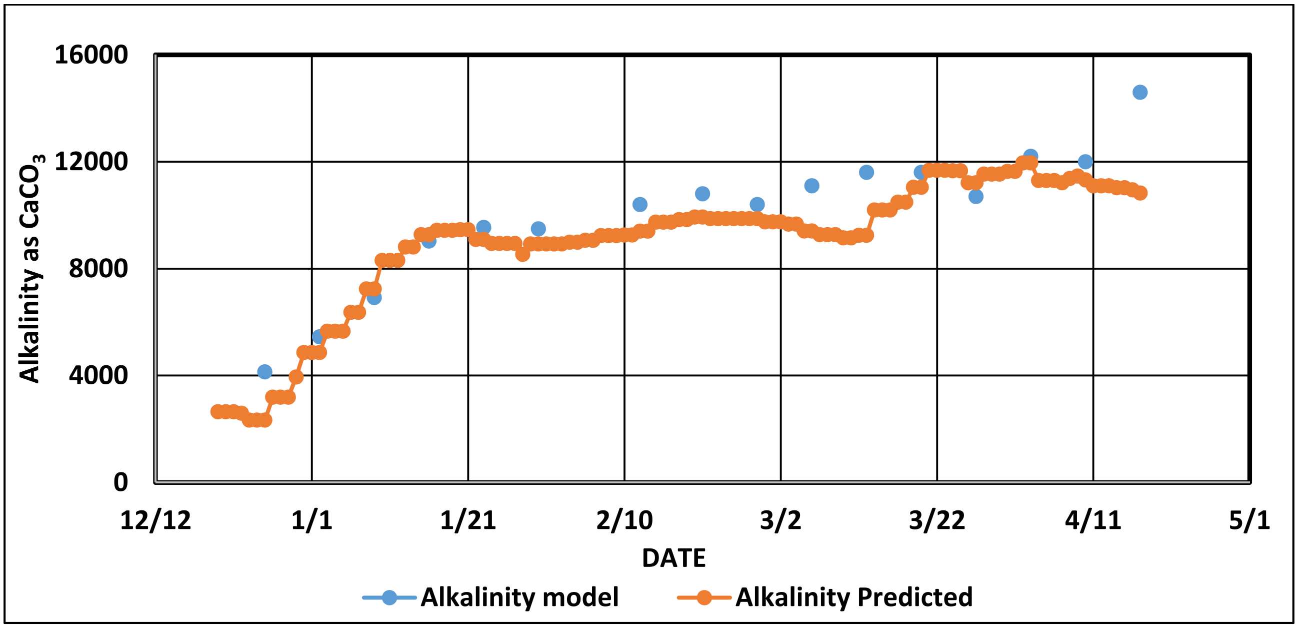


Figure 7 Alkalinity in digester predicted and measured



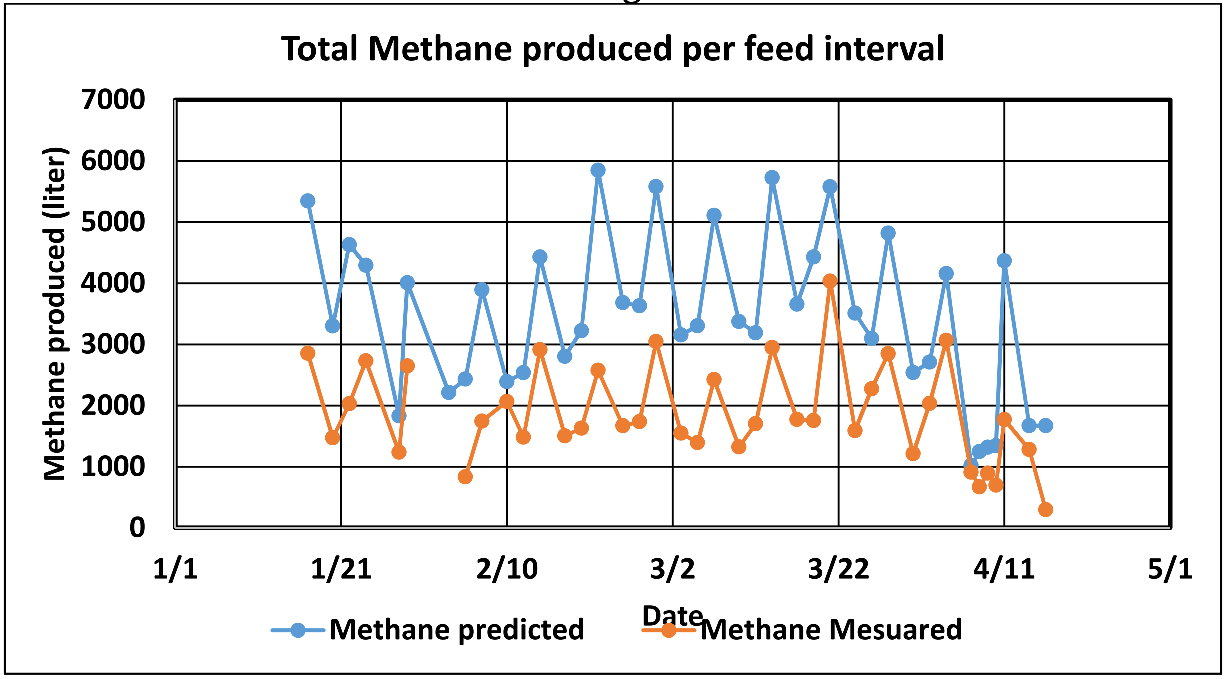
Conclusion

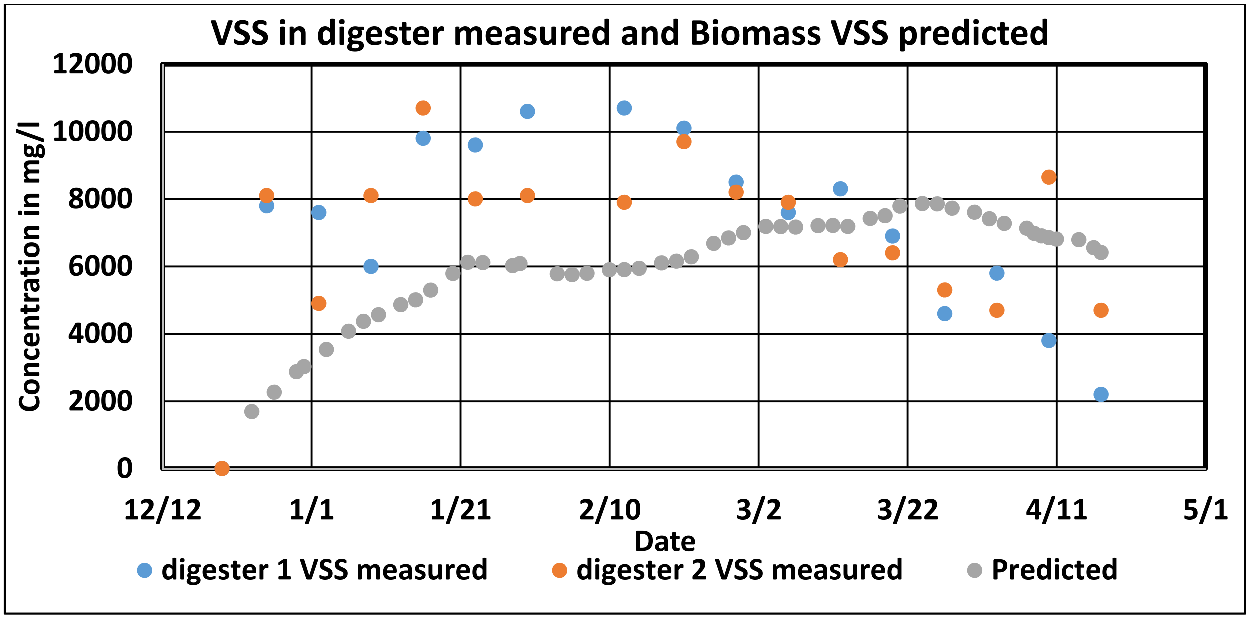
The decrease in the VSS in the later period cannot be replicated in the model because of following reasons:

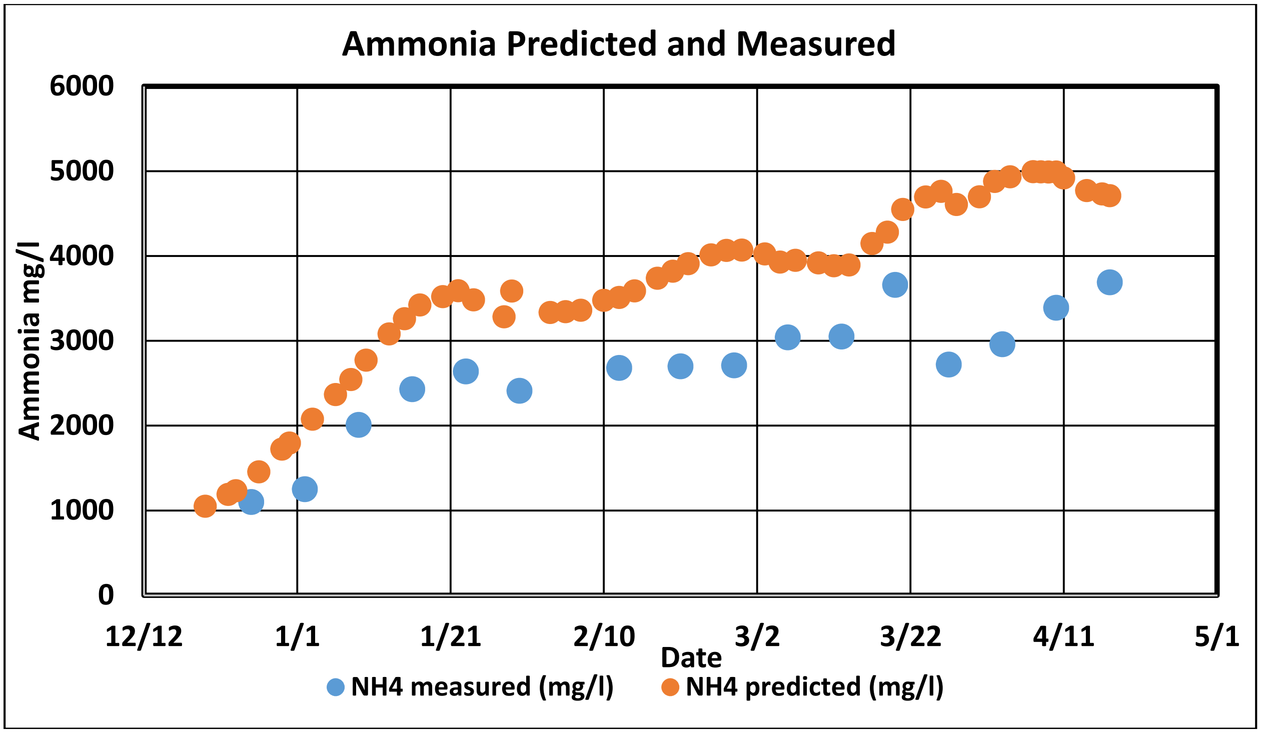
- A higher hydrolysis rate used which leaves almost negligible undigested solids, which eliminates the chance of using a yet higher hydrolysis rate which possibly could suppress the VSS trend in the post Feb-20 region.
- The model prediction of the ammonia and the alkalinity was fairly accurate and methane too had a closer fit with measured data; only the digester VSS prediction was not matching to the measured data. This facts points out that there may be some discrepancy in the measured VSS data.
- The point that the digester VSS data was not accurate is further supported by the fact that despite an increase in the influent COD the measured data shows a decreasing trend in the digester VSS during Mid Feb to April (fig-2).

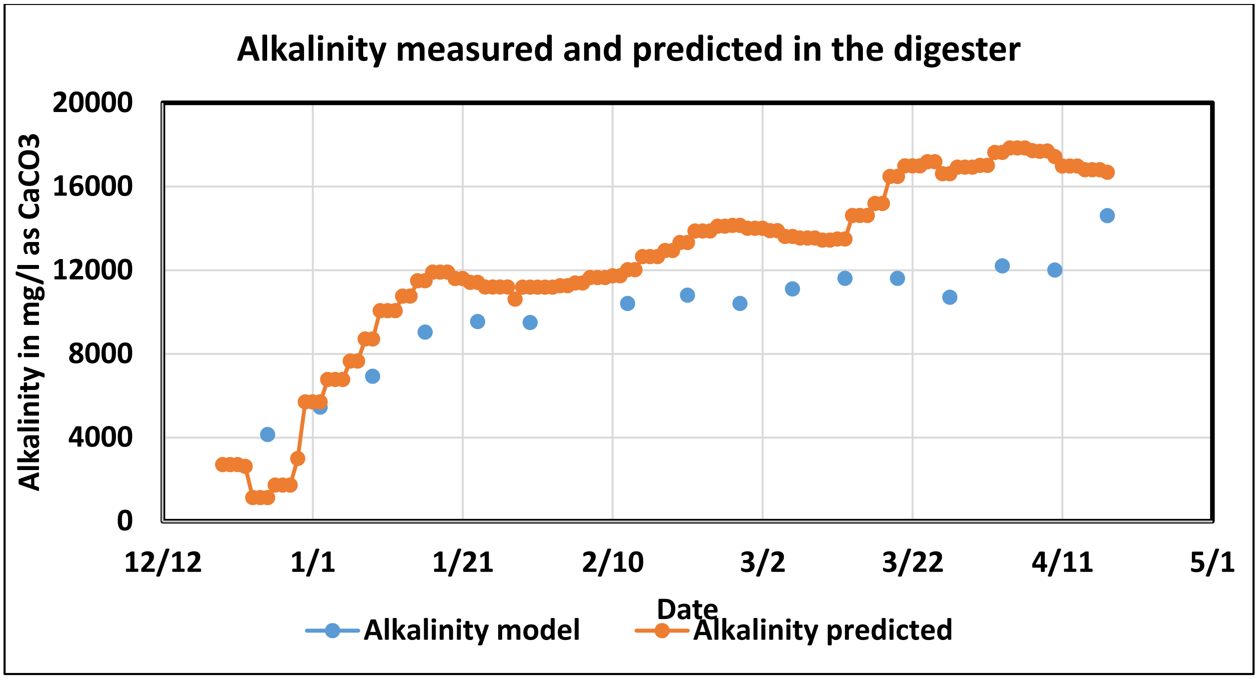
APPENDIX-1

Model simulation results using measured influent VS data

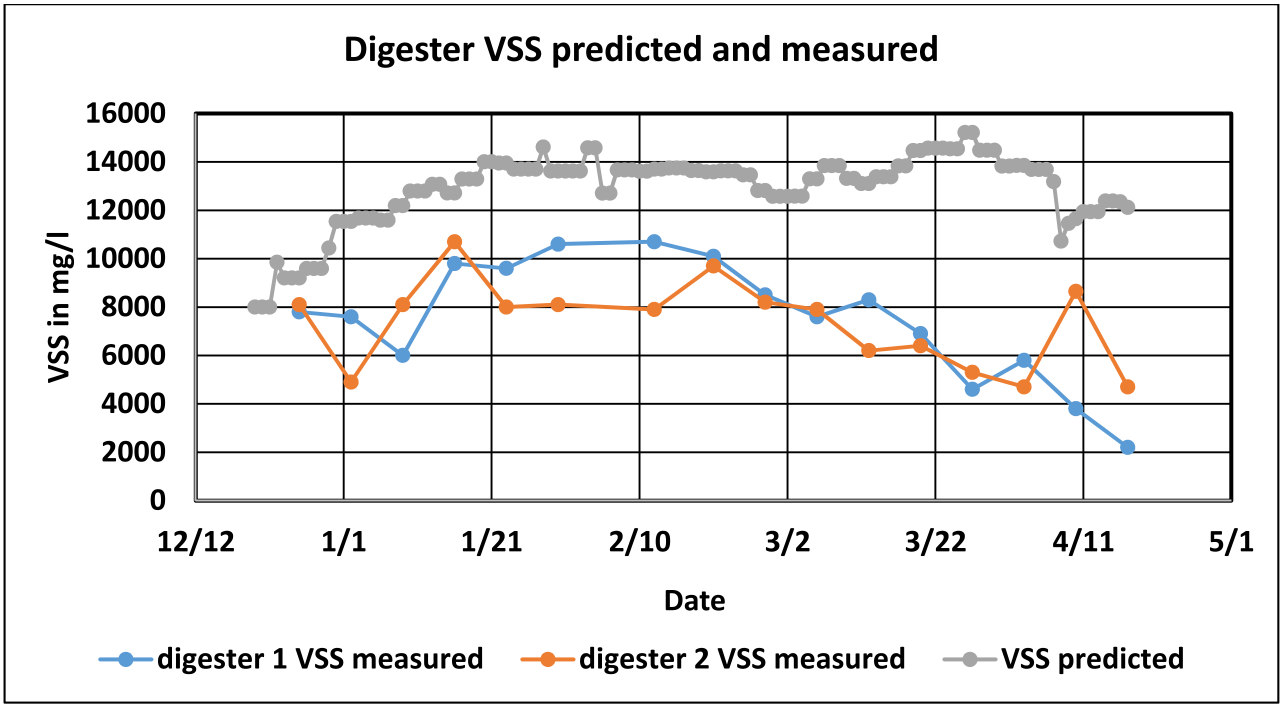


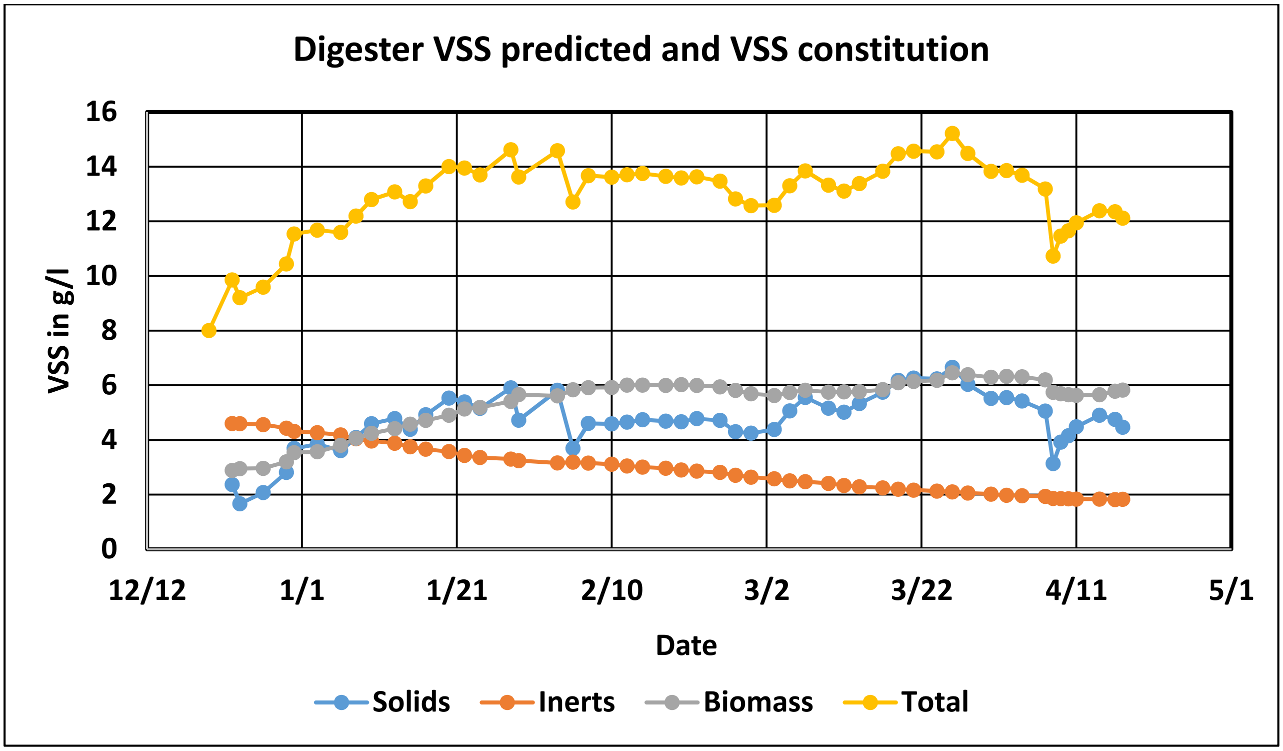


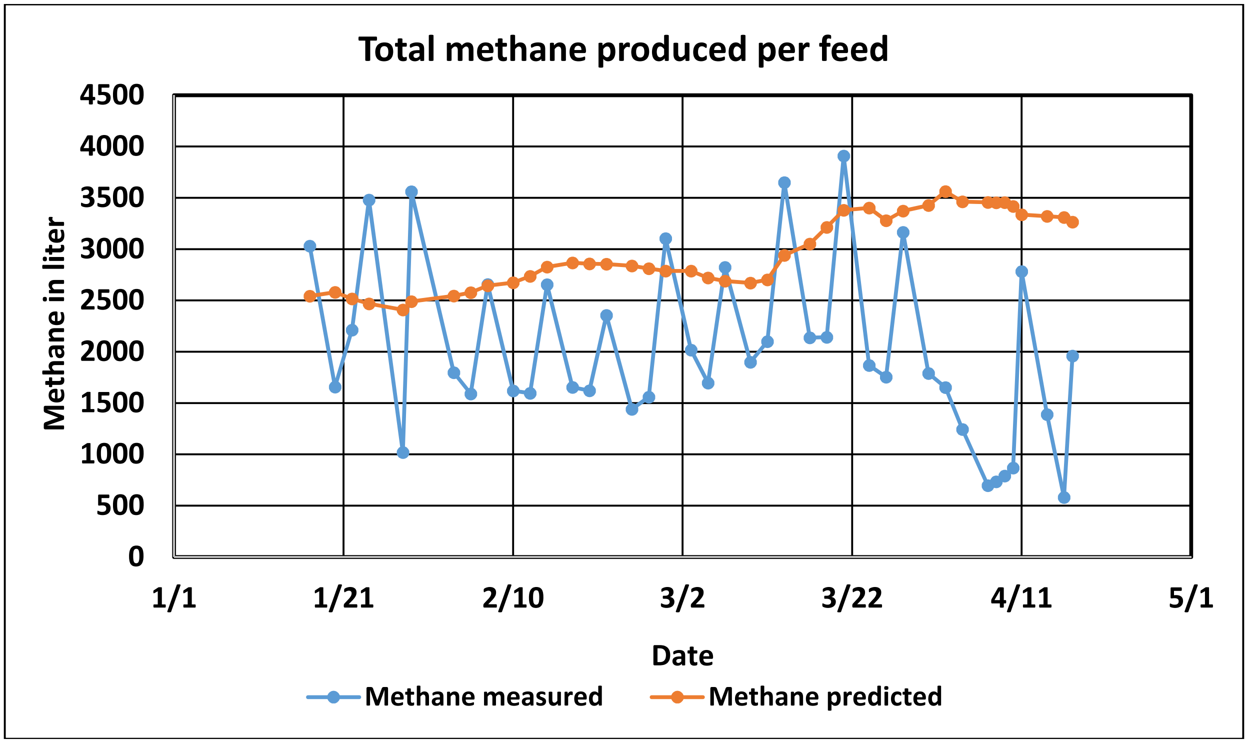

Ammonia Predicted and Measured
Ammonia mg/l
6000
5000
4000
3000
2000
1000
0
12/12
1/1
1/21
2/10
3/2
3/22
4/11
5/1
Date
NH4 measured (mg/l)
NH4 predicted (mg/l)

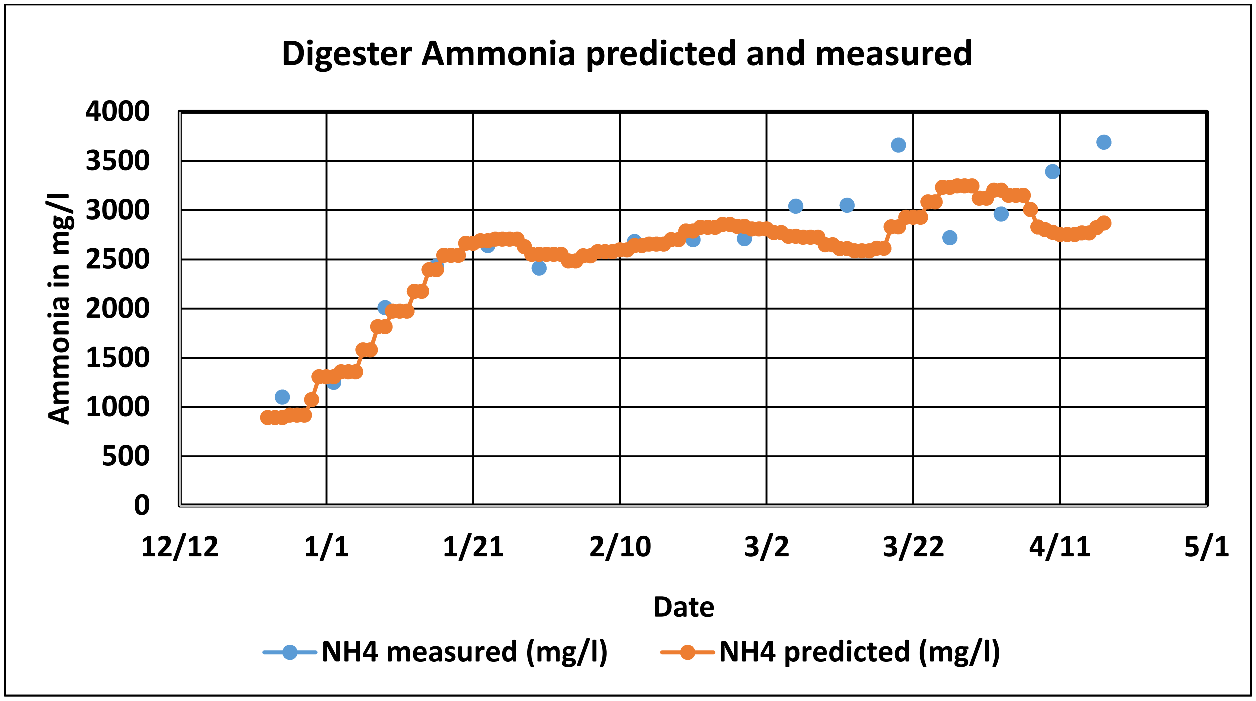

Alkalinity measured and predicted in the digester
Alkalinity in mg/l as CaCO3
20000
16000
12000
8000
4000
0
12/12
1/1
1/21
2/10
3/2
3/22
4/11
5/1
Date
Alkalinity model
Alkalinity predicted

APPENDIX-2
Model simulation results using measured influent COD data and Stallman Coefficient






Total methane produced per feed
Methane in liter
4500
4000
3500
3000
2500
2000
1500
1000
500
0
1/1
1/21
2/10
3/2
3/22
4/11
5/1
Date
Methane measured
Methane predicted


Digester Ammonia predicted and measured
Ammonia in mg/l
4000
3500
3000
2500
2000
1500
1000
500
0
12/12
1/1
1/21
2/10
3/2
3/22
4/11
5/1
Date
NH4 measured (mg/l)
NH4 predicted (mg/l)

Appendix-3
Initial conditions used to simulate the food waste digester

Variable	**Value**
Rapidly Hydrolysable (Xrh)	0.426678
Slowly Hydrolysable (Xsh)	3.598118
Preexisitng RH (Xrh0)	0
Preexisting SH (Xsh0)	0
Soluble Inerts (Si)	0.90192
Particulate Inerts (Xi)	6.46
Soluble Amino Acids (Saa)	3.69E-03
Amino Acid Utilizers (Xaa)	0.61077
Soluble Fatty Acids (Sfa)	0.0908
Fatty Acid Utilzers (Xfa)	0.580196
Soluble Sugars (Ssu)	8.23E-03
Sugar utilizers (Xsu)	1.109
Propionate (Spro)	0.032058
Propionate Utilzers (Xpro)	0.1533
Valerate (Sva)	8.39E-03
Butyrate (Sbu)	0.013345
But/Val Utilzers (Xc4)	0.285
Acetate (Sac)	0.080966
Acetate Utilzers (Xac)	0.908
Hydrogen Utilzers (Xh2)	0.448
Soluble Hydrogen (Sh2)	1.66E-07
Soluble Methane (Sch4)	0.06441
Methane Gas (Sgas_ch4)	1.496109
CO2 Gas (Sgas_co2)	0.016828
Hydrogen Gas (Sgas_h2)	5.00E-06
Soluble Inorganic Carbon (SIC)	0.068248

Soluble Ammonium (Snh4)	0.058569
Proton (SH)	1.00E-07
Bicarbonate (SHCO3)	0.056894
Soluble CO2 (Sco2)	0.011354
Feed2 RH (Xrh2)	0
Feed2 SH (Xsh2)	0
Composite Material (Xc)	1.07E-04
Composite Material (Xc0)	0
Composite Material (Xc2)	0
Endogenous Decay (Xed)	6.86E-06
pH Inhibition for Acetate Utilizers	1

Appendix N: Sludge Dewatering Test

Dewatering Evaluation of U.S. Air Force Academy Food Waste Digester

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Claire W. Carlson Chair in Environmental Engineering
Bucknell University
Lewisburg, PA

OVERVIEW

A dewaterability test was performed to evaluate the food waste digestate from the U.S. Air Force Academy anaerobic digester. Testing was performed using a standardized protocol developed at Bucknell University such that the only variable is the digestate characteristics. In addition, the cation and PO_4^{3-} concentrations were measured.

TESTING METHODS

Dewaterability. The dewaterability of the samples was analyzed using a standardized laboratory protocol developed at Bucknell University. First, the optimum polymer dose was determined by establishing the polymer dose-response curve using capillary suction time (CST) as the measure of conditioning. The polymer was an SNF 6440 SH, high molecular weight, cation polymer made to a 0.5% concentration on the day of the dewatering experiment. A 500 mL sample of digestate is placed in a 2 L, baffled circular container. The polymer is added to the solids and mixed using a single paddle mixer at 563 rpm (G = 1000/s) for 30 s, followed by 54 rpm (G = 100/s) for 90 s, after which the CST was measured. The dosage with the lowest CST is considered the optimum polymer dose, and this sample will be dewatered.

Dewatering is performed by first gravity draining the solids on belt filter press fabric. The drained solids are then placed in a specially designed belt filter press centrifuge cup. These cups comprise a piece of belt filter press fabric that was suspended approximately half way up the depth of the cup, as shown in Figure 1. The samples are then centrifuged at 3000 x g for 10 minutes, and the cake is scraped off the belt filter press fabric for analysis of total solids (TS) and VS according to Standard Methods (APHA, 2012). The gravitational force can be adjusted to better simulate either belt filter press or centrifuge pressures experienced in full scale equipment. This method provides reproducible results that are similar to full-scale equipment.

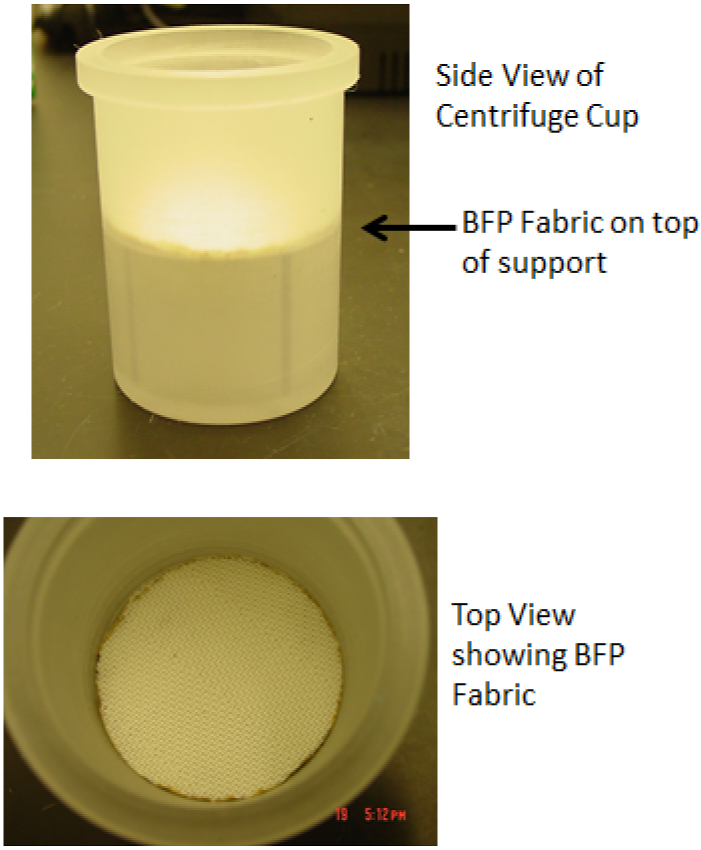
Side View of Centrifuge Cup
BFP Fabric on top of support
Top View showing BFP Fabric
19 5:12PM

Figure 1. Belt filter press centrifuge cups used for dewatering experiments.

Cations and PO_4^{3-} Analysis. The cations, Na+, NH4+, K+, Mg2+, Ca2+ and PO43- were all analyzed using a ion chromatography. A 50 mL aliquot was placed in a centrifuge tube and centrifuge for 10 minutes at 3000 x g. The centrate was then filtered through a 0.45 μm filter. Cations and anions were analyzed using ion chromatography. Specifically, the cations Na+, NH4+, K+, Mg2+, and Ca2+ were analyzed using a cation exchange column and the phosphate concentration was measured using an anion exchange column on a Dionex (Sunnyvale, CA) IC system.

RESULTS

The results of the testing are summarized in Table 1. The M/D ratio of the sample was relatively high, with a value of 53. The high M/D ratio is mainly due to the high ammonium and sodium concentrations with a relatively low concentration of calcium and magnesium. The dewaterability in terms of the cake solids averaged 9.5% in duplicate samples. This is the lowest cake solids measured in comparison to many other samples tested using this same laboratory protocol. Figure 1 shows the results of other testing in comparison to the US AF Academy sample. The reason for the lower cake solids is unknown, but could be due to the relatively high VS/TS fraction of the digestate which is around 0.85. Most of the samples tested had VS fractions between 0.6-0.78.

Table 1. Summary of testing results for digestate sample.

Parameter	**Value**
Digester TS (%)	2.37
Soluble PO_4^{3-} (mg/L)	85
Soluble Na^+ (mg/L)	545
Soluble NH_4^+ (mg/L)	2740
Soluble K^+ (mg/L)	748
Soluble Ca^{2+} (mg/L)	56
Soluble Mg^{2+} (mg/L)	11
M/D Ratio	53
Cake Solids (%)	9.5

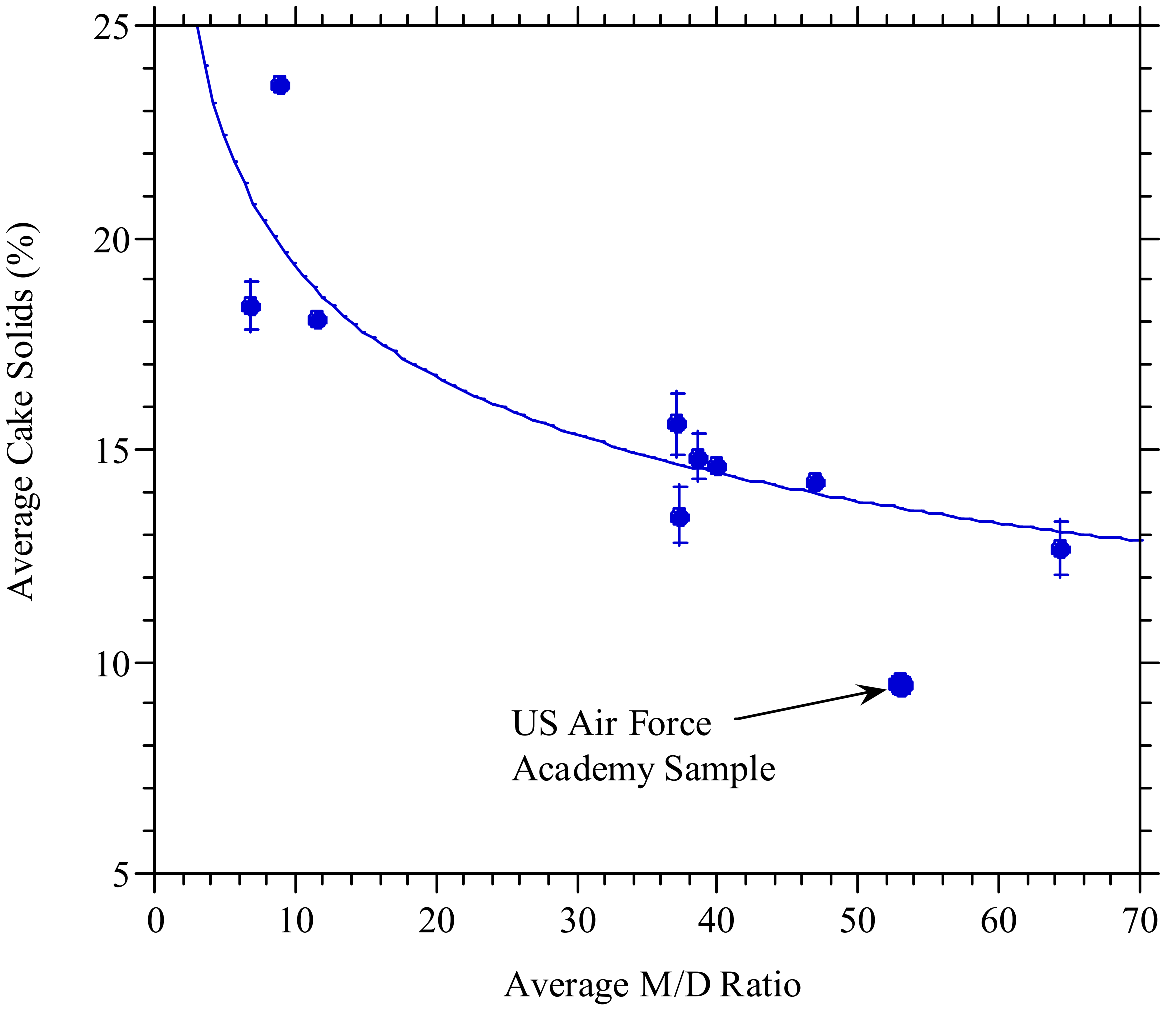

Figure 1. Cake solids as a function of average M/D Ratio. Adapted from Higgins et al. (2014).

SUMMARY

The results from the testing show that the digestate has relatively poor dewaterability likely due to a combination of a high M/D ratio and low inert concentration and possibly other unknown factors.

REFERENCES

Higgins, M.J., S. Beightol, C. Bott, P. Schauer (2014) Does Bio-P Impact Dewatering after Anaerobic Digestion? *Proc. 2014 Water Env. Federation Annual Conference,* Austin, Texas.

Appendix O: Greenhouse Gas Accounting Calculations

$\text{Mgal} := 1000000 \cdot \text{gal}$

Calculate Methane Production in 1 Mgal facility

$CH_4 := 270 \cdot \frac{L}{kg}$ Volume of methane produced per mass COD fed to digester

$COD := 120000 \cdot \frac{mg}{L}$ COD of Feed

$CH_{4.produced} := COD \cdot 1 \cdot \frac{\text{Mgal}}{40 \cdot \text{day}} \cdot CH_4 = 1.083 \times 10^5 \cdot \frac{ft^3}{day}$ 40 d is SRT in Phase III

Calculate net gasoline gallon equivalents generated

$\text{Boiler} := 109 \cdot kW$ From parasitic loads calculation

$CH_{4.LHV} := 914 \cdot \frac{BTU}{ft^3}$

$CH_{4.recovery} := 93.6\%$ From TDA report

$\text{gasoline}_{LHV} := 114000 \cdot \frac{BTU}{gal}$

$$\text{gas}_{net} := \frac{CH_{4.produced} \cdot CH_{4.LHV} \cdot CH_{4.recovery} - \text{Boiler}}{\text{gasoline}_{LHV}} = 2.682 \times 10^5 \cdot \frac{gal}{yr}$$

Calculate CO2 offset from bioCNG production

$\text{gas}_{ghg} := 8.78 \cdot \frac{kg}{gal}$

$CO2_{offset} := \text{gas}_{net} \cdot \text{gas}_{ghg} = 2.596 \times 10^3 \cdot \frac{ton}{yr}$

Calculate Energy Input

$\text{elect}_{demand} := 86 \cdot kW$ From parasitic loads calc.

$\text{elec}_{ghg} := 1.34 \cdot \frac{lb}{kW \cdot hr}$

$CO2_{produced} := \text{elect}_{demand} \cdot \text{elec}_{ghg} = 505.086 \cdot \frac{ton}{yr}$

Calculate CO2 in biogas

$$CO_{2.biogas} := CH_{4.produced}\cdot\frac{40\%}{60\%}\cdot\frac{44\cdot gm}{22.4\cdot L} = 1.617\times10^{3}\cdot\frac{ton}{yr}$$

Calculate Net GHG emissions

$$GHG_{net} := CO2_{produced} + CO_{2.biogas} - CO2_{offset}$$

$$GHG_{net} = -473.987\cdot\frac{ton}{yr}$$

Comparison from WERF Sustainable Food Waste Evaluation

$$Landfill := 0.15\cdot\frac{lb}{lb}\cdot92000\cdot\frac{mg}{L}\cdot\frac{1\cdot Mgal}{40\cdot day} = 525.796\cdot\frac{ton}{yr}$$

Tons CO2/year produced
92000 mg/L is the TS of the feed

$$Compost := 0.05\frac{lb}{lb}\cdot92000\cdot\frac{mg}{L}\cdot\frac{1\cdot Mgal}{40\cdot day} = 175.265\cdot\frac{ton}{yr}$$

$$Food\_waste_{dry} := \frac{Landfill}{0.15} = 3.505\times10^{3}\cdot\frac{ton}{yr}$$

$$Food\_waste_{wet} := \frac{Food\_waste_{dry}}{9.2\%} = 104.318\cdot\frac{ton}{day}$$

$$Food\_waste_{wet} = 9.464\times10^{4}\cdot\frac{kg}{day}$$

Appendix P: Economic Analysis Calculations

Estimate Biogas Production from Military Base Food Waste

Base Sizes for Comparison

$$Pop := \begin{pmatrix} 10000 \\ 20000 \\ 40000 \end{pmatrix} \cdot person$$

Per capita food waste generation

$$Production_{wet} := 0.635 \cdot \frac{lb}{person \cdot day}$$

Based on EPA 2012 document listing 4.38 lb/person/day and food waste fraction of 14.5%

$$Production := Production_{wet} 24.5\% = 0.156 \cdot \frac{lb}{person \cdot day}$$

dry pounds per day based on ESTCP study

Food Waste Characteristics and Performance from ESTCP Pilot Data

$$TS_{fw} := 245000 \frac{mg}{L}$$

$$VS_{fw} := 96\%$$

$$COD_{fw} := 324000 \cdot \frac{mg}{L}$$

$$TS_{FOG} := 100\%$$

$$VS_{FOG} := 100\%$$

$$COD_{FOG} := 2.89 \cdot \frac{gm}{gm}$$

$$\rho_{fw} := 1.1 \cdot \frac{gm}{ml}$$

$$\rho_{FOG} := 0.95 \cdot \frac{gm}{ml}$$

$$VSR_{all} := 81\%$$

Based on pilot results

$$VSSR_{all} := 94\%$$

$$CH4_{all} := 7.0 \cdot \frac{ft^3}{lb}$$

$$SELR_{all} := 0.44 \cdot \frac{g}{g \cdot day}$$

$$CH4_{LHV} := 914 \cdot \frac{BTU}{ft^3}$$

Determine Undiluted Feed Characteristics Assuming 10% FOG by COD

$$COD_{feed} := \frac{1.2 \cdot L \cdot \rho_{FOG} \cdot COD_{FOG} + 100 \cdot L \cdot COD_{fw}}{101.2 \cdot L} = 3.527 \times 10^5 \cdot \frac{mg}{L}$$

$$VS_{feed} := \frac{1.2 \cdot L \cdot VS_{FOG} \cdot \frac{1000000 \cdot mg}{L} + 100 \cdot L \cdot VS_{fw} \cdot TS_{fw}}{101.2 \cdot L} = 2.443 \times 10^{5} \cdot \frac{mg}{L}$$

$$Food_{waste} := \frac{Production \cdot Pop}{TS_{fw}} = \begin{pmatrix} 2.88 \times 10^{3} \\ 5.761 \times 10^{3} \\ 1.152 \times 10^{4} \end{pmatrix} \cdot \frac{L}{day}$$

$$Feed_{vol} := Food_{waste} \cdot 1.012 = \begin{pmatrix} 2.915 \times 10^{3} \\ 5.83 \times 10^{3} \\ 1.166 \times 10^{4} \end{pmatrix} \cdot \frac{L}{day}$$

$$COD_{mass.feed} := Feed_{vol} \cdot COD_{feed} = \begin{pmatrix} 1.028 \times 10^{3} \\ 2.056 \times 10^{3} \\ 4.112 \times 10^{3} \end{pmatrix} \cdot \frac{kg}{day}$$

$$VS_{mass.feed} := Feed_{vol} \cdot VS_{feed} = \begin{pmatrix} 712.013 \\ 1.424 \times 10^{3} \\ 2.848 \times 10^{3} \end{pmatrix} \cdot \frac{kg}{day}$$

Determine the VSS Concentration in the CSTR

$$VSS_{CSTR} := VS_{feed} \cdot \left(1 - VSSR_{all}\right) = 1.466 \times 10^{4} \cdot \frac{mg}{L}$$

Assume in feed VS = VSS

Determine CSTR Size based on SELR from pilot data

$$Vol_{CSTR} := \frac{COD_{feed} \cdot Feed_{vol}}{VSS_{CSTR} \cdot SELR_{all}} = \begin{pmatrix} 159.43 \\ 318.86 \\ 637.72 \end{pmatrix} \cdot m^{3}$$

Determine CSTR Heating Demand (assume additional 15% for shell losses from tanks)

$$Heat_{demand} := Feed_{vol} \cdot 8.34 \cdot \frac{lb}{gal} \cdot 1 \cdot \frac{BTU}{lb \cdot R} \cdot (100 - 60) \cdot (R) = \begin{pmatrix} 3.137 \\ 6.274 \\ 12.547 \end{pmatrix} \cdot kW$$

Determine Methane Production from CSTR

$$VS_{destroyed} := Feed_{vol} \cdot VS_{feed} \cdot VSR_{all} = \begin{pmatrix} 6.675 \times 10^{-3} \\ 0.013 \\ 0.027 \end{pmatrix} \frac{kg}{s}$$

$$CH4_{biogas} := VS_{destroyed} \cdot CH4_{all} = \begin{pmatrix} 10.501 \\ 21.002 \\ 42.005 \end{pmatrix} \cdot \frac{m^3}{hr}$$

Equivalent NG production as 1000 cubic feet

$$Energy_{NG} := CH4_{biogas} \cdot \frac{CH4_{LHV}}{NG_{LHV}} \cdot 95\% = \begin{pmatrix} 2.871 \times 10^{3} \\ 5.743 \times 10^{3} \\ 1.149 \times 10^{4} \end{pmatrix} \cdot \frac{1000 \cdot cf}{yr}$$

Determine Energy Value of biogas as Electrical Power Generation

$$Energy_{biogas.power} := Energy_{NG} \cdot CH4_{LHV} \cdot 38\% = \begin{pmatrix} 33.344 \\ 66.687 \\ 133.375 \end{pmatrix} \cdot kW$$

Determine Energy Value of biogas as CHP Heat

$$Energy_{biogas.chp.heat} := CH4_{biogas} \cdot CH4_{LHV} \cdot 42\% = \begin{pmatrix} 41.722 \\ 83.443 \\ 166.887 \end{pmatrix} \cdot kW$$

Greater than heat demand no need for additional heating.

Determine Energy Value as natural gas (assume condensing boiler with on scrbbed gas with overall efficiency of 95%)

$$Energy_{biogas.boiler.heat} := CH4_{biogas} \cdot CH4_{LHV} \cdot 94\% - \frac{Heat_{demand}}{95\%} = \begin{pmatrix} 2.842 \times 10^{3} \\ 5.685 \times 10^{3} \\ 1.137 \times 10^{4} \end{pmatrix} \cdot \frac{GJ}{yr}$$

Determine Energy Value of biogas as vehicle fuel expressed in gallons per year (assume condensing boiler with on scrbbed gas with overall efficiency of 95%)

$$Energy_{biogas.veh} := \frac{CH4_{biogas} \cdot CH4_{LHV} - \frac{Heat_{demand}}{95\%}}{116000 \cdot \frac{BTU}{gal}} = \begin{pmatrix} 2.476 \times 10^{4} \\ 4.952 \times 10^{4} \\ 9.905 \times 10^{4} \end{pmatrix} \cdot \frac{gal}{yr}$$

In GGE

$$\mathrm{USAFA}_{\mathrm{production}} := \mathrm{Production}_{\mathrm{wet}}\cdot 4500\mathrm{person} = 1.429\cdot\frac{\mathrm{ton}}{\mathrm{day}}$$

Based on national average fuel production rates

$$\mathrm{tenthousand}_{\mathrm{production}} := \mathrm{Production}_{\mathrm{wet}}\cdot 10000\mathrm{person} = 3.175\cdot\frac{\mathrm{ton}}{\mathrm{day}}$$

$$\mathrm{USAFA\_Energy\_high}_{\mathrm{biogas.veh}} := 2.476\cdot 10^{4}\,\frac{\mathrm{gal}}{\mathrm{yr}}\cdot\frac{\mathrm{USAFA}_{\mathrm{production}}}{\mathrm{tenthousand}_{\mathrm{production}}} = 1.114\times 10^{4}\cdot\frac{\mathrm{gal}}{\mathrm{yr}}$$

$$\mathrm{USAFA}_{\mathrm{production.measured}} := 5\,\frac{\mathrm{ton}}{\mathrm{week}}$$

$$\mathrm{USAFA\_Energy\_low}_{\mathrm{biogas.veh}} := 2.476\cdot 10^{4}\,\frac{\mathrm{gal}}{\mathrm{yr}}\cdot\frac{\mathrm{USAFA}_{\mathrm{production.measured}}}{\mathrm{tenthousand}_{\mathrm{production}}} = 5.57\times 10^{3}\cdot\frac{\mathrm{gal}}{\mathrm{yr}}$$

Cost Calculations

$\varepsilon_p := 75\%$ $\varepsilon_m := 92\%$ Pump and motor efficiencies

Digester System

Capital Costs - Based on cost curve

Power Requirements - Assumes typical heads and flows for equipement.

$$\mathrm{Primary} := \frac{500\cdot\mathrm{gpm}\cdot 10\cdot\mathrm{ft}\cdot 8.34\cdot\frac{\mathrm{lbf}}{\mathrm{gal}}}{\varepsilon_p\cdot\varepsilon_m} = 1.366\cdot\mathrm{kW}$$

$$\mathrm{Secondary} := \frac{2\cdot 350\cdot\mathrm{gpm}\cdot 15\cdot\mathrm{ft}\cdot 8.34\cdot\frac{\mathrm{lbf}}{\mathrm{gal}}}{\varepsilon_p\cdot\varepsilon_m} = 2.868\cdot\mathrm{kW}$$

$$\mathrm{Solids}_{\mathrm{recirc}} := \frac{2\cdot 350\cdot\mathrm{gpm}\cdot 25\cdot\mathrm{ft}\cdot 8.34\cdot\frac{\mathrm{lbf}}{\mathrm{gal}}}{\varepsilon_p\cdot\varepsilon_m} = 4.78\times 10^{3}\,\mathrm{W}$$

$$\mathrm{Solids}_{\mathrm{trans}} := \frac{\mathrm{Feed}_{\mathrm{vol}}\cdot 40\cdot\mathrm{psi}}{\varepsilon_p\cdot\varepsilon_m} = \begin{pmatrix} 0.013 \\ 0.027 \\ 0.054 \end{pmatrix}\cdot\mathrm{kW}$$

$$\mathrm{Mixing} := \frac{6\cdot\frac{\mathrm{W}}{\mathrm{m}^{3}}\cdot\mathrm{Vol}_{\mathrm{CSTR}}}{\varepsilon_p\cdot\varepsilon_m} = \begin{pmatrix} 1.386 \\ 2.773 \\ 5.545 \end{pmatrix}\cdot\mathrm{kW}$$

$$\text{Total} := \text{Primary} + \text{Secondary} + \text{Solids}_{\text{recirc}} + \text{Solids}_{\text{trans}} + \text{Mixing} = \begin{pmatrix} 10.413 \\ 11.813 \\ 14.613 \end{pmatrix} \cdot \text{kW}$$

Moisture Removal System

Capital Costs- Use quote from C2 Energy originally for Miami-Dade

$$\text{Equip}_{\text{quote}} := 120000$$

$$\text{Size} := \frac{\text{CH4}_{\text{biogas}}}{63\%} = \begin{pmatrix} 16.669 \\ 33.337 \\ 66.674 \end{pmatrix} \cdot \frac{\text{m}^3}{\text{hr}}$$

$$\text{Size}_{\text{quote}} := 500 \cdot \frac{\text{ft}^3}{\text{min}}$$

$$\text{Equip} := \text{Equip}_{\text{quote}} \cdot \left(\frac{\text{Size}}{\text{Size}_{\text{quote}}} \right)^{0.6} = \begin{pmatrix} 1.135 \times 10^4 \\ 1.72 \times 10^4 \\ 2.606 \times 10^4 \end{pmatrix}$$

$$\text{Moist}_{\text{cap}} := \text{Equip} \cdot 2 \cdot 125\% = \begin{pmatrix} 2.836 \times 10^4 \\ 4.299 \times 10^4 \\ 6.516 \times 10^4 \end{pmatrix}$$

Power Requirements

$$\text{CH4}_{\text{cp}} := 2.2537 \cdot \frac{\text{kJ}}{\text{kg} \cdot \text{K}} \qquad \text{CH4}_{\rho} := 16.043 \cdot \frac{\text{kg}}{1000\text{mol}} \cdot \frac{1 \cdot \text{mol}}{22.4 \cdot \text{L}}$$

$$\text{CO2}_{\text{cp}} := 0.846 \cdot \frac{\text{kJ}}{\text{kg} \cdot \text{K}} \qquad \text{CO2}_{\rho} := 44.01 \cdot \frac{\text{kg}}{1000 \cdot \text{mol}} \cdot \frac{1 \cdot \text{mol}}{22.4 \cdot \text{L}}$$

$$\text{biogas}_{\text{cp}} := 63\% \cdot \text{CH4}_{\text{cp}} + 37\% \cdot \text{CO2}_{\text{cp}} = 1.733 \cdot \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$\text{biogas}_{\rho} := 63\% \cdot \text{CH4}_{\rho} + 37\% \cdot \text{CO2}_{\rho} = 1.178 \frac{\text{kg}}{\text{m}^3}$$

$$\text{biogas}_{\text{cool}} := \frac{\text{CH4}_{\text{biogas}}}{63\%} \cdot \text{biogas}_{\text{cp}} \cdot \text{biogas}_{\rho} \cdot (100 - 40) \cdot \text{R} = \begin{pmatrix} 0.315 \\ 0.63 \\ 1.26 \end{pmatrix} \cdot \text{kW}$$

$$water := \begin{pmatrix} .284 \\ .524 \\ 1.007 \end{pmatrix} \cdot \frac{gal}{hr}$$

$$water_{cool} := water \cdot 8.34 \cdot \frac{lb}{gal} \cdot \left[1 \cdot \frac{BTU}{lb \cdot R} \cdot (100 - 40) \cdot R + 2.26 \cdot \frac{kJ}{gm} \right] = \begin{pmatrix} 0.716 \\ 1.321 \\ 2.539 \end{pmatrix} \cdot kW$$

$$cooling_{power} := \frac{biogas_{cool} + water_{cool}}{2.2}$$

Assumes chiller COP of 2.2

$$cooling_{power} = \begin{pmatrix} 0.469 \\ 0.887 \\ 1.727 \end{pmatrix} \cdot kW$$

Iron Sponge - Based on quote from Clean Methane Option 2, System 3 for Miami-Dade

Capital Costs

$$Equip_{quote} := 1015000$$

$$Size := \frac{CH4_{biogas}}{63\%} = \begin{pmatrix} 16.669 \\ 33.337 \\ 66.674 \end{pmatrix} \cdot \frac{m^3}{hr}$$

$$Size_{quote} := 1700 \cdot \frac{ft^3}{min}$$

$$Equip := Equip_{quote} \cdot \left(\frac{Size}{Size_{quote}} \right)^{0.6} = \begin{pmatrix} 4.605 \times 10^4 \\ 6.98 \times 10^4 \\ 1.058 \times 10^5 \end{pmatrix}$$

$$Moist_{cap} := Equip \cdot 2 \cdot 125\% = \begin{pmatrix} 1.151 \times 10^5 \\ 1.745 \times 10^5 \\ 2.645 \times 10^5 \end{pmatrix}$$

Power Costs = 0

Media Costs

$$Media_{consumption} := \frac{Size}{Size_{quote}} \cdot 1855 \cdot \frac{lb}{day} = \begin{pmatrix} 10.705 \\ 21.411 \\ 42.821 \end{pmatrix} \cdot \frac{lb}{day}$$

$$\text{Media}_{\text{cost}} := \text{Media}_{\text{consumption}} \cdot \frac{1.76}{\text{lb}} = \begin{pmatrix} 6.882 \times 10^{3} \\ 1.376 \times 10^{4} \\ 2.753 \times 10^{4} \end{pmatrix} \cdot \frac{1}{\text{yr}}$$

SulfaTrap - Based on TDA report

Capital Costs

$$\text{Equip}_{\text{quote}} := 74000$$

$$\text{Size} := \frac{\text{CH4}_{\text{biogas}}}{63\%} = \begin{pmatrix} 16.669 \\ 33.337 \\ 66.674 \end{pmatrix} \cdot \frac{\text{m}^{3}}{\text{hr}}$$

$$\text{Size}_{\text{quote}} := 2000 \cdot \frac{\text{m}^{3}}{\text{day}}$$

$$\text{Equip} := \text{Equip}_{\text{quote}} \cdot \left(\frac{\text{Size}}{\text{Size}_{\text{quote}}} \right)^{0.6} = \begin{pmatrix} 2.818 \times 10^{4} \\ 4.271 \times 10^{4} \\ 6.473 \times 10^{4} \end{pmatrix}$$

Capital not multiplied by 2 becuase TDA provided installed costs

$$\text{SulfaTrap}_{\text{cap}} := \text{Equip} \cdot 1 \cdot 125\% = \begin{pmatrix} 3.522 \times 10^{4} \\ 5.338 \times 10^{4} \\ 8.091 \times 10^{4} \end{pmatrix}$$

Operating costs based on TDA report. Cost per mass sulfur

$$\text{Operating\_Cost}_{\text{Unit.H2S}} := \frac{41.31}{\text{kg}}$$

$$\text{Conc}_{\text{H2S}} := 2890 \frac{\text{mg}}{\text{m}^{3}}$$

$$\mathrm{Conc}_{S} := \mathrm{Conc}_{H2S}\cdot\frac{32}{34} = 2.72\times 10^{3}\cdot\frac{mg}{m^{3}}$$

$$\mathrm{Operating\_Cost}_{Unit.S} := \mathrm{Operating\_Cost}_{Unit.H2S}\cdot\frac{\mathrm{Conc}_{H2S}}{\mathrm{Conc}_{S}} = 43.892\,\frac{1}{kg}$$

$$\mathrm{Operating\_Cost}_{VOL} := \mathrm{Operating\_Cost}_{Unit.S}\cdot\mathrm{Conc}_{S} = 1.194\times 10^{-4}\,\frac{1}{L}$$

$$\mathrm{SulfaTrap}_{Annual.Cost} := \mathrm{Size}\cdot\mathrm{Operating\_Cost}_{VOL} = \begin{pmatrix} 1.744\times 10^{4} \\ 3.489\times 10^{4} \\ 6.978\times 10^{4} \end{pmatrix}\cdot\frac{1}{yr}$$

VSA System - Based on TDA Report

Capital Costs

$$\mathrm{Equip}_{quote} := 295300$$

$$\mathrm{Size} := \frac{\mathrm{CH4}_{biogas}}{63\%} = \begin{pmatrix} 16.669 \\ 33.337 \\ 66.674 \end{pmatrix}\cdot\frac{m^{3}}{hr}$$

$$\mathrm{Size}_{quote} := 2000\cdot\frac{m^{3}}{day}$$

$$\mathrm{Equip} := \mathrm{Equip}_{quote}\cdot\left(\frac{\mathrm{Size}}{\mathrm{Size}_{quote}}\right)^{0.6} = \begin{pmatrix} 1.124\times 10^{5} \\ 1.704\times 10^{5} \\ 2.583\times 10^{5} \end{pmatrix}$$

$$\mathrm{Moist}_{cap} := \mathrm{Equip}\cdot 125\% = \begin{pmatrix} 1.405\times 10^{5} \\ 2.13\times 10^{5} \\ 3.229\times 10^{5} \end{pmatrix}$$

Note that TDA provided
installed cost. Not multiply by

Water Scrubber - Based on e-mails from Dirkse-Millieutechniek environmental for San Jose

Capital Costs

$$\mathrm{Equip}_{quote} := 817050$$

$$\text{Size} := \frac{\text{CH4}_{\text{biogas}}}{63\%} = \begin{pmatrix} 16.669 \\ 33.337 \\ 66.674 \end{pmatrix} \cdot \frac{\text{m}^3}{\text{hr}}$$

$$\text{Size}_{\text{quote}} := 2700 \cdot \frac{\text{m}^3}{\text{hr}}$$

$$\text{Equip}_{\text{scrub}} := \text{Equip}_{\text{quote}} \cdot \left(\frac{\text{Size}}{\text{Size}_{\text{quote}}} \right)^{0.6} = \begin{pmatrix} 3.86 \times 10^4 \\ 5.85 \times 10^4 \\ 8.868 \times 10^4 \end{pmatrix}$$

$$\text{Equip}_{\text{quote}} := 260000$$

$$\text{Size} := \frac{\text{CH4}_{\text{biogas}}}{63\%} = \begin{pmatrix} 16.669 \\ 33.337 \\ 66.674 \end{pmatrix} \cdot \frac{\text{m}^3}{\text{hr}}$$

$$\text{Size}_{\text{quote}} := 2700 \cdot \frac{\text{m}^3}{\text{hr}}$$

$$\text{Equip}_{\text{offgas}} := \text{Equip}_{\text{quote}} \cdot \left(\frac{\text{Size}}{\text{Size}_{\text{quote}}} \right)^{0.6} = \begin{pmatrix} 1.228 \times 10^4 \\ 1.862 \times 10^4 \\ 2.822 \times 10^4 \end{pmatrix}$$

$$\text{Scrub}_{\text{cap}} := \left(\text{Equip}_{\text{scrub}} + \text{Equip}_{\text{offgas}} \right) \cdot 2 \cdot 125\% = \begin{pmatrix} 1.272 \times 10^5 \\ 1.928 \times 10^5 \\ 2.922 \times 10^5 \end{pmatrix}$$

Power Costs

Pressurization of gas included included in pressurization for vehicle fuel

Water Circulation

$$\text{Power} := \frac{\dfrac{\text{Size}}{2700 \cdot \dfrac{\text{m}^3}{\text{hr}}} \cdot 1800 \cdot \dfrac{\text{m}^3}{\text{hr}} \cdot 8 \cdot \text{bar}}{\varepsilon_p \cdot \varepsilon_m} = \begin{pmatrix} 3.579 \\ 7.158 \\ 14.315 \end{pmatrix} \cdot \text{kW}$$

Tail Gas biofilter - Assume 5 kW

Natural Gas Pipeline Compressors - Based on Glauder from Miami-Dade

Capital Costs

$$\mathrm{Equip}_{\mathrm{quote}} := \frac{975000}{8}$$

$$\mathrm{Size} := \mathrm{CH4}_{\mathrm{biogas}} = \begin{pmatrix} 10.501 \\ 21.002 \\ 42.005 \end{pmatrix} \cdot \frac{\mathrm{m}^3}{\mathrm{hr}}$$

$$\mathrm{Size}_{\mathrm{quote}} := 268 \cdot \frac{\mathrm{ft}^3}{\mathrm{min}}$$

$$\mathrm{Equip}_{\mathrm{flow.based}} := \mathrm{Equip}_{\mathrm{quote}} \cdot \left(\frac{\mathrm{Size}}{\mathrm{Size}_{\mathrm{quote}}} \right)^{0.6} = \begin{pmatrix} 1.27 \times 10^4 \\ 1.924 \times 10^4 \\ 2.917 \times 10^4 \end{pmatrix}$$

$$\mathrm{Equip}_{\mathrm{quote}} := \frac{975000}{8}$$

$$\mathrm{Size} := 206\mathrm{kPa}$$

$$\mathrm{Size}_{\mathrm{quote}} := 50 \cdot \mathrm{psi}$$

$$\mathrm{Equip}_{\mathrm{pressure.based}} := \mathrm{Equip}_{\mathrm{quote}} \cdot \left(\frac{\mathrm{Size}}{\mathrm{Size}_{\mathrm{quote}}} \right)^{0.6} = 8.948 \times 10^4$$

$$\mathrm{Scrub}_{\mathrm{cap}} := \left(\frac{\mathrm{Equip}_{\mathrm{flow.based}} + \mathrm{Equip}_{\mathrm{pressure.based}}}{2} \right) \cdot 2 \cdot 125\% = \begin{pmatrix} 1.277 \times 10^5 \\ 1.359 \times 10^5 \\ 1.483 \times 10^5 \end{pmatrix}$$

Power Requirements

$k := 1.4$ Typical Value for k in adiabadic compressor calculations

$$\mathrm{Comp}_{\mathrm{NG.Power}} := \frac{\frac{k}{k-1} \cdot \mathrm{CH4}_{\mathrm{biogas}} \cdot 1 \cdot \mathrm{atm} \cdot \left[\left(\frac{206\mathrm{kPa}}{1 \cdot \mathrm{atm}} \right)^{\frac{k-1}{k}} - 1 \right]}{\varepsilon_p \cdot \varepsilon_m} = \begin{pmatrix} 0.337 \\ 0.674 \\ 1.348 \end{pmatrix} \cdot \mathrm{kW}$$

Microturbine Compressors - Based on Glauder from Miami-Dade

Capital Costs

$$Equip_{quote} := \frac{975000}{8}$$

$$Size := CH4_{biogas} = \begin{pmatrix} 10.501 \\ 21.002 \\ 42.005 \end{pmatrix} \cdot \frac{m^3}{hr}$$

$$Size_{quote} := 268 \cdot \frac{ft^3}{min}$$

$$Equip_{flow.based} := Equip_{quote} \cdot \left(\frac{Size}{Size_{quote}}\right)^{0.6} = \begin{pmatrix} 1.27 \times 10^4 \\ 1.924 \times 10^4 \\ 2.917 \times 10^4 \end{pmatrix}$$

$$Equip_{quote} := \frac{975000}{8}$$

$$Size := 620kPa$$

$$Size_{quote} := 50 \cdot psi$$

$$Equip_{pressure.based} := Equip_{quote} \cdot \left(\frac{Size}{Size_{quote}}\right)^{0.6} = 1.733 \times 10^5$$

$$Scrub_{cap} := \left(\frac{Equip_{flow.based} + Equip_{pressure.based}}{2}\right) \cdot 2 \cdot 125\% = \begin{pmatrix} 2.325 \times 10^5 \\ 2.407 \times 10^5 \\ 2.531 \times 10^5 \end{pmatrix}$$

Power Requirements

$k := 1.4$ Typical Value for k in adiabadic compressor calculations

$$Comp_{MT.Power} := \frac{\frac{k}{k-1} \cdot CH4_{biogas} \cdot 1 \cdot atm \cdot \left[\left(\frac{620kPa}{1 \cdot atm}\right)^{\frac{k-1}{k}} - 1\right]}{\varepsilon_p \cdot \varepsilon_m} = \begin{pmatrix} 1.016 \\ 2.033 \\ 4.065 \end{pmatrix} \cdot kW$$

Vehicle Fuel Compressors

Capital Costs are a component of the vehicle fueling station

Power Requirements - Isothermal Compression

$$Comp_{input} := 1 \cdot atm \cdot CH4_{biogas} \cdot \ln\left(\frac{24800 \cdot kPa}{1 \cdot atm}\right) = \begin{pmatrix} 1.626 \\ 3.251 \\ 6.503 \end{pmatrix} \cdot kW$$

Assume heat dissipation to maintian isothermal compression equal to power input to the compressor. Assume compressor 55% efficient.

$$\mathrm{Comp}_{\mathrm{VF.power}} := \mathrm{Comp}_{\mathrm{input}} + \frac{\mathrm{Comp}_{\mathrm{input}}}{55\%\cdot\varepsilon_{\mathrm{m}}} = \begin{pmatrix} 4.839 \\ 9.677 \\ 19.354 \end{pmatrix}\cdot\mathrm{kW}$$

Appendix Q: Engineering Guidance Document

Water Environment Research Foundation
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ENGINEERING GUIDANCE REPORT

RENEWABLE ENERGY PRODUCTION FROM DoD INSTALLATION SOLID WASTES BY ANAEROBIC DIGESTION

ESTCP Project ER-200933

Scott Vandenburgh and Patrick J. Evans
CDM Smith

June 2016

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14. ABSTRACT

Food waste generation and disposal is a significant source of greenhouse gas emissions and lost opportunity for energy recovery. Anaerobic digestion of food waste and purification of methane-rich biogas was conducted at the US Air Force Academy. Cost and performance of the technology with respect to renewable energy efficiency; biogas purification; digester capacity and stability; waste sludge generation and characteristics; operational reliability, safety, and ease of use; and greenhouse accounting were evaluated. Demonstration results indicated the process was capable of meeting or exceeding most performance objectives. The technology was capable of significant reductions in the solid waste stream while at the same time recovering energy that can be used as vehicle fuel or a variety of other uses. Cost-effectiveness of the technology was comparable or better to landfilling and composting especially for larger installations. The technology was also demonstrated to have favorable greenhouse gas offsets compared to composting and landfilling. An engineering guidance document was prepared that provides installations practical approaches for technology evaluation and implementation.

15. SUBJECT TERMS

Food waste, FOG, solid waste, anaerobic digestion, methane, biogas, biomethane, biogas purification, vehicle fuel, renewable energy, net zero, greenhouse gas, food-to-fuel.

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1.0 INTRODUCTION

This project demonstrated both the technological and the economic viability of anaerobic digestion of Department of Defense (DoD) wastes including pre- and post-consumer food waste, waste cooking oil, and grease trap waste as a viable means of disposal and renewable energy generation. The project demonstrated the ability to digest these wastes in a controlled and predictable manner to maximize the generation of biogas, a methane-rich, high energy product. The project also evaluated the economic viability and potential greenhouse gas offsets with the technology especially when biomethane was used as vehicle fuel. Full details of the ESTCP demonstration can be found in the Final Report (Evans et al. 2016). This document provides engineering guidance for DoD installations considering implementing of the technology.

2.0 BACKGROUND

The DoD is a significant consumer of energy and generator of solid waste. During FY 2009 the DoD consumed 209 trillion BTUs of energy (2.2×10^{17} J), excluding vehicle fuel (DoD 2010). Further, during the same period the DoD generated 5.2 million tons of solid waste. The consumption of energy and the generation of waste place economic, environmental and social burdens on the DoD. In recognition of the burden that these activities place on the Department, the DoD has initiated programs and policies to reduce energy consumption and waste generation.

- The Energy Policy Act of 2005 (EPACT) mandates that federal facilities receive at least 7.5% of their electricity from renewable resources by 2013. If the energy is generated on site from renewable resources the facilities receive double credit toward attainment of this goal.
- The 2008 National Defense Authorization Act (NDAA) implemented a renewable energy goal of 25% for the DoD.
- Executive Order 13423 requires that at least half of the statutorily required renewable energy consumed by the agency in a fiscal year comes from a new renewable source and to the extent feasible, the agency implement renewable energy generation projects on agency property for agency use. Further, the order requires increased diversion of solid waste as appropriate and maintenance of cost effective waste prevention and recycling programs in its facilities (USDOE 2008).
- The DOD Integrated (Non-Hazardous) Solid Waste Management Policy set minimum standards of 40% waste diversion of non-hazardous, non-construction and demolition integrated solid waste (Beehler 2008).

This project demonstrated utilization of anaerobic digestion to treat DoD wastes and produce renewable energy that can offset an installation’s energy demands and reduce its waste disposal rate. This project was measured against 30 performance objectives identified prior to the commencement of the research project. In total, the project met most of these objectives. Most notably, the project met objectives related to the following objectives:

- Energy Conversion
- Methane Production
- Natural Gas Specifications
- Loading Rate
- Solids Destruction
- Safety
- Ease of Use

The first three objectives from the list above were important as they showed that the process could be efficient, produce a valuable fuel that could be purified into a common fuel – compressed natural gas (CNG). Further the loading rate and the solids destruction objectives proved that a target loading rate could be achieved and that the process would significantly reduce the mass of product for ultimate disposal. Safety is always paramount so by showing that the process was safe and further easy to use, it proved that it could be implemented at a DoD installation.

By using the data obtained from the study, full-scale implementation was costed. The costs identified that significant amount of capital would need to be utilized to get the project started. However, the cost savings were significant enough that the project was competitive with common food waste disposal methods. In all the project estimated that a full-scale facility at various installations ranging from 10,000 personnel to 40,000 personnel had the capability to annually produce 25,000 gasoline gallon equivalents of biomethane (at a 10,000 personnel base), 50,000 gasoline gallon equivalents of biomethane (20,000 personnel base), and 99,000 gasoline gallon equivalents of biomethane at a 40,000 personnel base. At current gas prices this equated to an estimated food waste disposal cost as low as $50 per wet ton at the 10,000-personnel base and $22 per wet ton at the 20,000-personnel base. For the larger base of 40,000 personnel, the project projected to provide revenue at $2 per wet ton of food waste generated. In comparison, the cost of landfilling across the United States is $50 per wet ton and composting costs range from $29 to $52 per wet ton.

3.0 DRIVERS

There are many drivers for this project. As the costs obtained from the study indicate, there is an economic driver to implement the project. In addition, there are regulatory drivers as listed below.

- The DoD Strategic Sustainability Performance Plan provides an approach towards meeting these requirements which includes a focus on: 1) reducing energy needs and reliance on fossil fuels; and 2) water resources management.
- American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) 189.1-2009, Leadership in Energy and Environmental Design (LEED) and various Energy Policy Acts all have required more sustainable use of energy.
- The Army has implemented a Net-Zero installations policy seeking to increase and improve sustainability on installations.
- In addition, several other orders and acts promote energy sustainability and minimization of waste generation including:
- EPACT 2005
    - EO 13423
    - 10 United States Code 2577
    - Energy Independence and Security Act 2007
    - FY2008 NDAA
    - Pollution Prevention Act of 1990
    - DoD Instruction 4715.4 “Pollution Prevention”
    - DoD Integrated Solid Waste Management Policy

4.0 IMPLEMENTATION CHALLENGES

This study showed that there are considerable opportunities for food waste digestion at DoD installations. However, there are a number of challenges to get the project going. These challenges fall into the following categories: risk, familiarity with technology and compatibility with installation mission, costing gap analysis, and local conditions and markets.

4.1 RISK

The project requires significant risk of capital. In total the project is estimated to cost between $930,000 to $2.4 million depending on the size of the facility. Although, the program showed that the project was technologically feasible and met nearly all of the performance objectives, the anaerobic digesters showed signs of stress in the Phase III part of the study. Further, Phase IV was not run to full completion and quasi-steady state conditions were not achieved in Phase IV. Additionally, mono-digestion of food waste is not yet common throughout the country. Long term analysis of the impacts to pumping equipment and other components of the digestion were not determined in the study.

Additionally, the economics of the process are related to current market conditions. Some of the market risks are mitigated because gasoline prices are currently low relative to recent past. However, gasoline prices are extremely volatile. The costs are much less sensitive to electrical power costs relative to gasoline prices, but a steep rise in power costs may impact the financial viability of the project. Finally, the vehicle fuel cost contains fuel taxes. This is important as some states, such as Oregon, are moving away from fuel taxes toward taxing vehicles on miles driven. This could reduce the cost savings of the project.

4.2 FAMILIARITY WITH TECHNOLOGY AND COMPATIBILITY WITH FACILITY MISSION

Although anaerobic digestion is ubiquitous at wastewater treatment plants, they do not exist in great numbers at DoD installations. As such, implementation may require new staff or additional training of staff for the technology. Because the skillset will be unlike most other jobs on the installation, it may be necessary to train more than one staff member in the position so that the job is covered during vacations, sick leave, and staff turnover. Additionally, staffing projections for the facility do not warrant a full time position. Therefore, the staff dedicated to this will likely have other jobs.

4.3 COSTING GAP ANALYSIS

The final report on this project identified that the technology was cost competitive with current food waste disposal methods. However, it also identified two cost components that were not included in the technology. One of the end products of the study is a compressed biomethane, similar to compressed natural gas that can fuel a vehicle. The cost components of the study to not cover the cost of vehicle conversion to run on compressed biomethane. The cost of vehicle conversion is not widely published. However, the Honda Civic is currently offered with a gasoline engine or can be purchased to run on CNG. Based on the Manufacturers Suggested Retail Price (available from Honda.com) a Honda Civic with a CNG engine likely costs between $6,000 and

$8,000 more than a gasoline engine. Assuming an average fuel economy of 30 miles per gallon and around 7000 miles driven annually from a typical fleet vehicle, a base may need to retrofit or newly purchase between 110 to 430 (depending on installation size) CNG vehicles to fully utilize the biomethane produced from the digesters. As a result the missing cost for this conversion is likely in the range of $750,000 to $3,000,000 for a vehicle fleet capable of fully utilizing the biomethane.

Another cost not identified was the digestate disposal cost. Due to the significant solids destruction of the food waste in the anaerobic digester, the digestate could likely flow to a local water reclamation facility in the sewer system. As such, there are no expected transportation or hauling costs associated with the digestate. However, the local water reclamation facility may consider this a high strength discharge and elect to charge a service fee for handling it. Service fees from wastewater utilities vary depending on local conditions.

4.4 LOCAL CONDITIONS AND MARKETS

Local conditions and markets should be weighed prior to commencing with a food waste digester project. The costs for landfilling and composting as well as energy and gasoline prices were based on national averages. Local conditions may vary and impact the economic feasibility. In locations where gasoline tends to be higher, such as California, the anaerobic digestion process may be more economically feasible. However, in locations with low gasoline costs, high power costs, and low landfill tipping fees, the project may not be economically competitive.

Local staff acceptance may impact the ability of the project to succeed. In locations where the facility is a long way from typical transportation destinations, the reduced range of a CNG vehicle may not be acceptable. CNG vehicles typically have less than half the range compared to gasoline fueled vehicles. As such, drivers of the vehicles will have less flexibility for long trips. Additionally, the projections identify the production of between 68 gasoline gallon equivalents per day at a 10,000 personnel base to 270 gasoline gallon equivalents per day at the 40,000 personnel base. Installations should consider current fuel demands prior to investment. In the event that there is no demand for the converted biogas then this excess fuel would need to be flared and have no value to offset capital purchases.

5.0 ALTERNATE PROJECT CONSIDERATIONS

Section 4.0 discussed the challenges to implementing the project as a standalone facility at a DoD installation. As a result, it may be appropriate to explore alternate options. More proven than mono-digestion of food waste is co-digestion of food waste with wastewater solids. Co-digestion has become quite common at wastewater treatment plants as these facilities look to maximize their existing assets in their anaerobic digestion and energy systems. The facilities typically, receive a tipping fee for receiving the material and then are able to maximize the output of their engine generation equipment.

Co-digestion would be an option for any DoD installation that generates food waste. It would be a particular advantage for facilities that already have anaerobic digesters, like the United States Air Force Academy and Joint Base Lewis McCord. Although there facilities may not currently have energy production equipment such as biogas scrubbers and vehicle fueling systems, the costs of implementing these features would be reduced compared to a mono-digestion facility that would require the construction of the digestion facilities in addition to the energy recovery facilities. Further, the co-digestion within a DoD installation that already has anaerobic digestion would increase the total energy value in the biogas over a mono-digestion facility that processes only food waste or only municipal wastewater solids. This would effectively make more technologies available for utilization including combined heat and power generation facilities. Finally, the use of co-digestion eliminates the need for a sewer discharge fee that may be required to release digestate into a municipally owned wastewater treatment plant.

Prior to implementing co-digestion at a DoD-owned wastewater treatment plant the facility would need to be checked to determine if the existing digesters have capacity and ensure that the food waste does not impact the wastewater biosolids that would bring them out of compliance with existing regulations.

Since very few DoD installations have anaerobic digestion facilities on site, another option would be to investigate partnering with a local municipality. Many municipalities are already co-digesting on within their facilities and more are studying the process. Although, implementation of co-digestion at a DoD installation may have limited impact in the accounting of greenhouse gasses as the wastewater treatment utility would likely earn the greenhouse gas credits, the DoD installation may be able to reduce costs compared to traditional methods of food waste disposal. DoD installations should explore these partnerships and assess if a requested tipping fee for the food waste disposal is less than the current contracts for landfilling or for composting. Of note, the wastewater utility may require some pre-processing or pre-sorting of the food waste prior to delivery. It would be important to understand what the utility would like with regard to the food waste.

6.0 IMPLEMENTATION DESIGN RECOMMENDATIONS

Implementation of a food waste digestion or co-digestion facility should be well thought out and planned. **Figure 1** shows a potential decision tree for assessing if co-digestion or mono digestion of food waste is appropriate for a DoD installation. Based on the logic diagram, there are four potential outcomes (1) co-digestion at a DoD owned facility, (2) mono-digestion at a DoD owned facility, (3) co-digestion at a partner facility, or (4) continue with current food waste disposal methods.

This decision tree is only a quick tool to determine if food waste digestion may be appropriate. It should be noted that prior to commencing any food waste digestion program, a detailed study be conducted for the specific DoD installation. The decision tree identifies that a partnership with a local agency should be investigated, then negotiations should be conducted. Negotiations should target a tipping fee that is less than the results of the study conclusions. For example, facilities with populations less than 10,000 should consider tipping fees less than approximately $58 per wet ton or less than the facilities current disposal costs. Facilities around 20,000 should consider tipping fees less than $22 per wet ton. Large facilities should only consider partnerships with agencies willing to take the food waste at essentially no cost. It is likely that a site specific study will be needed to confirm these values and assist in negotiations. The site specific study would need to identify costs for the facility assuming a fully independent handling and handling of food waste and recovery of the generated biogas at the base.

Upon confirmation that food waste digestion provides a benefit, the installation should consider a number of factors in the facility design. A list of design criteria for a full-scale system is as shown in **Table 1**.

Table 1 presents the key results from this study that can be used to size equipment and facilities for an independent food waste handling system. It should be noted that **Table 1** does not include the influent characteristics of the food waste. These characteristics should be assessed based on actual food waste data from the plant. The researchers recognize that the food waste generated at the Air Force Academy and used as the basis for this study may be different than at other facilities. Food waste characteristics will affect digester performance but COD and SELR were determined to be a useful parameters for evaluating food waste suitability. In addition, Experience with co-digestion of food waste also suggests a minimum COD of 20,000 mg/L with the optimum > 50,000 mg/L (Hare 2016). The minimum VS/TS value is 65% with the optimum being > 85%. Also refer to Appendix C in the Final Report (Evans et al. 2016) for information relevant to desired waste stream characteristics. Further, the processing applied at the Air Force Academy, specifically the grinder and pulper, may not exist at all facilities. As a result, the facility will need to work with potential vendors of food waste pulping and grinding systems. These vendors are likely to process the food waste differently, which may have impacts on the food waste concentration and other characteristics.

Figure 1. Decision tree for evaluation of anaerobic food waste digestion options.

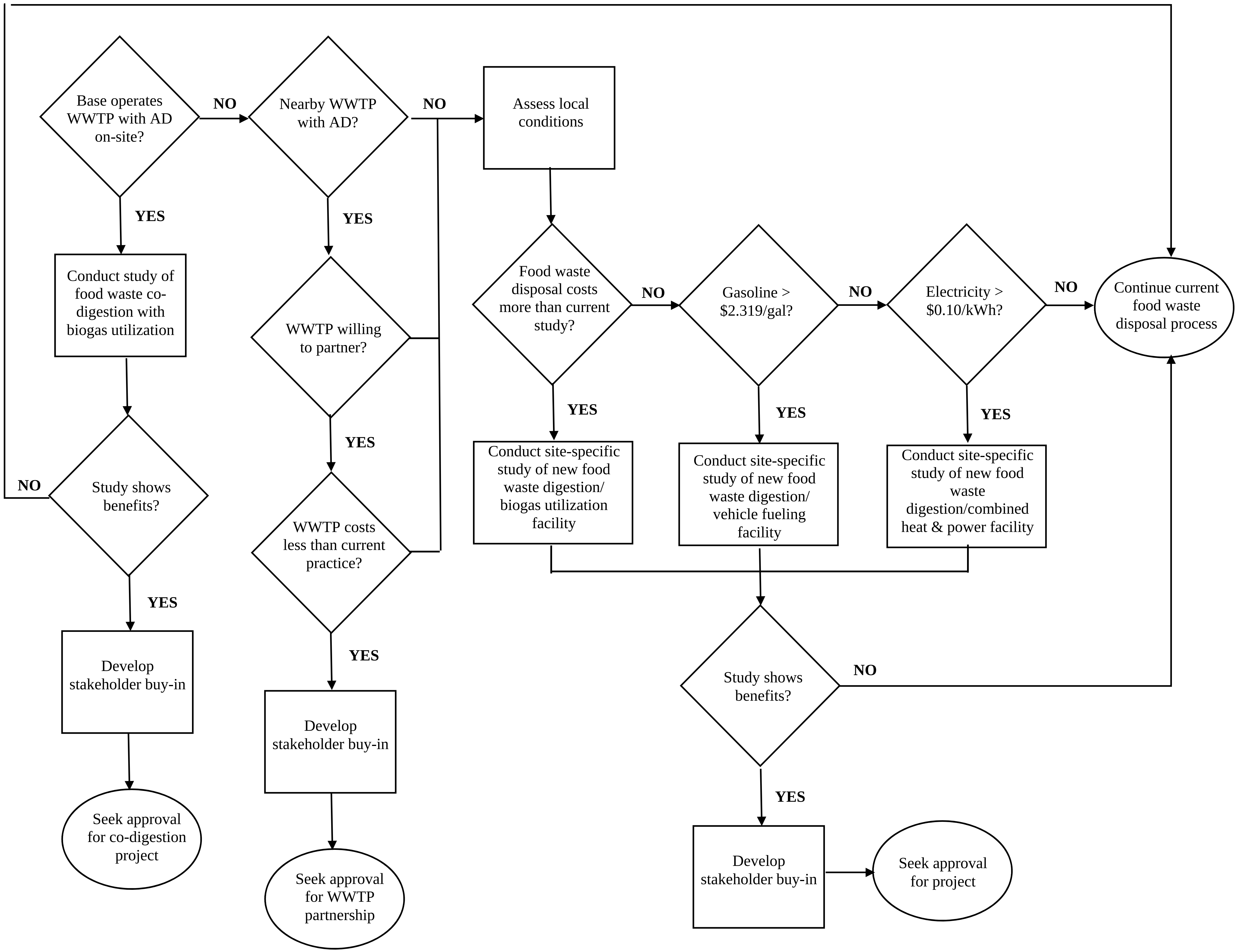
Base operates WWTP with AD on-site?
NO
Nearby WWTP with AD?
NO
Assess local conditions
YES
Conduct study of food waste co-digestion with biogas utilization
YES
WWTP willing to partner?
YES
NO
Study shows benefits?
YES
Develop stakeholder buy-in
Seek approval for co-digestion project
WWTP costs less than current practice?
YES
Develop stakeholder buy-in
Seek approval for WWTP partnership
Food waste disposal costs more than current study?
NO
Gasoline > $2.319/gal?
NO
Electricity > $0.10/kWh?
NO
Continue current food waste disposal process
YES
Conduct site-specific study of new food waste digestion/ biogas utilization facility
YES
Conduct site-specific study of new food waste digestion/ vehicle fueling facility
YES
Conduct site-specific study of new food waste digestion/combined heat & power facility
Study shows benefits?
NO
YES
Develop stakeholder buy-in
Seek approval for project

Table 1. Design criteria.

Parameter	Suggested Design Value	Comments
Methane Production (VS basis)	400 L CH_4/kg VS loaded	Use design value to predict methane production from digester. Use for sizing gas utilization equipment and determining potential revenues and offsets from biogas utilization
Methane Production (COD basis)	250 CH_4/kg COD loaded	Use design value to predict methane production from digester. Use for sizing gas utilization equipment and determining potential revenues and offsets from biogas utilization
Specific COD loading rate (SELR)	0.44 g-COD/g-VSS/day	Use design value for sizing the anaerobic digestion facilities.
pH	7.8	Design value for understanding operational pH in digester
TS Reduction	78%	Use design value for projecting solids to be disposed after process
VSS Reduction	92%	Use in combination with SELR to size anaerobic digestion facilities
Biogas CH_4 Content	60%	Use in combination with methane production to determine size of required digester gas piping and other digester gas conveyance system, flares, etc.
Biogas H_2S Content	2,900 mg/m^3	Use to size hydrogen sulfide removal systems

7.0 LESSONS LEARNED

Overall, the pilot digestion system was determined to be operationally friendly once it was up in running and the troubleshooting period was over. A full-scale facility should have less problems and troubleshooting requirements compared to the pilot. This is in part because a full-scale system would likely use larger pumps, with larger clearances, that are less susceptible to plugging. Further, there are many mechanical grinding equipment that are available and marketed to the wastewater treatment industry. These equipment tend to be sized for full-scale installations and are not easily deployed at the pilot scale.

Safety is the primary concern with a digestion process and the hydrogen sulfide release that occurred in the pilot facility necessitates that a full-scale facility be designed to mitigate potential safety hazards. As with pilot scale facility, it is prudent to construct the digestion facilities in compliance with the National Fire Protection Association (NFPA) publication 820. Although, this publication is for wastewater treatment facilities there is no equivalent publication for a food waste system. NFPA 820 will dictate the electrical classification for equipment, provide design requirements for heating and ventilation systems, and specify the monitoring requirements. NFPA 820 doesn’t specifically address hydrogen sulfide.

This study showed that solids destruction in food waste digestion is high compared to municipal wastewater treatment plant digesters. As a result, the stability of the digestion process was challenging to maintain in the third phase of the study. To compensate for the high solids destruction and loss of alkalinity, CDM Smith conducted Phase Iv of the study. Phase 4 utilized the digestate from the effluent of the digestion process to dilute the food waste to a concentration deemed to be pumpable. This effectively recycled solids and alkalinity back to the digesters and appeared to mitigate the stability issues in Phase III. As a result, future projects should consider using digestate to dilute the food waste solids for pumpability.

8.0 REFERENCES

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