ZERO NOX EMISSIONS FROM AN IC ENGINE FUELED BY BIOGAS FROM A HEATED, COVERED LAGOON DAIRY DIGESTER WITH EXHAUST GAS RECIRCULATION

FINAL REPORT

July 2015

Submitted to:
San Joaquin Valley Unified Air Pollution Control District

CALIFORNIA BIOENERGY

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Dallas, TX 75201

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Submitted to
Technology Advancement Program
San Joaquin Valley Unified Air Pollution Control District
1990 East Gettysburg Ave.
Fresno, CA 93726

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EXECUTIVE SUMMARY

California Bioenergy LLC (CalBio) received a grant from the San Joaquin Valley Air Unified Air Pollution Control District (SJVUAPCD) under the District's Technology Advancement Program (TAP). The purpose of this grant was to develop, test and hopefully demonstrate that a state-of-the-art internal combustion engine-generator utilizing a combination of exhaust gas recirculation (EGR), a non-selective catalytic reactor (NSCR), a hydrogen selective catalytic reactor (H-SCR) and an exhaust emissions control system could achieve effectively zero NOx emissions when utilizing biogas from a dairy manure heated, covered lagoon digester utilizing an air injection system to control H_2S levels in the biogas. This project was carried out over a 2-year period of time, from February 2012 through April of 2014 and the results of the data collection from both the digester and the engine-generator are included on this report.

The California Air Resources Board (ARB) standard for distributed generation systems is 0.07 pounds of NOx per megawatt-hour of useful energy output (lb/MWH). This goal was achieved intermittently by this engine, with NOx emissions on occasion as low as 0.028 lb/MWH (equivalent to 0.69 ppmvd or 0.009 g/BHP-hr) measured by the operator and Air District personnel.

Independent source testing did not confirm these low NOx results. In April of 2014 the experimental engine suffered a catastrophic failure due to coolant system failure and subsequent engine overheating. The project and ongoing testing was concluded prematurely. The following conclusions were therefore gleaned from this project:

1) High H_2S lagoon digester biogas can be successfully and inexpensively treated through the addition of 5 – 10% air into the head space of a covered lagoon digester. 70% to 90% reduction in H2S can be consistently achieved (from 2,000 to 5,000 ppm to less than 500 ppm) if the air injection is evenly dispersed throughout the headspace. Operating costs are minimal. Polishing of the resulting biogas is still needed by conventional chemical (e.g. iron sponge) scrubbers to achieve Central Valley Air District fuel sulfur standards of 40 ppm or less.
2) Exhaust from a rich burn IC engine can be cooled and recirculated back into the biogas fuel stream in amounts ranging up to 10% to add additional inerts into the fuel to increase engine efficiency and deaden combustion.
3) Exhaust from a rich burn IC engine utilizing tight lambda controls (0.980 – 0.988 range) combined with an EGR diluted biogas fuel mix can be successfully processed through a traditional NSCR catalyst to less than 2 ppm NOx. These results were not consistently achieved and further investigation of the reasons why NOx levels varied needs to be pursued.
4) Hydrogen gas (20% plus concentration) can be produced from low H_2S biogas feedstock utilizing a reformer.

5) Addition of a second stage H-SCR along with the addition of hydrogen into the exhaust stream does not result in a further reduction of NOx below the 2 ppm levels observed prior to the H-SCR system.
6) The combination of high CO_2 levels in the biogas along with the CO_2 and nitrogen introduced from the EGR system produced a fuel with high equivalent octane and enabled reliable IC engine operation at a compression ratio of 14:1 with high efficiency of over 39% at full power.
7) Although the overall EGR IC engine emission results were tantalizingly encouraging, the complexity of the overall system and the lack of a major engine manufacturer willing to support EGR with engine warranties and emission guarantees causes this approach to low NOx management to still be commercially unfeasible. The test engine never operated reliably and eventually suffered a catastrophic failure due to overheating in April 2014, prematurely ending the project. The ability to operate an IC engine at a higher compression ratio when using high CO_2 fuels does offer the potential for improvement in biogas engine efficiency and should be examined further.

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NOMENCLATURE

ACRONYM		UNITS	
˚C	=	Degrees Celsius	
CARB	=	California Air Resources Board	
CFM	=	Cubic Feet per Minute	
CH4	=	Methane	
CHP	=	Combined Heat & Power	
DE	=	Distributed Energy	
DG	=	Distributed Generation	
EPA	=	Environmental Protection Agency	
EGR	=	Exhaust Gas Recirculation	
˚F	=	Degrees Fahrenheit	
HEX	=	Heat Exchanger	
HHV	=	Higher Heating Value	
Hz	=	Hertz	
ISO	=	International Standards Organization	
kVA	=	Kilo-Volt-Amperes	
LHV	=	Lower Heating Value	
N2	=	Nitrogen	
NOx	=	Nitrogen Oxides	
O2	=	Oxygen	
PF	=	Power Factor	
PI&D	=	Process and Instrumentation Diagram	
PPM	=	Parts Per Million	
PWR	=	Output Power from Equipment	[kW]
RH	=	Relative Humidity	[%]
RT	=	Refrigerant Tons	[r/tons]
SCFM	=	Standard Cubic Feet per Minute	[scfm]
SCR	=	Selective Catalytic Reduction	
SMP	=	Sustaining Membership Program	
VAC	=	Volts Alternating Current	[V]
ΔP	=	Differential Pressure	[in.H2O or PSI]
ΔT	=	Differential Temperature	[˚F or ˚C]
λ	=	Air-Fuel Ratio	[-]
QHR	=	Heat Recovery Rate from Equipment	[BTU/hr]
ηfuel	=	Fuel Efficiency	[%]
ηthermal	=	Thermal Efficiency	[%]
ηsystem	=	System Efficiency	[%]
ηelectrical	=	Electrical Efficiency	[%]

1. INTRODUCTION

California Bioenergy LLC received a grant from the San Joaquin Valley Air Unified Air Pollution Control District under the District's Technology Advancement Program. The purpose of this grant was to develop and demonstrate a novel state-of-the-art internal combustion engine-generator utilizing exhaust gas recirculation (EGR) and non-selective catalytic reduction (NSCR) controls that exceeds the District's standards for NOx emissions when fueled by biogas from a heated, covered lagoon dairy manure digester. An additional goal of near-zero NOx will be investigated this system with a second stage after-treatment using hydrogen selective catalytic reduction (H-SCR) technology. The technology improvements also include an air injection system that dramatically reduces hydrogen sulfide (H_2S) in the biogas from the digester, which is essential for the operation of the proposed zero-NOx emission control technology on the engine. Figure 1 pictures the covered lagoon digester and engine-generator system adjacent to the dairy farm.

The EGR, NSCR and H-SCR emissions control system developed under this grant was installed on a 600 KW rich-burn engine-generator at on a dairy digester project near Bakersfield, CA. The engine produces electricity for export to the PG&E grid. The dairy provides manure to a heated, covered lagoon digester that produces biogas at an estimated average rate of approximately 50,000 cubic feet per day. The waste heat from the engine water jacket is circulated through a heat-exchange system in the covered lagoon digester to provide some temperature elevation to enhance digestion and gas production

The demonstration project assessed two new technologies:

a) An air injection system that is the first special feature of this system that reduces H_2S levels from 2,000 to 5,000 ppm to under 500ppm. This system was expected to reduce the cost of H_2S removal, for covered lagoon digesters producing electricity, to under $0.001/kWh, versus the $0.01-$0.02/kWh when using conventional iron sponge H2S absorber technology alone. This concept was explored and verified in a California Energy Commission Energy Innovations Small Grant Program research project, "Low-Cost Hydrogen Sulfide Reduction in Biogas Energy Systems", EISG Report # 07-16, 2011, which was performed by Williams and Summers, consultants on this project. Following removal of H_2S, the biogas is transported by pipeline to the gas handling and treatment equipment where it is dried in a gas chiller, processed through a polishing scrubber (iron sponge) to further reduce H_2S levels to less than 50 ppmv.

b) A new engine system combining exhaust gas recirculation back into the treated low H2S biogas fuel to create a virtual (no excess oxygen) lean burn environment and an NSCR after treatment catalyst installed on a 600kW - engine-generator to produce electricity for export.

Figure 1: Covered Lagoon Digester and Engine-Generator System.

The engine, emission and site controls system consisted of the following components:

- State-of-the-art engine with the following features:
  - ✓ High compression ratio: 14:1
  - ✓ Miller Cycle
  - ✓ Exhaust Gas Recirculation ("EGR") with exhaust cooling heat exchangers
  - ✓ High-energy ignition system, cylinder-selective spark timing, adjustable energy level
  - ✓ Detonation/Knock-Detect System: cylinder-selective knock & misfire levels
  - ✓ Air-fuel mixing system: Venturi Mixer
  - ✓ Fast-response electronic and electromagnetic actuators for: throttle, EGR-valve, turbocharger waste gate, and fuel delivery
- Emission Control System:
  - ✓ NSCR catalyst
  - ✓ Wideband ZR-O2 sensor in exhaust
  - ✓ Fuel actuation, using highly precise angular gap venture mixer technology paired with zero pressure regulator
  - ✓ Emission controls part of "fully integrated control and monitor system"

- The following special sensors are also included:
  - ✓ Exhaust emission sensors: NO, CO
  - ✓ Fuel quality: H_2S, CH_4
  - ✓ Fuel flow

Zero NOx emissions from an IC Engine fueled by biogas from a heated, covered lagoon dairy digester with Exhaust Gas Recirculation

The objective of this project was to demonstrate that ultra-low NOx and zero NOx emissions can be achieved from dairy biogas fueled IC generators. The proposed study monitored, sampled, and analyzed biogas flows and exhaust emissions, while implementing a unique innovative technologies for biogas cleanup, engine management, and exhaust treatment and scrubbing. The following items were monitored and assessed over an extended period of time:

- Exhaust emission sensors: NOx, CO
- Fuel quality: H_2S, CH_4, CO_2
- Fuel flow: standard cubic feet per minute
- Continuous automatic data acquisition (15-minute interval) of system power, flow, temperatures, pressures, and ambient conditions.

The project involves two phases:

Phase I. Emission Controls Optimization – Target: 2ppm NOx

Utilizing just the EGR and NSCR control systems (no H-SCR) produce ultralow NOx emissions.

Emission Sensors: Wideband oxygen sensors have been proven superior to binary oxygen sensors in emission control systems. Occurrences of hysteresis, drift, and interference with trace gases can cause a lack of precision that prevents control strategies from achieving extremely low emissions. With good emission sensors that detect these occurrences; counter measures can also be put in place, within the control system, to achieve lower emissions

Smart Interactive and Adaptive Control System: The open structure of the control system, communication with all other control and monitoring systems, as well as many additional sensors (fuel quality, emissions, etc.) provide additional necessary information to improve the emissions profile. Correlation between specific parameters and emissions can be implemented in a faster acting proactive feed-forward control algorithm. Interaction and knowledge of other control systems help ignore some occurrences (e.g., cycle misfire, load change) and counteract others (e.g., system instabilities, “hunting governor”) with change in Control Dynamic Parameters. Adaptive control parameters for sensor and catalyst aging are also included.

Phase II. After-Treatment – Target: 0 ppm NOx

In addition to very low emissions through a first stage NSCR system and optimized emission controls, utilize a second-stage H-SCR after-treatment system catalyst using hydrogen as a reagent. Demonstrate hydrogen can be generated from biogas using a hydrogen reformer.

The project comprised the following tasks:

1. Project administration, design of H2S control system and engine emissions control strategies.

2. Phase I emission control optimization: develop test plans, produce low H2S biogas, operate EGR engine and conduct tests onsite and post-test data reduction and analysis.

3. Phase I emission control optimization: develop advanced emission control software and installation onsite. Operate software and controls on digester biogas H2S treatment and EGR engine generator system and conduct tests onsite and post-test data reduction and analysis.

4. 2nd stage after-treatment system: Specifications of systems, procurement of H-SCR catalyst,biogas fuel operation, engineering work for mechanical and electrical installation of systems

5. Test and Fine tune the Phase II system: installation by mechanical and electrical subcontractors, commissioning of system, testing and controls integration.

6. Long-term Testing: collect data on the effectiveness of the Phase 1 and Phase 2 emissions control systems, and include newly found knowledge in software updates.

7. Data analysis conclusions and recommendations: analyze data, make conclusions and recommendations for both Phase 1 and Phase 2 to be included in final report.

Work on the project began in November, 2011; and was completed in April, 2014. The project was terminated early due to the catastrophic major failure of the engine when the cooling system and over temperature sensors/controls failed allowing the engine to overheat.

2. BACKGROUND

2.1 Dairy Farm Digester Energy Potential

Dairy digesters represent a major economic and environmental opportunity for the San Joaquin Valley. Capturing and converting biogas to electricity offers the potential for monetizing an otherwise unused resource, creating jobs and income for the local community while drastically reducing greenhouse gas emissions and odors.

As the global leader in dairy farming, the San Joaquin Valley has the ability to produce up to one gigawatt or more of biogas-fueled "peaker-power" projects – and can set an example of innovation and success for the rest of the world to look to and emulate. At the recent "Governor's Conference on Local Renewable Energy Resources" targeting 12,000MW of distributed local generation by 2020, the Central Valley allocation for bioenergy was 255MW, i.e., approximately 425 dairies x 0.6MW generation per dairy at a 33% capacity factor (runtime of 8 hours per day producing peak-demand electricity). In quantifying the benefit of this proposal's Phase I and Phase II, we will use this base-case engine profile (0.6MW) across 425 dairies to assess the likely impact on, and cost-per-ton of, emissions.

2.2 San Joaquin Valley Air Pollution Control District NOx Standards

While current and foreseeable market prices favor electricity production from dairy biogas (over gas cleanup and compression or pipeline injection), power generation technologies typically entail significant releases of NOx and other air emissions of concern. Although biogas developers have expressed concern with meeting the 0.15 grams/bhp-hr (11ppm NOx at 15% O2) standard promulgated by the San Joaquin Valley Air Pollution Control District, recent technological advances have opened the possibilities of achieving this standard in relatively cost effective ways.

This project evaluated two promising approaches to achieving ultra-low NOx emissions from biogas fueled engine generators: A non-selective catalytic reduction ("NSCR") technology in conjunction with a rich burn internal combustion ("IC") engine utilizing exhaust gas recirculation to create a virtual lean burn environment; and the same configuration with an added second stage Hydrogen enhanced Selective Catalytic Reduction exhaust treatment system.

Large natural gas fueled power plants achieve NOx emissions in the 2 ppm range and if small distributed generators could be implemented with NOx emissions at or below these levels there would be a NOx neutral way to destroy the significant amount of fugitive dairy manure methane (a potent greenhouse gas) released in the California Central Valley while generating significant renewable energy locally (saving transmission and distribution losses and costs) without compromising the Districts goals of significantly reducing NOx emissions.

In addition utilizing DE low NOx generators as "peakers" could shape electricity generation around the ever increasing amounts of afternoon solar energy further benefiting the local electric networks. Biogas generated at times when solar is in excess could then be utilized for other purposes such as for transportation fuels further reducing the net NOx emissions.

2.3 Technology Development to Exceed SJVAPCD Emissions Standards

Biogas from a covered lagoon digester was used to fuel an IC engine. It was attempted to achieve Zero NOx by pairing non-selective catalytic reduction ("NSCR") controls optimization with second stage after treatment using hydrogen SCR technology. The technology improvements also included an air injection system that reduces hydrogen sulfide (H_2S) from the digester to single-digit ppm, which was essential for the operation of the proposed zero-NOx emission control technology on the engine.

The original intent of this project was a technology development, implementation, and assessment effort, at a full-scale dairy project in Bakersfield, with its goal to prove the economic and operational viability of a zero-NOx emissions biogas-fired IC engine technology. It was hoped at the end of this project, to have a fully-operational, full-scale, zero-NOx dairy biogas power plant, with validated emissions data, that can serve as a template for future projects in the San Joaquin Valley and elsewhere.

The project was divided into two phases

- Phase I was to take the EGR engine from 11ppm to 2ppm NOx emissions
- Phase II was to take the EGR engine from 2ppm NOx to zero NOx emissions, followed by a year of operation and data collection
- As an integral part of these efforts, the EGR engine was to achieve reduced SOx and hydrogen sulfide emissions

An important goal of this project was to prove that low/zero-NOx technology can be implemented at full operational scale and with lower total cost of ownership than alternative engine technologies, including those producing significantly higher NOx emissions, thereby opening the door for biogas-fueled power production, while protecting air quality and improving the environmental attributes of the dairy community.

3. PHASE I: NSCR Emission Controls Optimization

3.1 Digester and Engine-Generator Descriptions

The demonstration emissions system was installed on a highly-modified Caterpillar engine-generator set located in an enclosure adjacent to the Stockdale Dairy Digester. The generating set is rated at 600 kW electric, but the plant operators have limited maximum power output to 550 kW for reasons of reliability and durability. The digester is an 8-million gallon covered lagoon with a heat exchange system to cool the engine. The initial work involved sampling of influent and effluent and deliver to Dellavalle laboratories for analyses of total solids, volatile solids, COD, pH and fertilizing nutrients- N,P,K; sample separated solids and analyze for total solids, volatile solids and bulk density.

A preliminary design of an in-situ H2S removal system for the Stockdale covered lagoon digester was also completed, as well as preliminary design of the continuous data gathering system for digester including biogas flow in scfh (standard cubic feet/hour), influent and effluent flow in gpm, and temperatures of inlet, outlet and interior of the digester. Figure 2 shows a schematic of the H_2S system including the air injection points in the covered lagoon digester. As shown the air is injected evenly over the length of the digester to achieve oxygen reaction with the H_2S. Figure 3 shows a schematic of the covered lagoon gas train to the engine-generator. Figure 4 then show a schematic of the experimental emissions control system employed by the engine.

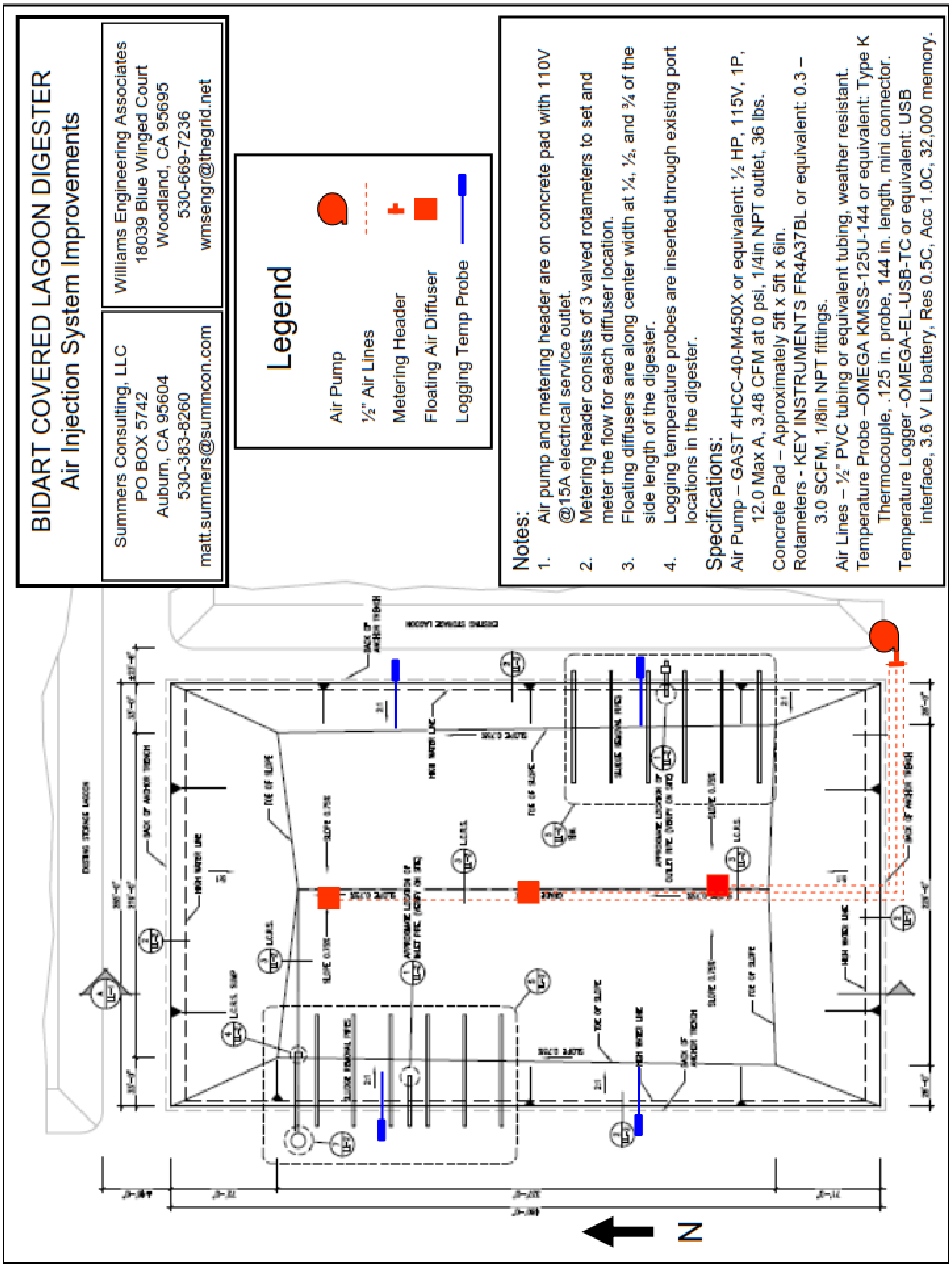

Figure 2: H_2S Control System - Air Injection into Stockdale Covered Lagoon Digester

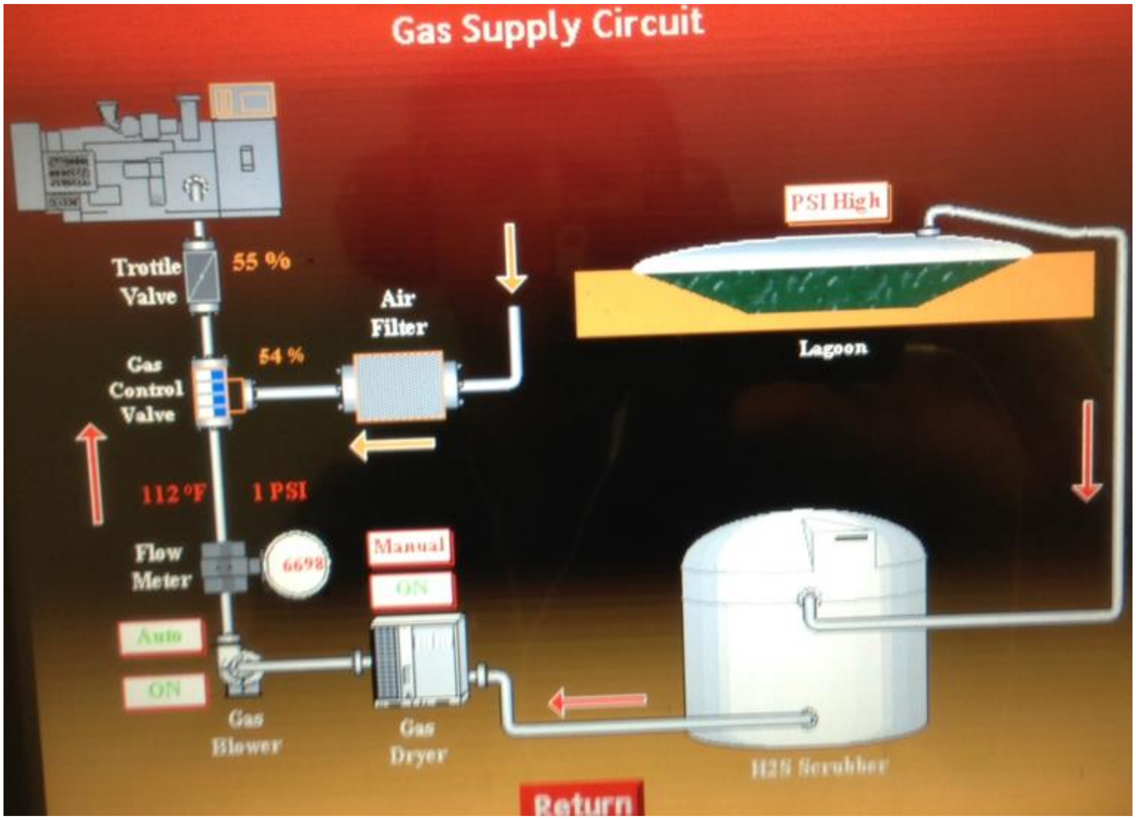

Figure 3: Gas Supply Circuit for Stockdale Covered Lagoon Digester

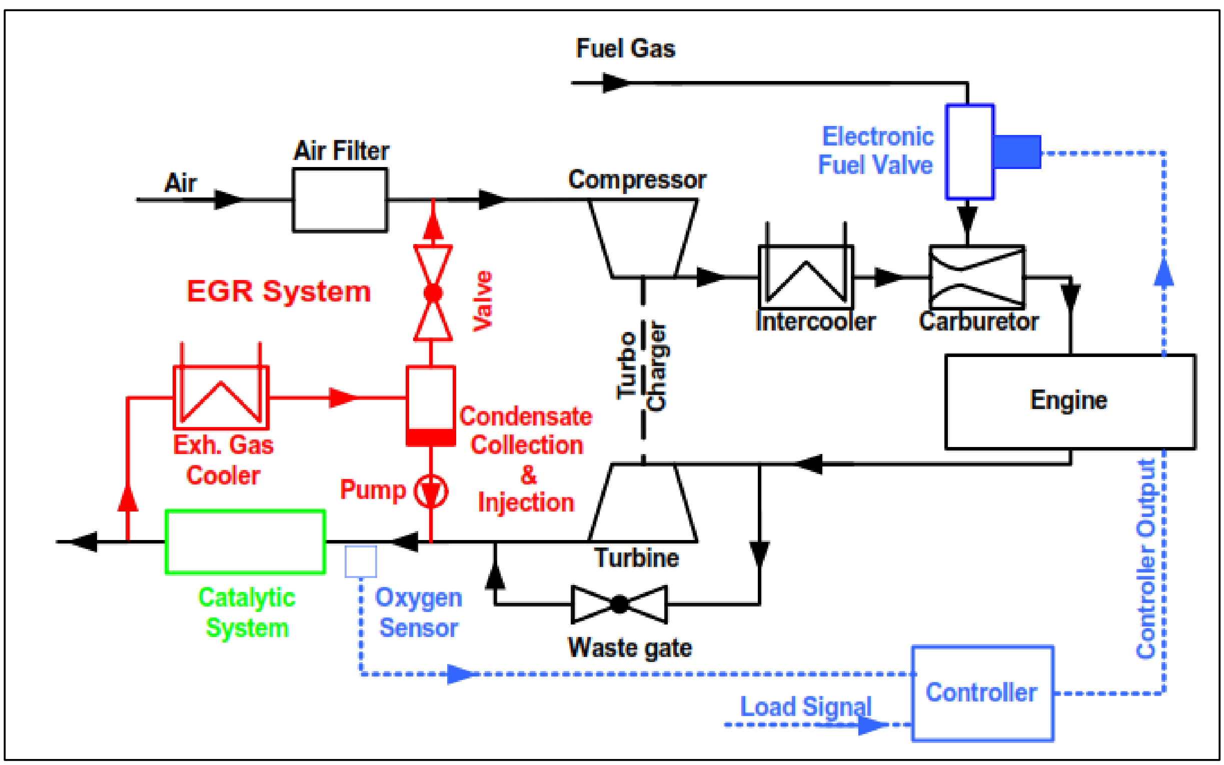

Figure 4: Engine Emissions Control Schematic

3.2 Digester Instrumentation and Performance Data: May – November 2012

The installation of the air injection system was completed in the spring of 2012. Electrical contractors completed their work to power the air blower system on April 20, 2012. Temperature probes were installed around the digester the first week of May 2012. The biogas flow meter on the vent was installed and calibrated. A weir flow meter located on the outlet of the lagoon digester was procured and installed to improve the accuracy of measurement of the manure flow rates through the lagoon. Air injection into the lagoon commenced in early May and monitoring of H2S concentration in the biogas was carried out in subsequent months.

The covered lagoon dairy manure digester produced significant quantities of biogas through the summer of 2012 as measured by the flow meter in the range of 40,000 – 50,000 standard cubic feet per day. Prior to the installation of the air injection system, the H_2S levels were consistently over 5000 ppmv. After commencing with air injection under the digester cover, the H_2S levels dropped significantly to under 1000 ppmv and at times under 100 ppmv. The ultimate goal was to reliably obtain <50ppm H_2S. Significant performance data was gathered on the lagoon digester and air injection system. Table 1 summarizes the digester performance over the initial 7-month period.

Bidart Stockdale Digester Performanc				2012								
Month/ year	Influent	Influent TS	Influent VS	Influent VS	Temp.	Organic loading rate	Hydraulic Retention Time	VS red.	Biogas Production	Methane	H_2S Content after air injection	Air Inject rate
	gal/day	%	% of TS	lb/day	Degrees F	lb VS/1000 cu ft/day	days	%	cu ft/day	%	ppmv	scfm
May-12	195,000	0.57%	70%	6,489		5.85	42.56	69%	40,790	68%	1000	1.77
Jun-12	177,500	0.50%	65%	4,811		4.33	46.76	62%	42,672	72%	342	3.6
Jul-12	257,032	0.37%	70%	5,552	89	5	32.29	69%	38,004		386	3.3
Aug-12	227,526	0.37%	65%	4,564	89	4.06	36.48	60%	19,896	68%	445	4.2
Sep-12	225,522	0.25%	54%	2,539	85	2.24	36.8	51%	54,054	60%	447	4.2
Oct-12	165,857	0.59%	65%	5,305	78	4.75	50.04	76%	46,245	63%	82	1.4
Nov-12	171,643	0.64%	73%	6,688	73	6.06	48.36	73%	40,608			
Average	202,869	0.47%	66%	5,135	83	4.61	41.90	66%	40,324	66%	450	3.08

Table 1: Stockdale Digester Performance during 2012 Prior to Engine Start-up

The actual H_2S levels measured, averaging ~450 ppm, although represents a 90% reduction in H_2S, were much higher than the goal of less than 50 ppm H_2S.

3.3 Engine-Generator Instrumentation and Performance Data

The first step in the preparation of the engine emissions system was to integrate engine control logic and Lambda set point bias using on-board electro-chemical emission sensors implemented in PLC logic. Also completed were the strategies, design layout and hydrogen injection plan for second stage catalyst (H-SCR), downstream of first stage. An H_2 SCR catalyst with housing, suitable for above mentioned strategy and a hydrogen reformer was sourced. The basic mechanical design phase, including calculation of performance parameters and defining mechanical connections is completed.

The engine was prepared for operations and emissions monitoring, as well as installing the components of the second stage after-treatment system and readying it for incorporation onto the engine platform. Next the engine was started and run on biogas fuel and initial emissions tests commenced. After these tests a cooling loop system issue caused the engine to be idled until repairs were made in October, 2012.

Emission tests were conducted at steady state loads with engine generator connected to a load bank. Emission Test Analyzer was a Testo 350 XL (Figure 5). Emission sample was taken from a sample port downstream of catalyst housing (Figure 6). Engine was tested at steady state loads: 300kW, 400kW and 500kW. At each load step a Lambda Set point variation (0.990 – 1.005, delta 0.003) was conducted, taking a 15 minute emission sample after it was ensured that air fuel ratio as well as governor control parameters were stable. Figure 7 shows a screen shot of the emission analyzer during the test runs. Table 2 summarizes the results of these early Phase I emissions tests.

Figure 5: Testo 350XL

Figure 6: Sample Port

Figure 7: Screenshot of emission testing

Power	NOx [ppm, uncorrected]	CO [ppm, uncorrected]
300 kW	0.9	19.5
400 kW	1.1	33.4
500 kW	0.8	95.6

Table 2: Initial Engine Emission Test Results-Phase I

Emission tests showed very low emission levels especially for NOx. These values seem to be at the low end of measuring range for the handheld equipment and definitely need to be further confirmed through third party emission test using EPA standards. In addition the catalyst is new, and further analysis needs to be conducted to confirm these low emission levels when the catalyst is more aged.

After baseline tests were taken, the advanced control strategies were uploaded to engine control module. Optimal Lambda set points as found in the base tests mentioned above as well as optimized control parameters were put in the dataset of the advanced control algorithms.

The onboard electro-chemical emission sensors that will be used for the advanced control strategy were validated against the Testo 350XL test results. With the base tests already showing impressive low emission levels, the next emission tests will incorporate the advanced control strategies.

4. PHASE II: H-SCR After-Treatment

4.1 Digester Instrumentation and Performance Data-December 2012-May 2013

The digester gas production continued to drop during October November and December, 2012 due to colder temperatures, to 40,000 scf/day. The H_2S levels continued to be lowered by air injection but results are erratic.

Influent and effluent samples were collected and analyzed .The volatile solids (VS) contents on January 8 were: influent 2320 mg/l, effluent 1480 mg/l, resulting in a 36% reduction in VS. The volatile solids (VS) contents on April 22 were: influent 3300 mg/l, effluent 1500 mg/l, resulting in a 55% reduction in VS. The average VS of these two readings were influent 2810 mg/l, effluent 1490 mg/l and 47 % reduction.

The H_2S removal system utilizing air injection was operated continuously and monitored by onsite personnel through January, 2013. A new air pump was installed on January 7, 2013. Figure 8 shows this new pump installation. H_2S readings of the biogas were obtained using a hand-held Drager monitor as well as a Landtec gas analyzer. These readings were taken both when the engine was running and when the engine was not running. The average H_2S reading when the engine was not running and the gas was being allowed to vent during January 2013 was ~400 ppm at the vent pipe. During the period of time, January 2013, that the engine was not running and the biogas was allowed to vent, the biogas was sampled at the biogas vent. The following parameters were also monitored: biogas flow in scf/day; influent average gallons/day; and estimated temperature of the digester contents. The average biogas flow was approximately 40,000 scf/day and the methane content was 75%, CO_2 content was 18% and the air content was 7%. The average influent flow was 157,000 gallons/day for an HRT of 53 days. In January the digester temperature ranged from 65 to 62 ^{o} F reflecting the drop in ambient temperature. Table 3 summarizes these digester performance data. Figure 9 shows the digester temperatures from late November 2012 to early January 2013.

In late January it was discovered that there was a leak in the air line supplying the air injection system; the leak was discovered to be a break in the buried plastic pipe which was subsequently repaired on April 22, 2013. Various H_2S readings were taken in February, March and April and these are summarized in Table 4. As shown the air injection rate was 1.2 to 1.4 scfm in February and April before the leak in the pipe was repaired; after the repair was done on April 22, the air injection rate increased to 2.4 scfm, and on May 1 it was reset at 3.8 scfm in accordance with the requirement for a higher oxygen level in the gas after the iron sponge. The average H_2S reading when the engine was running and the vent was closed during the engine testing ranged from 680 to 333 ppm before the iron sponge and 4 to 20 ppm after the iron sponge.

During the various periods of time in February, April and May 2013, tests were conducted with the engine running and the biogas vent was closed, the biogas was sampled at the engine. The following parameters were also monitored: biogas flow in scf/hour, methane and H_2S content of the biogas and estimated temperature of the digester contents. The total average biogas flow from the digester was difficult to estimate since the engine was run intermittently and biogas follow was only estimated for the days the engine was running. On April 22 the average methane content was 66%, CO_2 content was

31% and the air content was 3%. The average influent flow was not recorded because of battery failure at the flowmeter noted on April 22. During the February, March, and April time period the estimated digester temperature ranged from 60 to 70 ^{o}F. The temperature probes experience some unexplained spikes during this time period. Table 4 lists selected dates and the digester and engine performance during February, April and May 2013.

The total measured biogas produced by the lagoon is summarized by month in Table 5. As shown there was some variation in gas production, as measured through the sum of the vent gas meter and the engine gas meter. Due to the somewhat sporadic running of the engine in February, March and April, measured gas production was low, 6000 to 14,000 cubic feet per day as average over the whole month with the balance of the biogas being vented. Since the vent valve set at a high venting pressure, essentially closed, it was later found that not all the gas was being measured and that some was leaking out at an broken pipe joint. The average gas production numbers in May approximately 40,000 cubic feet per day are more indicative of total gas production since the engine was running more consistently.

Figure 8: New air pump installation at Stockdale Dairy Digester

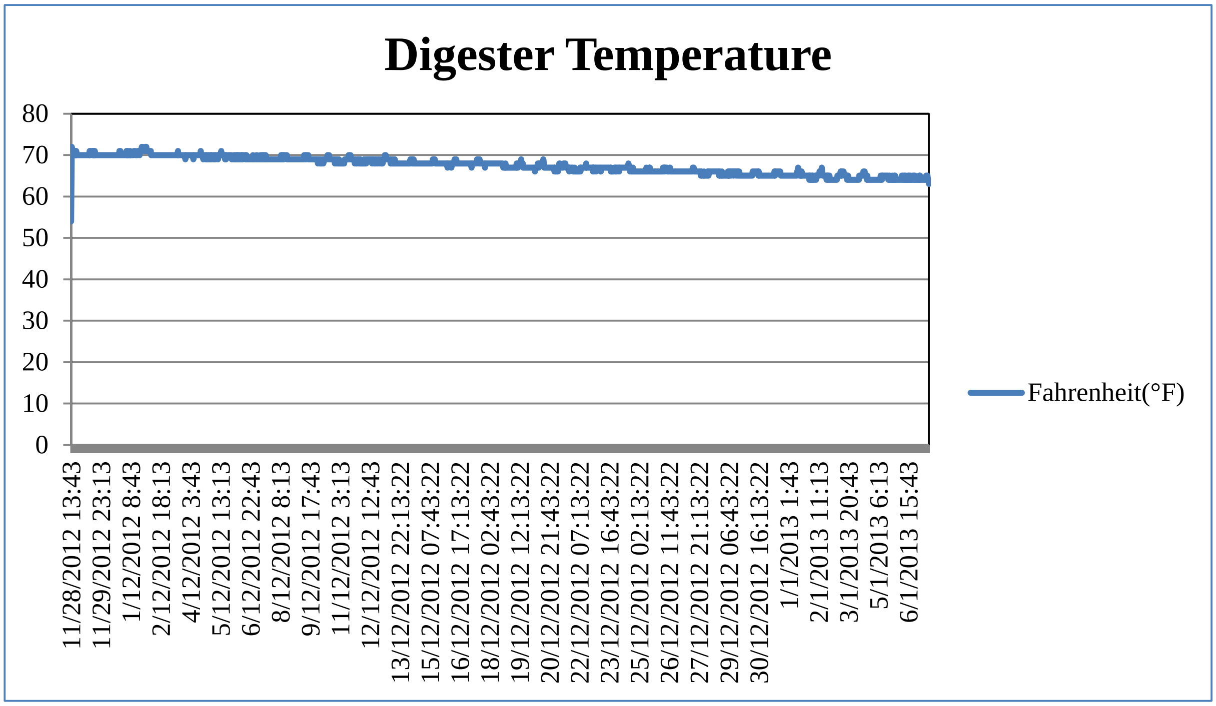

Figure 9: Digester temperatures from 28 November 2012 through 7 January 2013

Date	Time	Vent Valve Status	Biogas, post air injection		Digester Temp °F	Infl/Eff gal/day	HRT. days	Infl VS mg/l	Infl VS lb/day
			Cu ft/day	H_2S ppm					
7-Jan	8:30	Closed	-	400	65	158,000	53	2810	3700
15-Jan	Opened								
16-Jan	11:00		56,122						
18-Jan	11:00		40,098		62	151,000	55	2810	3500
25-Jan	11:00	closed	40,197		62	164,000	51	2810	3800

Table 3: Digester Performance during January 2013- Engine Not Running

Date	Time	Engine-Generator KW	Biogas					Air
			Est. MMBtu/hr	% Methane	Cu ft/hr	Average H2S from digester, ppm after Air Treatment	Average H2S out of scrubber, ppm	Inject rate scfm
25 Feb.	11 am	432	4.32	75	5,900	680	4	1.2
3 Apr.	11 am	540	5.4	75	7,300	400	14	1.4
16 Apr.	10 am	500	5.0	75	6,790	450	7	1.4
17 Apr.	8 am	500	5.0	75	6,790	440	20	1.4
22 Apr.	5 pm	500	5.0	66	7,700	333	10	2.4
29 Apr	3 pm	500	5.0	66	7,700	443	17	2.4
1 May	9 am	500	5.0	66	7700	350	19	3.8

Table 4: Digester Biogas Characteristics during February, April and May 2013

- This period involved an undetected broken biogas mains pipe causing a loss in measured biogas. Prior and later measurements indicate actual gross production at around 40,000 scf/day.

Month	Biogas Consumed by Engine (SCF/month)	Average Biogas used by engine (SCF/day)	Average Biogas measured at Vent (SCF/day)	Average Total biogas, (SCF/day)*	Total Biogas, (SCF/month)
January	34,481	1,112	19890	21,002	651,071
February	396,536	14,162	0	14,162	396,536
March	88,940	2,869	3284	6,153	190,744
April	350,287	11,676	2584	14,260	427,807
May	1,097,383	35,399	4629	40,028	1,240,882

Table 5: Measured Biogas Production at Vent and at Engine, January- May 2013

4.2 Engine-Generator Instrumentation and Performance Data: Oct 2012 - Jan 2013

After starting and running the engine on biogas fuel, significant run time and emissions tests were completed with and without H_2 injection. Ultra LOW NOx levels were observed in the exhaust emissions. The installation of 2^{nd} stage catalyst and hydrogen injection ports is described below:

Mechanical modifications to exhaust system were conducted to incorporate necessary hardware for Phase II. The selected H-SCR catalyst suitable was placed downstream of the main catalyst into the EGR return line (Figure 10). The hydrogen injection port for strategy I was located downstream of the main catalyst and upstream of the H-SCR catalyst (Figure 11). The hydrogen injection port for strategy II is located upstream of the main catalyst housing, downstream of the turbo charger (Figure 12).

Figure 10: H-SCR catalyst

Figure 11: H_2 Injection Port for Strategy I

Figure 12: H_2 Injection Port for Strategy II

The prototype hydrogen reformer was converted from operation on methane to digester gas through the following modifications:

- Recalculation of system parameters
- Modifications of sensors, actuators, heat exchangers and pumps
- Modifications to internal controls
- Performance test

A P&ID of the hydrogen reformer is shown in Figure 13 and a photo of this equipment is shown in Figure 14.

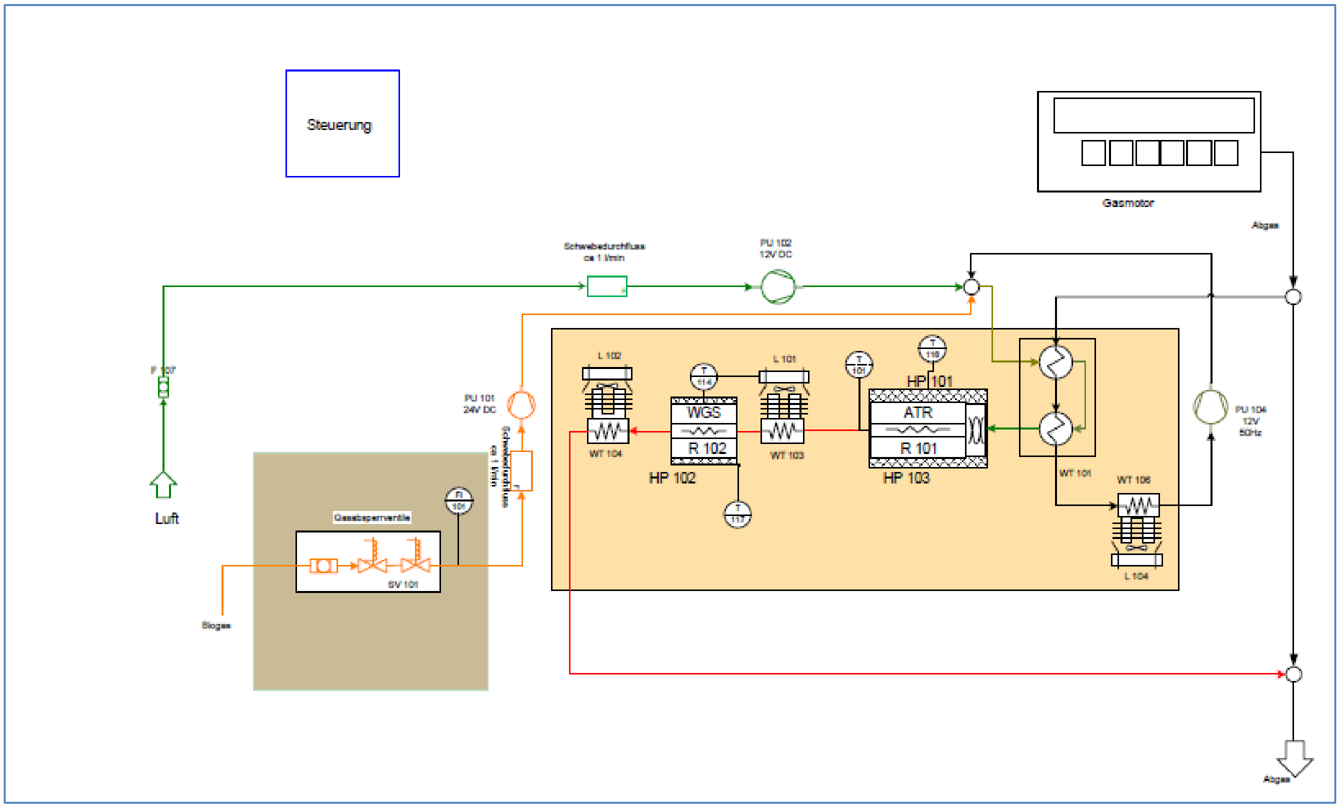

Figure 13: P&ID of Hydrogen Reformer

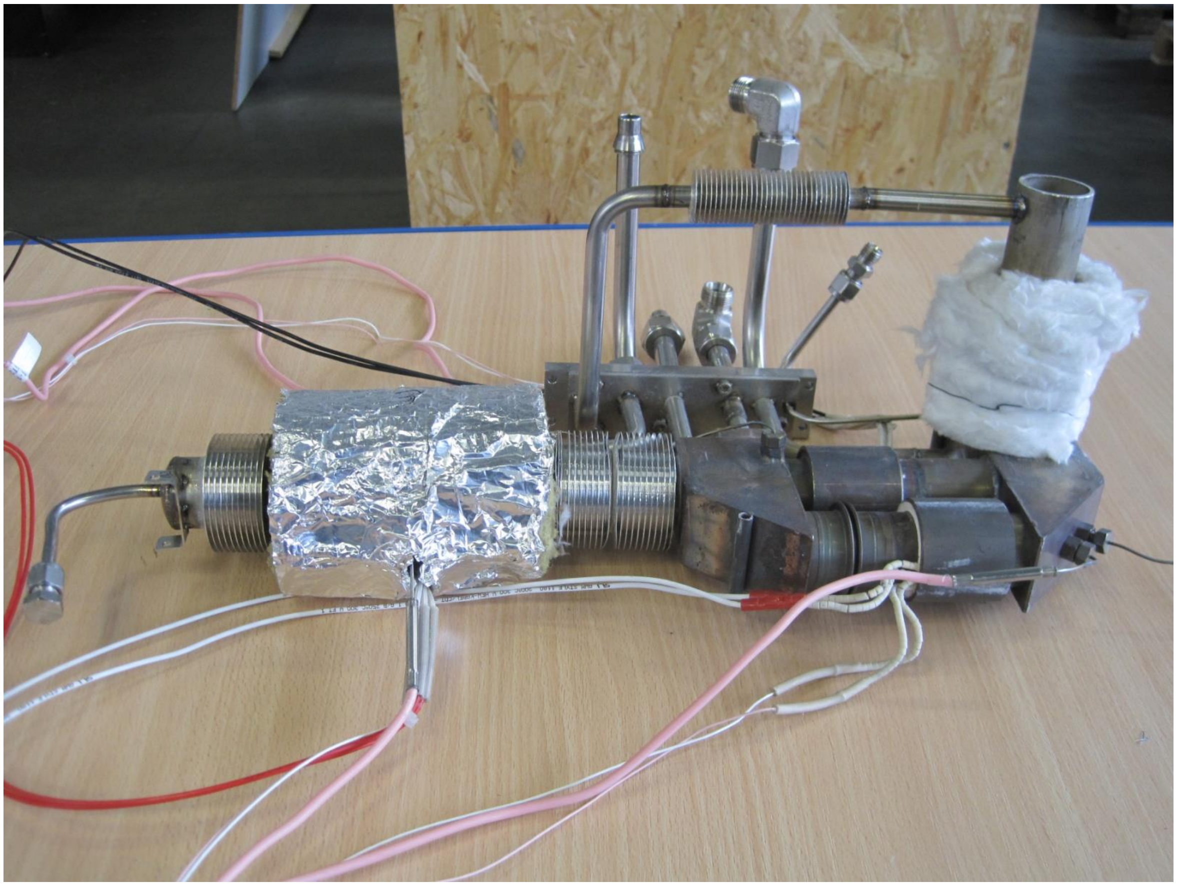

Figure 14: Photo of Hydrogen Reformer Prototype

Hydrogen Reformer Performance Test Results: The test results in Figure 15 showed a maximum hydrogen content of 24.27% in the reformed gas stream, which equals to 0.1 mol/min or 2.07 liter/min volumetric gas flow.

Assuming a worst case scenario of NOx = 0.15 g/bhp-hr in the gas stream after the first stage catalytic clean-up at maximum power output, approximately 1.0 liter/min hydrogen would be needed to theoretically reduce all remaining NOx in the second stage after treatment system to N2 and H2O.
The reformer is therefore capable to produce at least twice the amount of hydrogen necessary for a complete reduction of all NOx.

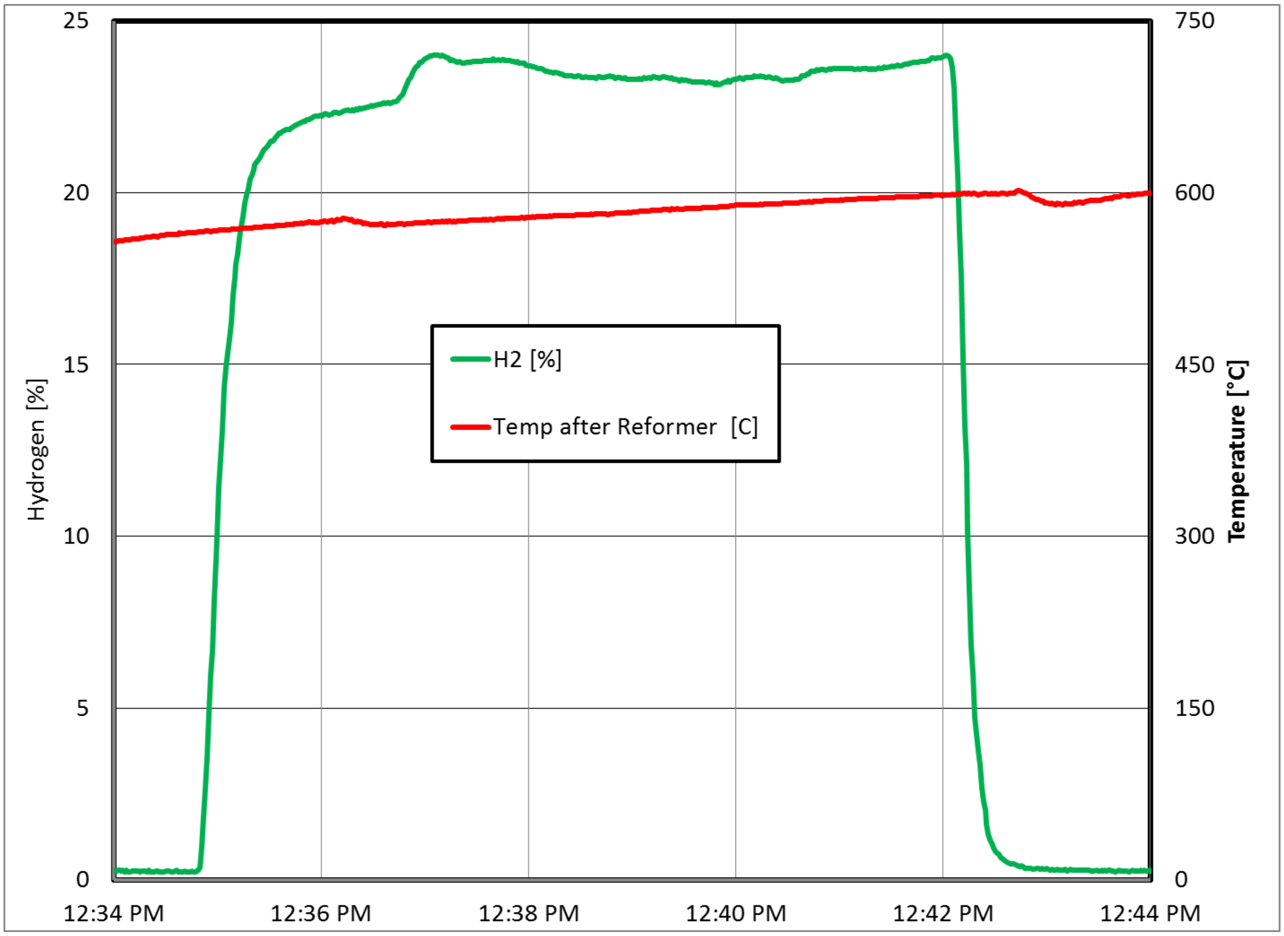

Figure 15: H_2 Reformer Performance Test

Proof of concept tests using bottled hydrogen resulted in only slight improvements to already extreme low baseline emissions. Additional testing would have been required with an aged catalyst. Due to lack of further reduction in NOx from H_2 injection and the significant reduction in NOx just from the exhaust gas recirculation and emission control activities focused on continuing to optimize and make more robust the control and advanced control strategies so as to potentially deliver the low NOx results across extended periods of operating time and across different ambient conditions. The results are benefited by the cool ambient temperatures allowing intercooler and other engine operating temperatures to be in ideal ranges. In the summer it will become more challenging to operate the engine at its targeted power levels and in its desired control ranges. It was decided to add fuel sensors to the control algorithms. CH_4 sensors and O_2 sensors in the fuel line were helpful in determining fuel efficiency and digester air injection efficiency and thus maintaining optimal emissions levels. Reliable fuel content sensors are typically challenging to obtain and operate so this effort will be limited to trying to implement one particular type of sensor.

5. Long-term testing @ PHASE I emissions optimization

5.1 Engine testing - February-March 2013

With the recalibrated fuel flow meter, fuel consumption and fuel efficiency could be measured. The methane content of the digester gas has repeatedly been in the range of 60% – 65%. A lower heating value of 650 BTU/scf was used to calculate electric specific fuel consumption and electric efficiency. Table 6 shows the results for the typical load range of 300 – 550 kW.

Electric Power	Fuel Flow	Specific Fuel Consumption (LHV)	Electric Efficiency
[kW]	[scfh]	BTU/kW-hr	%
300	4,367	9,462	36.1
400	5,473	8,894	38.4
500	6,749	8,772	38.9
550	7,290	8,615	39.6

Table 6: Fuel consumption and Fuel Efficiency-Feb-Mar 2013

Baseline testing was repeated using on-board electrochemical sensors to ensure validity of reported low emission levels since the previous testing now that we have additional engine run time. Low concentration calibration gas was used to calibrate electro chemical emission sensors before and after test. Calibration gas concentration for NO is 50 ppm; concentration for calibrating CO sensor is 200 ppm. Lambda sweeps were performed at load steps 300kW, 400kW and 500kW. Emission and other engine related data was sampled for 10 min at a sample rate of 1s for each load/lambda. Tables 7, 8 and 9 show the average emissions for the sample period as well as statistical emission results (Minimum and Maximum sample of the 600 samples) as well as the relative standard deviation of lambda, measured with the wideband oxygen sensor in the exhaust stream.

The very low variation of Lambda is an indication of very stable operation of all engine subsystems:

- good mixing of the air, fuel and recirculated exhaust gas
- stable combustion with very low cycle to cycle variations
- optimized load governing (throttle actuation) system, well synchronized with fuel actuation system (air fuel ratio controller)

Some of the average emissions are shown in negative territory. The low achieved emissions are truly a challenge to measure accurately. The noise on the sensors, defined as the Standard Deviation during Zero-Calibration is in the same range as the measured mean values. The Standard Deviation during Zero-Calibration is 0.2 ppm for the NO-Sensor and 1.2 ppm for the CO Sensor, corrected to 15% Oxygen. For all tested load levels the window for optimum NOx and CO emissions is between lambda = 0.988 – 0.996. In this window neither NOx nor CO show high variations, illustrated by the min and max values during the 10 min test runs; another indication of the very stable engine operation. An interesting observation, is the fact of increase of NOx as well as CO on the lean side of the optimal operation window. It appears that the reaction and storage mechanism of the catalyst and washcoat system gets excited in the optimal operation window, which leads to very high CO conversions even though the air fuel ratio is slightly richer.

Lambda SP	NOx	CO		NOx – Min	NOx - Max	CO - min	CO - max	Lambda - Rel Std Dev
[-]	[ppm @ 15%O2]							[%]
0.986	-0.4	10.1		-0.7	0.0	-0.2	31.6	0.16%
0.986	-0.9	7.5		-1.2	-0.6	0.3	47.8	0.18%
0.988	-0.7	2.3		-1.0	-0.4	-0.3	4.5	0.15%
0.990	-0.1	2.1		-0.5	0.2	-0.3	4.5	0.15%
0.990	-0.4	5.7		-0.8	-0.1	2.7	9.3	0.16%
0.994	0.2	9.1		-0.8	11.1	3.5	19.8	0.15%
0.998	153.0	235.6		91.6	175.5	172.7	263.1	0.14%
1.002	177.5	300.6		167.8	190.2	290.6	308.6	0.15%

Table 7: Emission test results at 300 kW-Feb Mar 2013

Lambda SP	NOx	CO		NOx – Min	NOx - Max	CO - min	CO - max	Lambda - Rel Std Dev
	ppm @ 15%O2							%
0.984	0.2	40.2		-0.2	0.6	10.7	119.4	0.15%
0.988	0.2	-0.7		-0.2	0.6	-2.9	2.0	0.15%
0.992	0.1	-1.1		-0.2	0.5	-3.5	2.5	0.14%
0.996	0.3	17.9		-0.3	4.2	-1.1	58.2	0.16%
0.998	39.8	44.3		1.0	127.2	12.7	95.3	0.13%
1.000	178.4	183.2		109.5	199.4	148.8	197.6	0.15%
1.002	151.1	213.8		41.9	179.4	145.2	241.4	0.15%

Table 8: Emission test results at 400 kW-Feb Mar 2013

Lambda SP	NOx	CO		NOx – Min	NOx - Max	CO - min	CO - max	Lambda - Rel Std Dev
	ppm @ 15%O2							%
0.984	0.2	71.4		-0.2	0.7	16.1	155.1	0.15%
0.988	-0.1	0.7		-0.5	0.2	-2.0	5.2	0.15%
0.992	-0.3	-0.4		-0.6	0.1	-2.5	1.8	0.13%
0.996	-0.6	-0.1		-1.0	0.3	-3.2	14.0	0.15%
0.998	-0.6	1.2		-1.1	2.6	-1.3	8.0	0.14%
1.000	21.9	35.1		-0.4	121.4	7.3	123.6	0.15%
1.002	150.1	213.1		41.0	178.4	144.6	240.7	0.15%

Table 9: Emission test results at 500 kW-Feb Mar 2013

SJVUAPCD with Emission Testing using TESTO XL 350: The Bakersfield office of the SJVUAPCD visited on 2/26/2013 and exhaust emission samples were collected by their staff directly from the stack post catalyst using a long stainless steel sampling tube. Good data was verified with low O_2 measurements as shown in Figure 16 and Table 10.

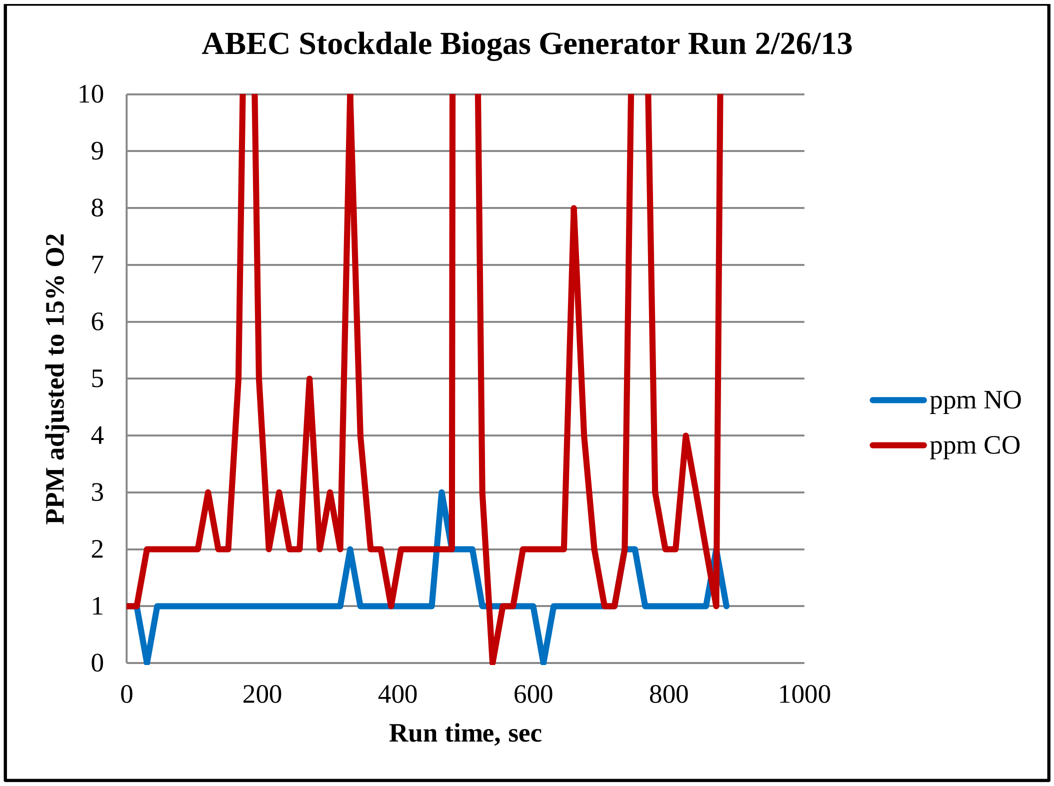

Figure 16: SJVUAPCD TESTO XL 350 - NO and CO emissions curves at 500kW

Date / time	sec Runtime	% O2	% O2rf	ppm NO	ppm NO2	ppm CO	CalBio Notes
2/26/2013 13:44:46 tt	0	0.07	15.0	1	0.0	1	
2/26/2013 13:45:01 tt	15	0.08	15.0	1	0.0	1	
2/26/2013 13:45:16 tt	30	0.07	15.0	0	0.0	2	
2/26/2013 13:45:31 tt	45	0.07	15.0	1	0.0	2	
2/26/2013 13:45:46 tt	60	0.06	15.0	1	0.0	2	
2/26/2013 13:46:01 tt	75	0.05	15.0	1	0.0	2	
2/26/2013 13:46:16 tt	90	0.02	15.0	1	0.0	2	
2/26/2013 13:46:31 tt	105	0.04	15.0	1	0.0	2	
2/26/2013 13:46:46 tt	120	0.02	15.0	1	0.0	3	
2/26/2013 13:47:01 tt	135	0.02	15.0	1	0.0	2	
2/26/2013 13:47:16 tt	150	0.02	15.0	1	0.0	2	
2/26/2013 13:47:31 tt	165	0.02	15.0	1	0.0	5	
2/26/2013 13:47:46 tt	180	0.02	15.0	1	0.0	17	
2/26/2013 13:48:01 tt	195	0.02	15.0	1	0.0	5	
2/26/2013 13:48:16 tt	210	0.02	15.0	1	0.0	2	
2/26/2013 13:48:31 tt	225	0.01	15.0	1	0.0	3	
2/26/2013 13:48:46 tt	240	0.01	15.0	1	0.0	2	
2/26/2013 13:49:01 tt	255	0.02	15.0	1	0.0	2	
2/26/2013 13:49:16 tt	270	0.01	15.0	1	0.0	5	
2/26/2013 13:49:31 tt	285	0.00	15.0	1	0.0	2	
2/26/2013 13:49:46 tt	300	0.00	15.0	1	0.0	3	
2/26/2013 13:50:01 tt	315	0.01	15.0	1	0.0	2	
2/26/2013 13:50:16 tt	330	0.02	15.0	2	0.0	10	
2/26/2013 13:50:31 tt	345	0.02	15.0	1	0.0	4	
2/26/2013 13:50:46 tt	360	0.02	15.0	1	0.0	2	
2/26/2013 13:51:01 tt	375	0.00	15.0	1	0.0	2	
2/26/2013 13:51:16 tt	390	0.02	15.0	1	0.0	1	
2/26/2013 13:51:31 tt	405	0.02	15.0	1	0.0	2	
2/26/2013 13:51:46 tt	420	0.02	15.0	1	0.0	2	
2/26/2013 13:52:01 tt	435	0.01	15.0	1	0.0	2	
2/26/2013 13:52:16 tt	450	0.02	15.0	1	0.0	2	
2/26/2013 13:52:31 tt	465	0.00	15.0	3	0.0	2	
2/26/2013 13:52:46 tt	480	0.02	15.0	2	0.0	2	
2/26/2013 13:53:01 tt	495	0.01	15.0	2	0.0	139	
2/26/2013 13:53:16 tt	510	-0.01	15.0	2	0.0	19	
2/26/2013 13:53:31 tt	525	0.00	15.0	1	0.0	3	
2/26/2013 13:53:46 tt	540	0.01	15.0	1	0.0	0	
2/26/2013 13:54:01 tt	555	0.01	15.0	1	0.0	1	
2/26/2013 13:54:16 tt	570	0.01	15.0	1	0.0	1	
2/26/2013 13:54:31 tt	585	0.01	15.0	1	0.0	2	
2/26/2013 13:54:46 tt	600	0.02	15.0	1	0.0	2	
2/26/2013 13:55:01 tt	615	0.00	15.0	0	0.0	2	
2/26/2013 13:55:16 tt	630	0.01	15.0	1	0.0	2	
2/26/2013 13:55:31 tt	645	0.00	15.0	1	0.0	2	
2/26/2013 13:55:46 tt	660	0.01	15.0	1	0.0	8	
2/26/2013 13:56:01 tt	675	0.00	15.0	1	0.0	4	
2/26/2013 13:56:16 tt	690	0.02	15.0	1	0.0	2	
2/26/2013 13:56:31 tt	705	0.01	15.0	1	0.0	1	
2/26/2013 13:56:46 tt	720	0.00	15.0	1	0.0	1	
2/26/2013 13:57:01 tt	735	0.01	15.0	2	0.0	2	
2/26/2013 13:57:16 tt	750	0.01	15.0	2	0.0	15	
2/26/2013 13:57:31 tt	765	0.01	15.0	1	0.0	13	
2/26/2013 13:57:46 tt	780	0.01	15.0	1	0.0	3	
2/26/2013 13:58:01 tt	795	0.01	15.0	1	0.0	2	
2/26/2013 13:58:16 tt	810	0.00	15.0	1	0.0	2	
2/26/2013 13:58:31 tt	825	0.00	15.0	1	0.0	4	
2/26/2013 13:58:46 tt	840	0.01	15.0	1	0.0	3	
2/26/2013 13:59:01 tt	855	0.00	15.0	1	0.0	2	
2/26/2013 13:59:16 tt	870	0.00	15.0	2	0.0	1	
2/26/2013 13:59:31 tt	885	0.00	15.0	1	0.0	24	

Table 10: SJVUAPCD TESTO XL 350- Raw emissions data 2/26/2013 at 500kW

5.2 Engine testing : May - June 2013

Engine testing was performed 5/15-5/16/2013, shortly after the engine generator had reached 300 operating hours. Zero calibration of the onboard CO and NOx sensors using surrounding air were conducted before and after every test run. It is assumed that this will increase sensor accuracy in the low ppm range and negative values of reported emissions occurred less often than in the previous tests. A gas analysis was taken on 4/22/2013 with following compositions: CH4:66.1 %; CO2:31.5 %; O2:0.3 %; N2:2.1 %. The air injection rate under the cover of the digester to reduce raw H2S on this date was 2.1 scfh.

After 4/22/2013 and prior to the tests conducted 5/15-5/16/2013 the air injection rate was increased to 3.8 scfh (an 81% increase) in order to assure an oversupply of oxygen for the sulfur removal. It is assumed that the nitrogen amount in the fuel gas was proportionally increased with the injection rate and that the additional oxygen would end up with the additional nitrogen in the fuel gas. The corrected gas composition will thus be assumed to be: CH4:64.6 %; CO2:30.8%; O2: 0.8%;
N2: 3.8%. The heating values for this gas composition are: HHV=654 BTU/scfh;
LHV=589 BTU/scfh

Table 11 shows the results for the tested load range of 300 – 500 kW

Electric Power	Fuel Flow	Specific Fuel Consumption (LHV)	Electric Efficiency
kW	scfh	BTU/kW-hr	%
300	4,676	9,181	37.2
400	5,988	8,817	38.7
500	7,337	8,643	39.5

Table 11: Fuel Consumption and Fuel Efficiency-May 2013

Emission testing included Lambda sweeps performed at load steps 300kW, 400kW and 500kW. Exhaust emissions and other engine related data was sampled for 10 minutes at a sample rate of 1s for each load/lambda. After each sample period the sensors were purged for 10 minutes with surrounding air. The average data for NOx and CO of the last 5 minutes of the sensor purge period was used as Zero calibration for the sensors. Tables 12, 13 and 14 show the average corrected emissions for the sample period as well as statistical emission results (Minimum and Maximum sample of the 600 samples) as well as the relative standard deviation of lambda, measured with the wideband oxygen sensor in the exhaust stream. The emission results are very similar as the ones presented in the previous test. Optimum Lambda window appears to be between Lambda SP 0.984 and 0.992, with a widening range on the leaner side with increasing power output (Lambda SP up to 0.996 at 500 kW). Overall the optimum window has shifted slightly to lower lambda SP values since the last report. It has to be seen if this process continues.

Lambda SP	NOx	CO		NOx – Min	NOx - Max	CO - min	CO - max	Lambda - Rel Std Dev
[-]	ppm @ 15%O2							%
0.980	0.3	239.6		-0.1	0.7	137.9	391.9	0.15%
0.984	0.2	14.1		N/A	N/A	N/A	N/A	N/A
0.988	0.2	4.5		-0.2	0.7	-1.1	27.6	0.17%
0.992	2.4	9.4		0.0	18.6	2.7	29.6	0.14%
0.994	112.5	82.9		50.8	156.0	56.8	107.1	0.15%

Table 12: Emission test results at 300 kW-May 2013

Lambda SP	NOx	CO		NOx – Min	NOx - Max	CO - min	CO - max	Lambda - Rel Std Dev
	ppm @ 15%O2							%
0.980	0.4	186.5		-0.1	0.9	66.2	351.5	0.14%
0.982	0.1	65.2		-0.5	0.6	3.9	160.0	0.14%
0.984	0.0	29.4		-0.6	0.7	0.3	107.9	0.13%
0.988	0.0	-0.1		-0.5	0.6	-3.5	4.9	0.14%
0.992	0.0	1.8		-0.5	1.1	-2.8	15.4	0.12%
0.994	3.0	2.3		-0.2	38.9	-1.8	15.9	0.13%
0.996	98.6	67.7		3.6	161.7	21.6	101.0	0.13%

Table 13: Emission test results at 400 kW-May 2013

Lambda SP	NOx	CO		NOx – Min	NOx - Max	CO - min	CO - max	Lambda - Rel Std Dev
	ppm @ 15%O2							%
0.980	0.5	231.5		0.1	0.9	125.3	376.7	0.12%
0.984	0.1	17.5		-0.2	0.5	-3.3	67.3	0.11%
0.988	0.4	-0.3		-0.1	0.8	-2.6	2.4	0.14%
0.992	0.2	-0.8		-0.3	2.2	-3.1	1.7	0.14%
0.996	0.6	1.7		-0.4	15.5	-2.8	18.5	0.14%
0.998	85.9	81.0		3.0	170.1	23.5	135.7	0.11%

Table 14: Emission test results at 500 kW-May 2013

5.3 Engine testing – August - 2013

Various issues at the engine and site infrastructure occurred since the previous testing. Failures in exhaust gaskets due to a poor design of connections and supports from exhaust system to turbo charger lead to gas blow-by of the turbo charger, not providing enough exhaust energy to create boost pressure. The engine could not run above 300 kW under these circumstances. The gaskets were replaced various times but deterioration would occur shortly after replacement, not leaving enough time for emission analysis necessary for further reporting. In October of 2013 a complete new design of the exhaust to turbo coupling system was engineered. The system was installed in December of 2013 and the engine was brought back into service in January of 2014.

An emission test at 800-hours of engine operation was performed on August 15, 2013, shortly after a preliminary exhaust gasket replacement. This 12-hour emission test was conducted with following parameters**:** generator load: 550 kW, continuous operation**;** air-fuel ratio control set point: constant, balance between optimum NOx and CO trade-off; the non-calibrated set point was 0.984
The emission test was conducted in 48 continuous 15 minute test intervals; each interval included:

- 4 min of rinse time (sensors connected to fresh air)
- 11 min of exhaust sample, sample rate 1s
- Storage of load and emission data from the last 10 min of exhaust sample
  - Average load
  - Average NO and CO
  - Standard Deviation for NO and CO

Figures 17 and 18 show the results of this emission test. Average emissions as well as the standard deviations during each test interval were very low and consistent over the entire 12 hour test period.

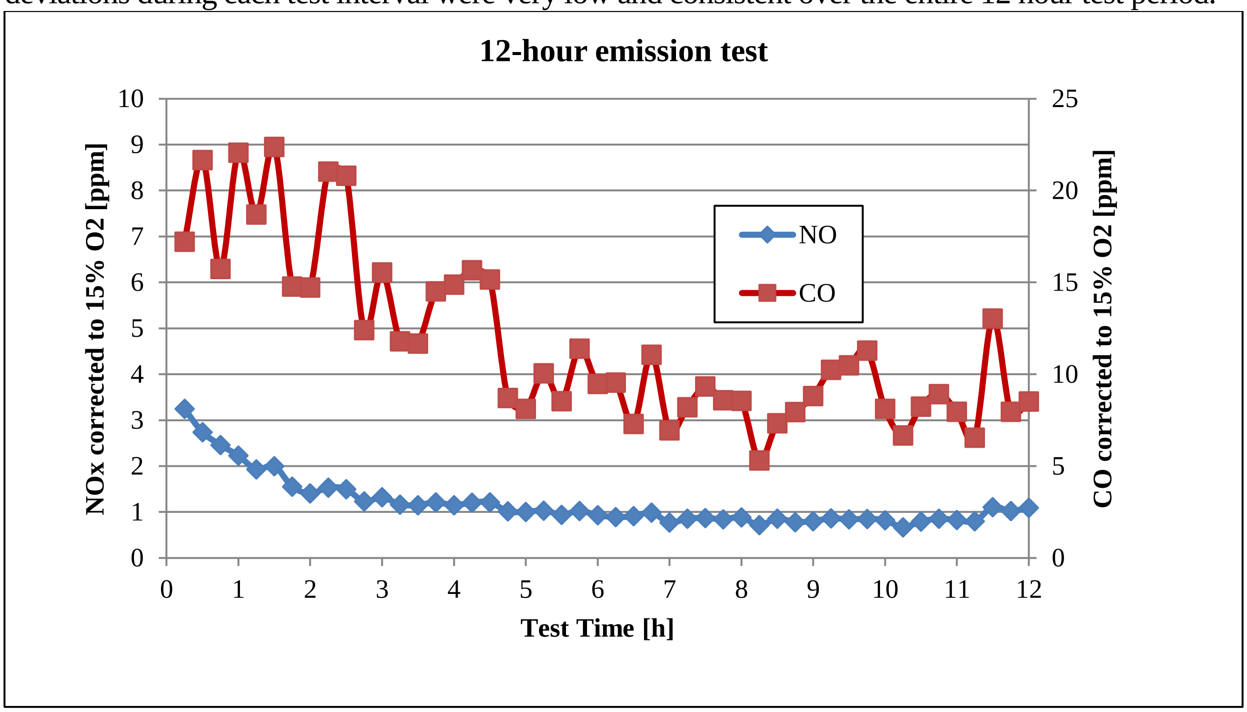

Figure 17: NO and CO emissions during 12 hour test run at 550 kW-August 2013

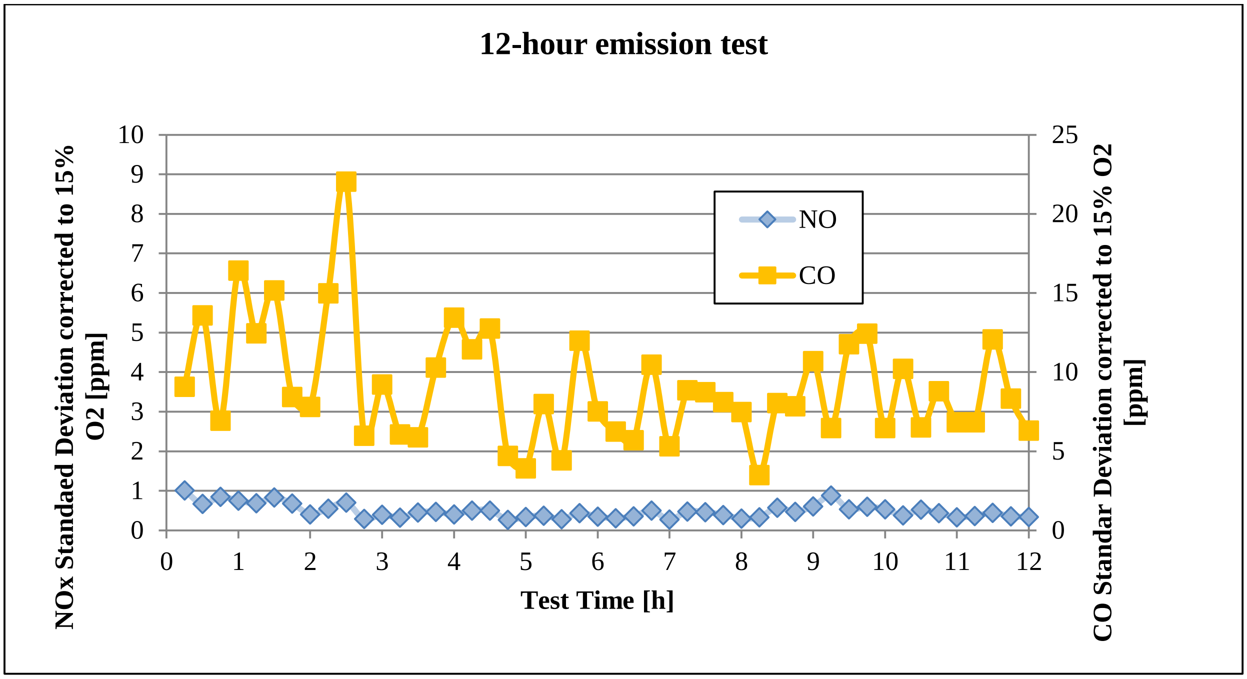

Figure 18: NO and CO emissions standard deviation during 12 hour test run at 550 kW-Aug 2013

Shortly after the above test was finished, piping of the external cooling loop were damaged. The external cooling loop rejects engine coolant heat and oil heat to the digester lagoon. After cooling loop repair, issues with connection between exhaust and turbo charger became obvious leading to above mentioned re-engineered system.

5.4 Engine testing: February – March 2014

Continuation of emission testing was conducted in February of 2014, after engine runtime had exceeded 1,000 hours. Lambda sweeps for 300kW, 400kW and 500 kW were conducted between 2/11/2014 and 2/17/2014. A fuel gas analysis was conducted on 1/30/2014 with following compositions: CH_4: 70.6 %, CO_2: 24.5 %, O_2: 0.8 %, N_2: 4.1 %, H_2S before scrubber: 287 ppm
H_2S after scrubber: 12 ppm. The heating values for this gas composition were: Higher Heating Value (HHV): 716 BTU/scf; Lower Heating Value (LHV): 644 BTU/scf. Table 15 shows the fuel consumption results for the tested load range of 300 – 500 kW.

Electric Power	Fuel Flow	Specific Fuel Consumption (LHV)	Electric Efficiency
[kW]	[scfh]	BTU/kW-hr	%
300	4,267	9,160	37.3
400	5,481	8,824	38.7
500	6,664	8,583	39.8

Table 15: Fuel Consumption and Fuel Efficiency-February 2014

Emission tests included Lambda sweeps which were performed at load steps 300kW, 400kW and 500kW. Emission and other engine related data was sampled for 11 min at a sample rate of 1 second for each load/lambda. Average values and standard deviations were calculated and stores for the last 10 minute sample time. After each sample period the sensors were purged for 4 minutes with surrounding air. The average data for NOx and CO of the last minute of the sensor purge period was used as Zero calibration for the sensors.

This test procedure was typically repeated 4 times at each load/lambda point resulting in a total of 60 min test period with 40 min of sampled exhaust gas, sample rate 1s. At load/lambda points where emission rates were extremely high the total test time was reduced to one or two sample periods in order to not emit excessive pollutants and to prevent sensor saturation.

Tables 16, 17 and 18 show the average corrected emissions and standard deviations.

Lambda SP	NOx	CO		STD NOx	STD CO
[-]	[ppm @ 15%O2]				
0.980	7.1	424.7		2.1	119.0
0.982	11.6	194.3		10.9	34.9
0.984	21.6	170.2		19.7	22.3
0.986	154.0	261.4		57.6	24.7

Table 16: Emission test results at 300 kW-February 2014

Lambda SP	NOx	CO		STD NOx	STD CO
[-]	[ppm @ 15%O2]				
0.980	1.4	574.6		0.3	112.3
0.982	0.9	173.7		0.4	67.9
0.984	1.4	67.6		1.1	17.3
0.986	4.6	111.6		6.3	37.6
0.988	37.1	185.0		21.2	35.6

Table 17: Emission test results at 400 kW-February 2014

Lambda SP	NOx	CO		STD NOx	STD CO
[-]	[ppm @ 15%O2]				
0.982	11.0	243.1		3.4	121.8
0.984	7.9	48.3		3.7	17.5
0.986	10.6	32.4		6.2	6.2
0.988	3.9	34.8		2.7	9.9
0.990	51.5	185.3		27.1	54.8

Table 18: Emission test results at 500 kW-February 2014

5.5 Third Party Emissions Testing – March 2014

A USEPA Compliance Source Test Report was conducted on March 20, 2014, and this report in full is attached in Appendix A. Table 19 summarizes these results of this compliance source test.
The results were disappointing in that the engine system had started to demonstrate variability as the emissions levels increased. The conclusions are discussed in the next section.

AEROS ENVIRONMENTAL, INC.

Summary Of Results

Bidart Dairy Stockdale
Stockdale Highway Facility
Digester Gas IC Engine

Project 056-8267
March 20, 2014
ATC No. S-7658-1-0

Pollutant	ppm	ppm @ 15% O_2	g/BHP-hr	Permit Limits
NOx	64.7	18.3	0.27	
	68.6	19.4	0.29	0.15 g/BHP-hr
	70.8	20.0	0.30	and
Mean	**68.0**	**19.2**	**0.28**	11 ppm @ 15% O_2
CO	146	41	0.37	
	146	41	0.37	1.75 g/BHP-hr
	144	41	0.36	and
Mean	**145**	**41**	**0.37**	212 ppm @ 15% O_2
VOC (NMEOC)	75	21	0.11	
	114	32	0.17	0.15 g/BHP-hr
as methane	107	30	0.16	and
Mean	**99**	**28**	**0.14**	32 ppm @ 15% O_2
VOC (NMOC)	29	8	0.11	
	42	12	0.17	
as propane	39	11	0.16	
Mean	**37**	**10**	**0.15**	N/A
Fuel Sulfur Content as H_2S	**275**			50 ppm

Table 19: Compliance Source Test Report Summary Results. Tested March 20, 2014

6. DISCUSSION AND CONCLUSIONS

While the emission data taken at 800-hr engine run-time is similar to the data presented in Section 5.2 (300-hr runtime), the emission results have deteriorated significantly since then. Emission levels, particularly CO are highly increased and operational Lambda window has shortened in comparison to the 300-hour and 800-hour testing. Analysis of engine operation suggest a very stable combustion performance with following data:

- Covariance of Throttle position: 0.11%
- Covariance of Gas Mixer position: 0.16%
- Covariance of gas flow: 0.10%
- Covariance of lambda measured in exhaust stream: 0.08%
- Covariance of manifold pressure: 1.76%

It is therefore assumed that emission performance deterioration is based on reduced catalyst performance. The cause of reduced catalyst performance and if it is reversible (e.g. masking of catalyst) or irreversible (e.g. structural damage, thermal damage or poisoning) is not known at this point and needs further investigation. The lower exhaust temperature at 300 kW (700 F after Catalyst vs. above 800 F at 400 and 500 kW) might be an additional reason for the poor emission results especially at the 300 kW load point. Figures 19, 20 and 21 illustrate the differences of catalyst out emissions at the 300-hr and the 1000-hr runtime mark.

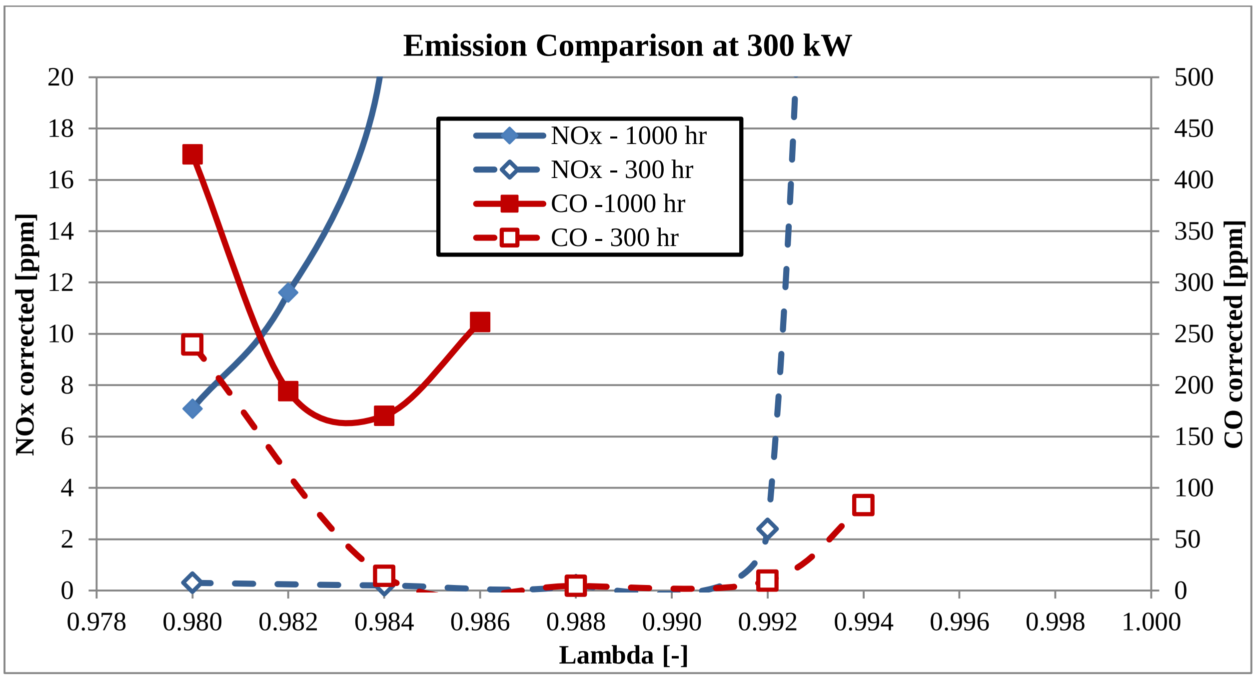

Figure 19: Emission Comparison after 300 and 1000 hr runtime – 300 kW

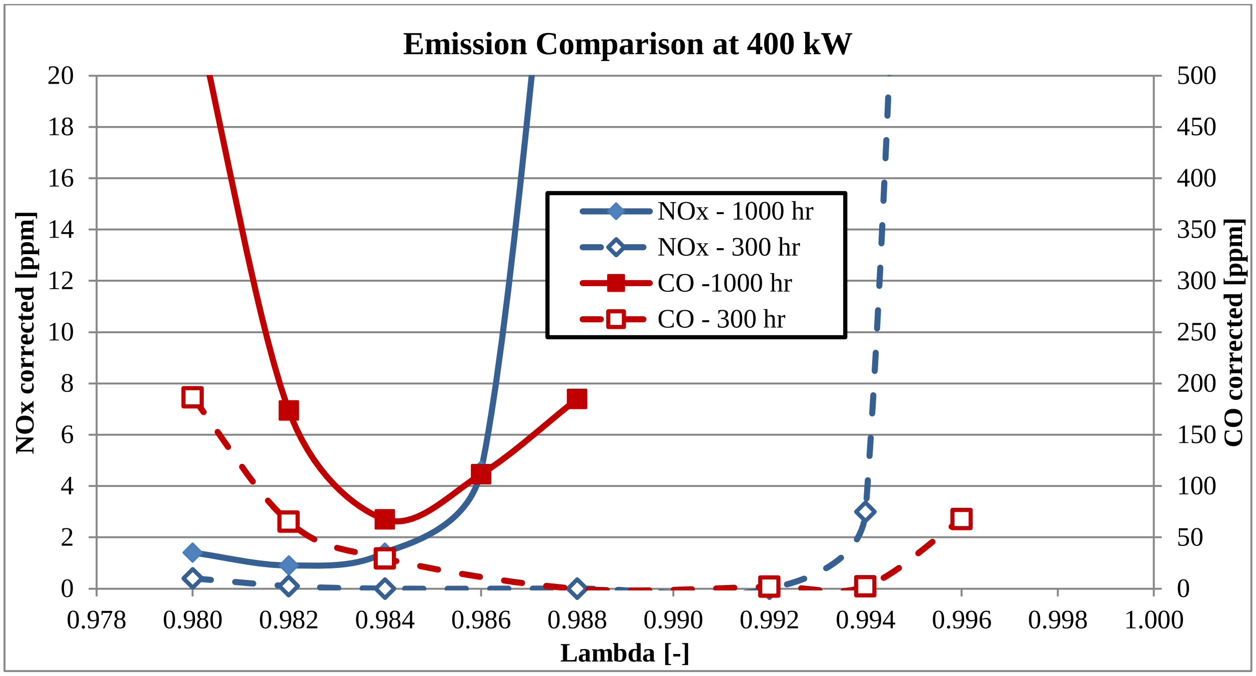

Figure 20: Emission Comparison after 300 and 1000 hr runtime – 400 kW

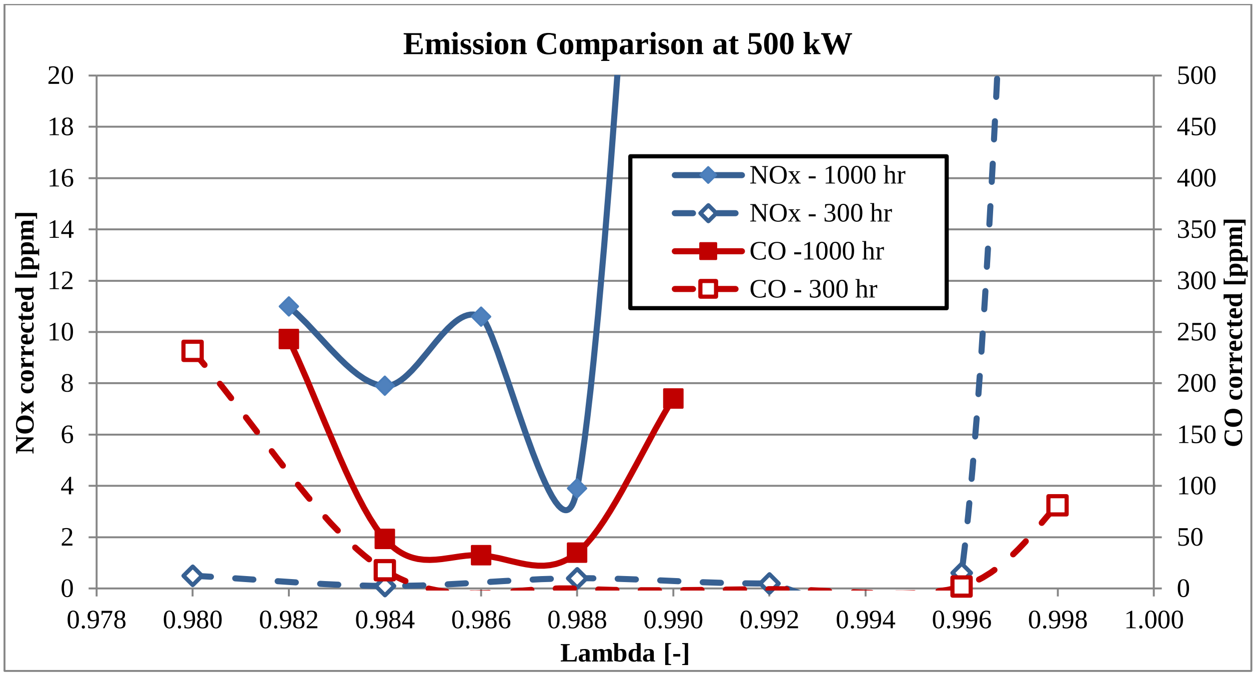

Figure 21: Emission Comparison after 300 and 1000 hr runtime – 500 kW

The California Air Resources Board (ARB) standard for distributed generation systems is 0.07 pounds of NOx per megawatt-hour of useful energy output (lb/MWH). This goal was achieved intermittently by this engine, with NOx emissions on occasion as low as 0.028 lb/MWH (equivalent to 0.69 ppmvd or 0.009 g/BHP-hr) measured by the operator and Air District personnel.

Independent source testing did not confirm these low NOx results confirming the variability of the results as shown in Table 19. In April of 2014 the experimental engine suffered a catastrophic failure due to coolant system failure and subsequent engine overheating. The project and ongoing testing was concluded prematurely. The following conclusions were therefore gleaned from this project:

1) High H_2S lagoon digester biogas can be successfully and inexpensively treated through the addition of 5 – 10% air into the head space of a covered lagoon digester. 70% to 90% reduction in H2S can be consistently achieved (from 2,000 to 5,000 ppm to less than 500 ppm) if the air injection is evenly dispersed throughout the headspace. Operating costs are minimal. Polishing of the resulting biogas is still needed by conventional chemical (e.g. iron sponge) scrubbers to achieve Central Valley Air District fuel sulfur standards of 50 ppm or less

2) Exhaust from a rich burn IC engine can be cooled and recirculated back into the biogas fuel stream in amounts ranging up to 10% to add additional inerts into the fuel to increase engine efficiency and deaden combustion temperatures.

3) Exhaust from a rich burn IC engine utilizing tight lambda controls (0.980 – 0.988 range) combined with an EGR diluted biogas fuel mix can be successfully processed through a traditional NSCR catalyst to less than 2 ppm NOx. These results were not consistently achieved and further investigation of the reasons why NOx levels varied needs to be pursued.

4) Hydrogen gas (20% plus concentration) can be produced from low H_2S biogas feedstock utilizing a reformer.

5) Addition of a second stage H-SCR along with the addition of hydrogen into the exhaust stream does not result in a further reduction of NOx below the 2 ppm levels observed prior to the H-SCR system.

6) The combination of high CO_2 levels in the biogas along with the CO_2 and nitrogen introduced from the EGR system produced a fuel with a high equivalent octane (methane number) and enabled reliable IC engine operation at a compression ratio of 14:1 with high efficiency of over 39% at full power.

7) Although the overall EGR IC engine emission results were tantalizingly encouraging, the complexity of the overall system and the lack of a major engine manufacturer willing to

support EGR with engine warranties and emission guarantees causes this approach to low NOx management to still be commercially unfeasible. The test engine never operated reliably and eventually suffered a catastrophic failure due to overheating in April 2014, prematurely ending the project. The ability to operate an IC engine at a higher compression ratio when using high CO_2 fuels does offer the potential for improvement in biogas engine efficiency and should be examined further.