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FINAL PROJECT REPORT

BIOGAS-FUELLED HCCI POWER GENERATION SYSTEM FOR DISTRIBUTED GENERATION

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Prepared by: Makel Engineering Inc.

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PREPARED BY:

Primary Author(s):
Darby B. Makel, Ph.D.
Brandon Blizman

Makel Engineering, Inc.
1585 Marauder St.,
Chico CA, 95973
(530) 895-2770
www.makelengineering.com

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Prepared for:

California Energy Commission

Prab Sethi
Contract Manager

Aleecia Gutierrez
Office Manager
Energy Generation Research Office

Laurie ten Hope
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Robert P. Oglesby
Executive Director

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PREFACE

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

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The Biogas Fuelled HCCI Power Generation System for Distributed Generation is the final report for the Biogas Fuelled HCCI Power Generation System for Distributed Generation project (contract number PIR-08-042) conducted by Makel Engineering, Inc., Key Subcontractors, UC Berkeley and Sacramento Municipal Utility District (SMUD). The information from this project contributes to Energy Research and Development Division's [insert RD&D program area from bulleted list above] Program.

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ABSTRACT

Researchers led by Makel Engineering, Inc., developed and demonstrated a low-cost, low-emission homogenous charge compression ignition power generation system (genset) that efficiently produces electricity from biogas. This energy conversion system is capable of producing up to 100 kilowatts of electricity while maintaining emissions levels consistent with the California Air Resources Board's 2007 emissions targets. Typical homogenous charge compression ignition engines are based on standard diesel engine designs with reduced complexity and cost. It uses a hybrid robust thermal control system to control homogenous charge compression ignition combustion in an internal combustion engine coupled to an induction generator. Key design elements, including an automated control system that maintains optimal operating conditions, allowed for the development of a genset three times larger than previous Makel Engineering, Inc. designs.

Testing was first conducted with natural gas and simulated biogas at Makel Engineering's testing facility in Chico, California. The genset was then re-located to the field demonstration site at Tollenaar Holsteins Dairy facility in Elk Grove, California, where 300 hours of further testing with actual dairy biogas from an anaerobic digester occurred. The results of the tests indicated that scaled-up, biogas-fueled engine technology is a viable pathway for distributed power generation with low British Thermal Unit value fuels. Thus, researchers addressed the California Energy Commission's primary goal of improving the cost and value of electric energy in California by developing a low-cost, high-efficiency distributed power generation unit fueled by biogas.

Keywords: HCCI, low NO_x, lean burn diesel, dairy biogas, distributed power generation

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EXECUTIVE SUMMARY

Introduction

The research team, which consists of members from Makel Engineering, Inc. (MEI), Sacramento Municipal Utility District, and the University of California, Berkeley, developed a homogenous charge compression ignition (HCCI) engine-generator (genset) that efficiently produces electricity from biogas. The design of the HCCI engine-generator set, or "genset," is based on a combination of spark ignition and compression ignition engine concepts, which enables the use of fuels with very low energy content (such as biogas from digesters) to achieve high thermal efficiency while producing low emissions. Field demonstrations at a dairy south of Sacramento, California show that this low-cost, low-emission energy conversion system can produce up to 100 kilowatts (kW) of electricity while maintaining emission levels that meet the California Air Resources Board's (ARB) strict regulations.

This project built off of the research team's recent and ongoing work with HCCI engines. MEI has three HCCI development platforms: 1) a multi-cylinder HCCI genset, 2) a multi-cylinder HCCI genset with combined heat and power (CHP) capabilities, and 3) a scaled-up multi-cylinder HCCI genset. The first platform was a success; MEI developed and demonstrated the multi-cylinder landfill gas-fueled HCCI power generation system capable of meeting the ARB's emission standards. This system, known as *MEI model 300*, was developed under a California Energy Commission research grant (see Energy Commission publication CEC-500-2007-078[1]) and served as a proof of concept for multi-cylinder HCCI operation with biogas. The second platform, called *MEI model 301*, was also developed during an Energy Commission grant project, and is capable of producing both electricity and hot water while operating in HCCI combustion mode. This CHP genset is closely based on the first platform since it uses the industrial automated control system MEI developed for use with their HCCI engines. The third platform, called *MEI model 302,* was developed during this project and is a scaled up version of MEI's first model 300 HCCI platform. MEI model 302 produces about three times more electrical power with similar efficiency as MEI model 300. It employs the same industrial automated control system as the second platform MEI model 301, but uses a slightly different method for controlling the HCCI combustion. Table 1 illustrates the differences between the three HCCI gensets that MEI has developed and demonstrated.

[1] Makel, D.B., et al., "Landfill Gas-Fueled HCCI Demonstration System, PIER Final Project Report # CEC-500-2007-078," accessed online 02/14/2014 at http://www.energy.ca.gov/2007publications/CEC-500-2007-078/CEC-500-2007-078.PDF Energy Commission publication CEC-500-2007-078

Table 1: Makel Engineering's HCCI Gensets

	HCCI GENSETS			
SPECIFICATION	Model #	300	301	***302***
	Development Project	Multi-Cylinder HCCI	Multi-Cylinder HCCI with CHP Capability	***Scaled up Multi-Cylinder HCCI***
	Nominal Electrical Output (kW)-nominal	30	30	***100***
	Recovered Heat Available (kW)-nominal	Not equipped	50	***Not equipped***
	Displacement (L)	6.6	6.6	***14.6***
	Brake Thermal Efficiency (%, LHV-basis)	35	35	***33***
	CHP Efficiency (%, HHV-basis)	N/A	70	***N/A***
	Fuel	Methane based Biogas, Natural gas	Methane based Biogas, Natural gas	***Methane based Biogas, Natural gas***
	Start-up Method	Heated Oil Loop	Spark Ignition	***Spark Ignition***
	HCCI Thermal Management Method	Exhaust Heat Recovery with Individual Trim Heating	Heated Gas Mixing with Individual Trim Heating	***Exhaust Gas Recirculation with Individual Trim Heating***
	Control System	Manual Operation	Automated Thermal Management	***Automated Thermal Management***
	Remote Monitoring and Control	Not equipped	Internet Connected	***Internet Connected***

Project Purpose

The overall project goals are as follows:

- Demonstrate the market ready potential of low-emission conversion technology as a low cost and high efficiency source of electric power generation from biogas
- Generate electric power
- Meet or exceed current and future California atmospheric emissions requirements

Project Results

When this project began, most HCCI engines had been operated in laboratory environments.[2] [3] [4]By testing the newly developed HCCI demonstration engine in the field, the

[2] Tannert, Chuck, "Re-Inventing the Engine" Popular Mechanic's Magazine, pg 71-74, July 2008.
[3] Blom, Daniel, et al.,"HCCI Engine Modeling and Control using Conservation Principles" Lund University, SAE-2008-01-0789, April 2008.

research team was able to gather the necessary data to optimize the engine control system to allow for operation in HCCI mode using dairy biogas as fuel .The HCCI genset met project goals for efficiency, power, and emissions. This project met program objectives, prompting Makel Engineering, Inc. to ramp up its efforts to produce commercial HCCI gensets. The authors have formed the following conclusions based on the demonstration of the engine:

- The development of a rugged automated industrial control system for controlling HCCI combustion was challenging but successful. The resulting hybrid HCCI control system allowed for unattended, stable HCCI operation. Additionally, the control system has the capability of remote monitoring and control of the genset. These control system developments will help MEI with long term deployment of units in the field.
- HCCI technology is scalable. The authors believe that a larger class of HCCI engines capable of greater than 100kW electrical output is feasible. MEI intends to keep the HCCI genset installed at the Tollenaar Dairy and continue to gather valuable longer term data.
- Power generation from HCCI technology has proven that distributed generation technologies exist that can meet the strict air quality guidelines in California.
- This HCCI genset has an efficiency of about 33 percent while producing less than 0.07 pounds per megawatt-hour of nitrogen oxide emissions and generating up to 100 kW of electrical power.

Benefits to California

The primary benefit of HCCI technology is that it is one of a few energy conversion technologies capable of achieving California's long term goals for reduced greenhouse gas emissions (AB 32); especially fuel flexible and renewable systems in line with state's renewable portfolio standards (RPS). This project significantly advanced the acceptance and adoption of HCCI biogas gensets for dairy applications and reduced barriers to use of this technology with other biogas sources and distributed generation applications. HCCI is a suitable power generation source capable of supporting California's increased energy needs and reduced emission's necessities. When this technology is commercialized, HCCI will support greater penetration of clean renewable energy sources such as biogas, resulting in lower electricity costs and reduced greenhouse gas emissions for California.

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[4] Kakuya, Hiromu, et al., "Investigation of SI-HCCI Combustion Control Method in a Multi-Cylinder Gasoline Engine" Hitachi, Ltd., SAE-2008-01-0792, April 2008.

CHAPTER 1: Introduction

1.1 Background and Overview

An emerging technology, known as homogenous charge compression ignition (HCCI), has been investigated as a suitable alternative capable of supporting California's increased energy and reduced emission's necessities. Coupled with an increasing demand on the state's power distribution system there are a limited number of energy conversion technologies capable of achieving the California's long term goals for reduced greenhouse gas emissions; especially those which are fuel flexible and renewable.

Current energy conversion technologies such as turbines and internal combustion engines (ICE's) require expensive exhaust post treatment systems in order to comply with the air quality management districts (AQMD) regulations regarding nitrogen oxides (NO_x) and other criteria pollutants. Development of cost effective, HCCI systems require an engine technology with inherently low emissions and does not require post exhaust cleanup.

HCCI engine technology provides a low risk path to high efficiency, low emissions and low cost power generation. HCCI technology is capable of achieving efficiency and emissions that meet California's long term goals and which are unlikely to be achieved by any other reciprocating engine system. HCCI is uniquely suited to address the key challenges related to biogas power generation such as low energy content, variable ignition characteristics (octane value), and contaminants.

Using the body of work performed by Makel Engineering, Inc. (MEI)[coupled with the results from similar HCCI testing performed in laboratories worldwide; MEI demonstrated a field-tested biogas fueled HCCI engine/generator system capable of achieving the California's stretch emissions goals.

The focus of this project was to develop and demonstrate a scaled-up HCCI genset targeting biogas as fuel source.

1.2 Overall Project Goals and Objectives

- Demonstrate the market ready potential of low-emission conversion technology as a low cost and high efficiency source of electric power generation from biogas.
- Generate electric power
- Meet or exceed current and future California atmospheric emissions requirements.

1.2.1 Technical Performance Objectives

- Generate electric power in excess of 100kW (200kW target) from biogas fuel source
- Achieve greater than 30 percent (35 percent target) brake thermal efficiency (LHV)

- Emissions: meet or exceed California ARB 2013 targets for combustion of biogas[5]
    - NOx < 0.07 lb/ MWh
    - CO < 0.10 lb/ MWh
- Operate in HCCI mode utilizing natural gas and biogas as fuel.

1.2.2 Economic Performance Objectives

- Affordability (LCOE-$/kWh) <0.14 – at or below BACT for Biogas AD Dairy[6]
- Capital Costs ($/kW) < 2,000 – at or below BACT for Biogas AD Dairy[7]

1.2.3 Performance Goals

Makel Engineering installed the HCCI genset and related generation equipment at a dairy as a demonstration. HCCI performance characteristics were monitored while targeting the following performance goals listed in Table 2:

Table 2: Biogas HCCI Performance Targets for Proposed Systems

Target Parameter	Program Goal
Power Output (kW)	**>100** (200 target)
System Efficiency—BTE, LHV	**>30%** (35% target)
Air Emissions – NOx (lb/MWh)	**<0.07**
Air Emissions – CO (lb/MWh)	**<0.10**
Affordability - LCOE ($/kWh)	**<$0.14**
Capital Costs - Prime Mover ($/kW)	**<$2000**

[5] "Distributed Generation Certification Regulation," Section 94203, Table 3

[6] "Comparative Costs of California Central Station Electricity Generation Technologies" publication # CEC-200-2007-011-SF, page 10, Table 3

[7] "Comparative Costs of California Central Station Electricity Generation Technologies" publication # CEC-200-2007-011-SF-APB, page 5

1.3 Project Approach: Three Phases of Development

MEI has divided the tasks for this program into three phases. The first phase consisted of gathering as much crucial information off of the existing MEI model 300 and to design the scaled up system. The second phase entailed the fabrication and verification of the system. The third phase was field testing of the system at a dairy. A tasks list is included in Table 3.

Table 3: Technical Task List

Task #	Phase	Task Name
1.0	1,2,3	Administration
2.1	1	Scale Up Operation of 30kWHCCI
2.2	3	Rule 21 Interconnection
2.3	1	Initial Genset Design & Baseline Test Plan
2.4	2	HCCI Genset System Assembly
2.5	2	Initial Testing
2.6	2	Genset Re-Design, Assembly & Baseline Test
2.7	3	Field Test Plan
2.8	3	Site Development, Installation & Initial Field Test
2.9	3	Field Testing
2.10	3	Technology Transfer Activities
2.11	3	Production Readiness Plan

CHAPTER 2:
Scale up Operation of MEI Model 300

The goal of scale up testing was to gather additional data from MEI's existing HCCI genset. Gathering additional data allowed for MEI to further develop models for the scalability of HCCI technology. Scale up testing was conducted in two phases: verification of operation at MEI's facility and testing for scaling. Verification testing was basically confirming that all systems were re-installed at MEI's testing facility, that the engine was operational and that the emission monitoring system was reporting properly. Testing for scaling was essentially recording engine operation conditions while adjusting the inlet temperature and fuel quality/flow levels. Tests included varying operating conditions such as: air fuel ratio, boost pressure as well as measurements of pressure drop throughout the intake system. The HCCI system operated in the same way as previous testing with landfill gas and natural gas.

2.1 Scale up Operation Results

2.1.1 Verification of operation

Verification that the 30kW HCCI genset was functional at MEI's testing facility was crucial to all scale up tests. The HCCI genset was successfully installed at MEI's testing facility. The HCCI genset was started using the HCCI Startup Procedure. It was electrically synchronized to the building and preliminary test runs were conducted.

2.1.2 Testing for scaling

Gathering empirical data during nominal operating conditions supported the design for the HCCI system. The sequence of tests performed on the HCCI genset at MEI's testing facility were designed to characterize the pressure drop the throughout the intake system as well as examine the power requirements of the intake heaters during operation. Additionally, exhaust gas ports were added to each cylinder to distinguish the emissions profile for each cylinder.

2.1.2.1 Pressure characterization

The intake and exhaust systems were ported allow for an absolute pressure sensor to make pressure measurements at key locations. Components MEI targeted for scale up testing include: intake filter, the compressor side of the turbocharger, heat recovery heat exchanger and the turbine side turbocharger. Pressure measurements were recorded for nominal operation conditions using NG as fuel. The flow characteristics through these components were used to develop a model for predicting pressured drop through the scaled up HCCI intake system.

2.1.2.2 Power to intake heaters

For optimization of power output and system efficiency in an HCCI engine, a means to adjust the inlet temperature to each cylinder is required. The goal is to supply each cylinder with a slightly elevated or decreased inlet temperature. This is accomplished by passing the air fuel intake charge through six parallel paths in a manifold called the individual cylinder temperature control (ICTC) manifold. The ICTC is comprised of engineered manifolding, heaters and thermocouple probes.

The power required to maintain each cylinder with a suitable temperature during nominal operation was recorded. The bulk inlet temperature was set to about 245°C. An optimal inlet temperature profile was generated by adjusting the inlet temperature up on an individual cylinder and monitoring efficiency. The optimal inlet temperature and corresponding power required to maintain that temperature for each particular cylinder's intake. No significant change in power required for off nominal compared to nominal operation was noted.

A watt to intake flow per cylinder ratio of at least 2.8 was determined for the scaled up HCCI system. The required mass flow per cylinder would increase with a larger engine. Knowledge of the amount of heat input required will help to determine what type of inlet heating would be feasible. An understanding of the power required to maintain an optimal inlet temperature for each cylinder drove the design and form factor of scaled thermal conditioning system.

2.1.2.3 Individual cylinder exhaust characterization

The exhaust system was ported at eight different exhaust measurement locations. These measurements include the following: a port for each cylinder (6 cylinders), an aggregated port pre-catalytic converter and post catalytic converter. A series of three way valves allowed for the desired exhaust port to be selected and the exhaust gasses fed to the gas analyzer system.

The exhaust gas profile was established by passing gas samples through MEI's gas analysis system. Fuel conversion efficiency for each cylinder was tabulated assuming that the same air and fuel mass flow enters each cylinder.

Testing indicated the following:

- The HCCI genset was not firing optimally as indicated by lower fuel conversion efficiency in cylinders 1 and 6.
- A watt to intake flow per cylinder ratio of at least 2.8 would be required for the scaled up HCCI system.
- About 3 kPA of boost pressure is lost through the heat exchanger and the valves on the path to the cylinder
- The cold startup system was not robust
  - A re-design of the heating blocks solved this issue
- Additional testing using the 30 kW HCCI system proved useful to test new turbocharger iterations

CHAPTER 3:
Rule 21 Grid Interconnection

Working with the Sacramento Municipal Utility District (SMUD), MEI submitted a "Rule 21" interconnection application. While temporary operation for this testing was granted, MEI, SMUD and the Tollenaar Holsteins Dairy are in the process of getting a long term agreement in place. The interconnection requirements for Distributed Generation (DG) are determined by the California Public Utilities Commission (CPUC). Electric Rule 21 outlines the interconnection, operational and metering requirements for generating facilities that are connected to the power distribution systems.

3.1 Interconnection Schematic and Line Drawings

The HCCI genset is operated by a digital genset controller, which also provides the grid interconnection protection logic. A Basler IPS100 Protection System relay protects, monitors, and controls the interconnection between MEI's HCCI genset and the SMUD grid. A Basler DGC2020 digital genset controller monitors the generator. The outputs on the IPS100 relay are normally open and connected in series with an auxiliary mechanical relay. The relay contacts are programmed to be held closed and will open on failure if any one of three conditions occurs. These conditions are:

- A trip condition is asserted
- Internal diagnostics indicate a relay failure
- Power is lost to the relay

The main contactor actuating circuit for the motor contactor is connected through a normally open contact on the auxiliary mechanical relay. When the at least one of the failure conditions occur, the auxiliary mechanical relay is de-energized opening the circuit to the main contactor. The contactor will then open breaking the connection between the generator and the grid. There are no other switches or device contacts in the relay trip circuit.

The single line diagram for the SMUD interconnection at the test site is shown in Figure 1. Table 4 lists the protective relay settings.

Figure 1: Grid Interconnection Diagram

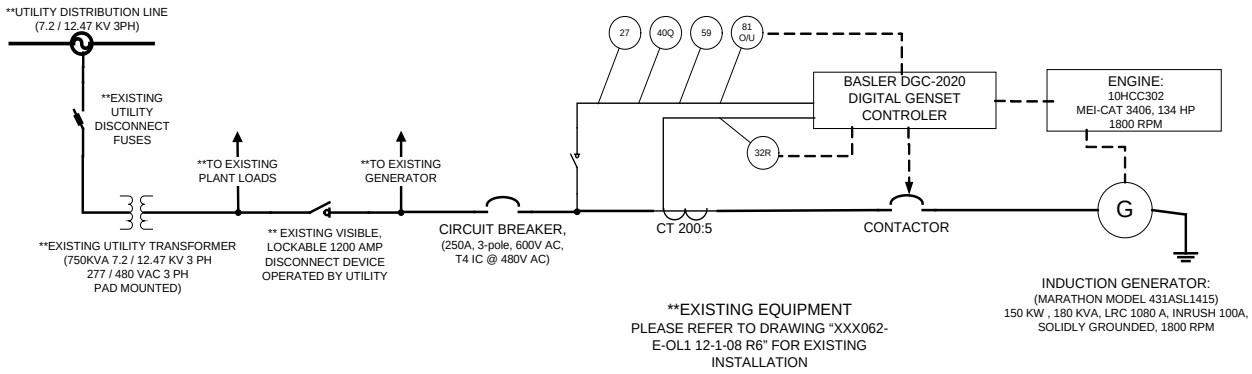


Table 4: Protective Relay Settings

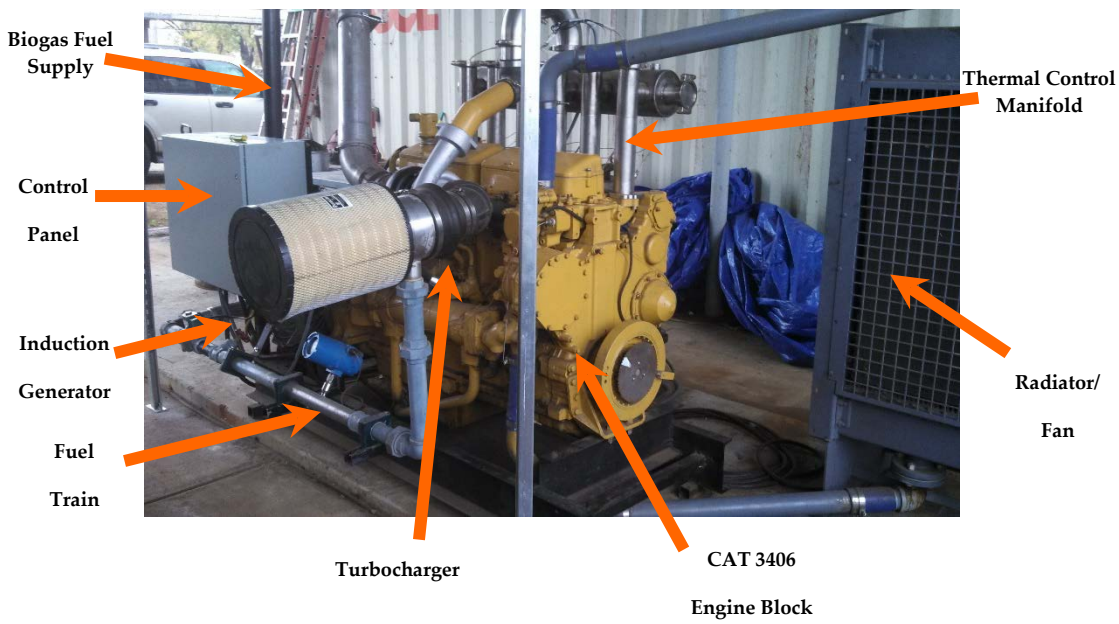
Device #	Function	Trips Breaker	Trip Setting	Duration
27	Undervoltage	OUT1 (open)	90% of nom, 50% of nom	120 cycles, 10 cycles
32R	Reverse power	OUT1 (open)	75 kW	30 cycles
40Q	Loss of Excitation	OUT1 (open)	0% of nom	10 cycles
59	Overvoltage	OUT1 (open)	110% of nom, 120% of nom	30 cycles, 6 cyles
81O	Overfrequency	OUT1 (open)	60.5 Hz	10 cycles
81 U	Underfrequency	OUT1 (open)	59.3 Hz	10 cycles

CHAPTER 4:
Initial Genset Design

4.1 HCCI System

The HCCI genset consists of a combination of stock engine components and customized components. These include: a modified fixed displacement reciprocating engine, an electric generator, thermal conditioning system for the air-fuel mixture, instrumentation and actuators, and an automated control system. Figure 2 shows the HCCI system. For further detail, a process flow diagram is included in Figure 40 in Appendix A.

Figure 2: HCCI System



4.1.1 HCCI Operation

4.1.1.1 Power output greater than 100KW

Scale up testing has allowed MEI to establish a nominal engine block size operation to HCCI operation scaling factor for the 30kW HCCI genset. This scaling factor was used to select an appropriate prime mover.

4.1.1.2 System efficiency greater than 30 percent (target 35 percent)

Previous HCCI engine tests have demonstrated that HCCI engines have efficiencies in the range of 30 percent to 40 percent. System brake thermal efficiency (η_t) is defined as the ratio of the power output at the engine's shaft to fuel input (less any unburned fuel) for the system. The system efficiency computation is listed in Equation 1.

Equation1: **System Efficiency**

$$\eta_t = \frac{(P_{gen})(3600)}{(m_{fuel})(LHV_{fuel})(\eta_c)}$$

Where (P_{gen}) is the brake electrical power output in kW at the engines output shaft, (m_{fuel}) is the mass flow of the fuel in kilograms per hour and (LHV_{fuel}) is the lower heating value of the fuel in kilojoules per kilogram (typically 47,200 kJ/kg). Combustion efficiency (η_c) was determined by the ratio of the amount of unburned hydrocarbons (UHC) in the exhaust pre-catalytic converter to the percentage of fuel in the intake charge. MEI's previous testing has established a relationship between system efficiency and NO_x. MEI operated the scaled up HCCI genset at conditions that satisfy both efficiency and emission goals for this program.

4.1.1.3 NOx less than 0.07 (lb/MWh)

HCCI engine tests have demonstrated that HCCI engines have ultra-low NOx (below levels requiring after treatment). The method for maintaining reduced NOx levels during operation is to run at equivalence ratios less than 0.40.

4.1.1.4 CO less than 0.10 (lb/MWh)

HCCI engines have a potential for an increase in unburned hydrocarbons (UHC) and CO emissions with operation at lean conditions. In order to reduce UHC and CO emissions a two-way oxidation catalytic converter was utilized in the exhaust system.

4.1.2 Biogas Operation

For the demonstration portion of this project, MEI installed the system at Tollenaar Holsteins Dairy (a 2000 head of cattle facility) in Elk Grove, California (see Figure 3). This was determined to best meet MEI's requirements for site selection. It currently has existing digester; fuel delivery system and grid interconnect. The interconnection at this has the capability of accepting 500kW and only 165kW was currently being produced with their existing genset.

Figure 3: Tollenaar Holsteins Dairy in Elk Grove, California

4.1.3 Costs

4.1.3.1 Levelized Cost of Energy of less than 0.14 ($/kWh)

The levelized cost of energy (LCOE) was determined using the Cost of Generation model found on the California Biomass collaborative website. Basic assumptions include a 5 percent interest rate on a 20 year loan, a 20 year straight depreciation schedule, an engine efficiency of 30 percent, a $0.0247 / kWh cost for fuel, a capacity factor of 90 percent and a combined tax rate of 40.75 percent. The levelized cost was computed using Equation 2.

Equation 2:

$$Levelized\ \cos t = \frac{(\text{Total Present Worth} * \text{Capital Recovery Factor})}{(\text{Annual Net Electricity Generation})}$$

$$\text{Total Present Worth} = \sum_{t=1}^{T} \frac{Cost_t}{(1+r)^t}$$

$$\text{Capital Recovery Factor} = \frac{r*(1+r)^T}{((1+r)^T - 1)}$$

*from CEC-2000-2009-017

This analysis considers the life-cycle costs associated with system (the grid interconnection, fuel, prime mover, and generator) divided by the annual electric power (kWh) generated by the system. The estimated LCOE for this system is less than $0.14 $ / kWh.

4.1.3.2 Capital costs less than 2,000 ($/kW)

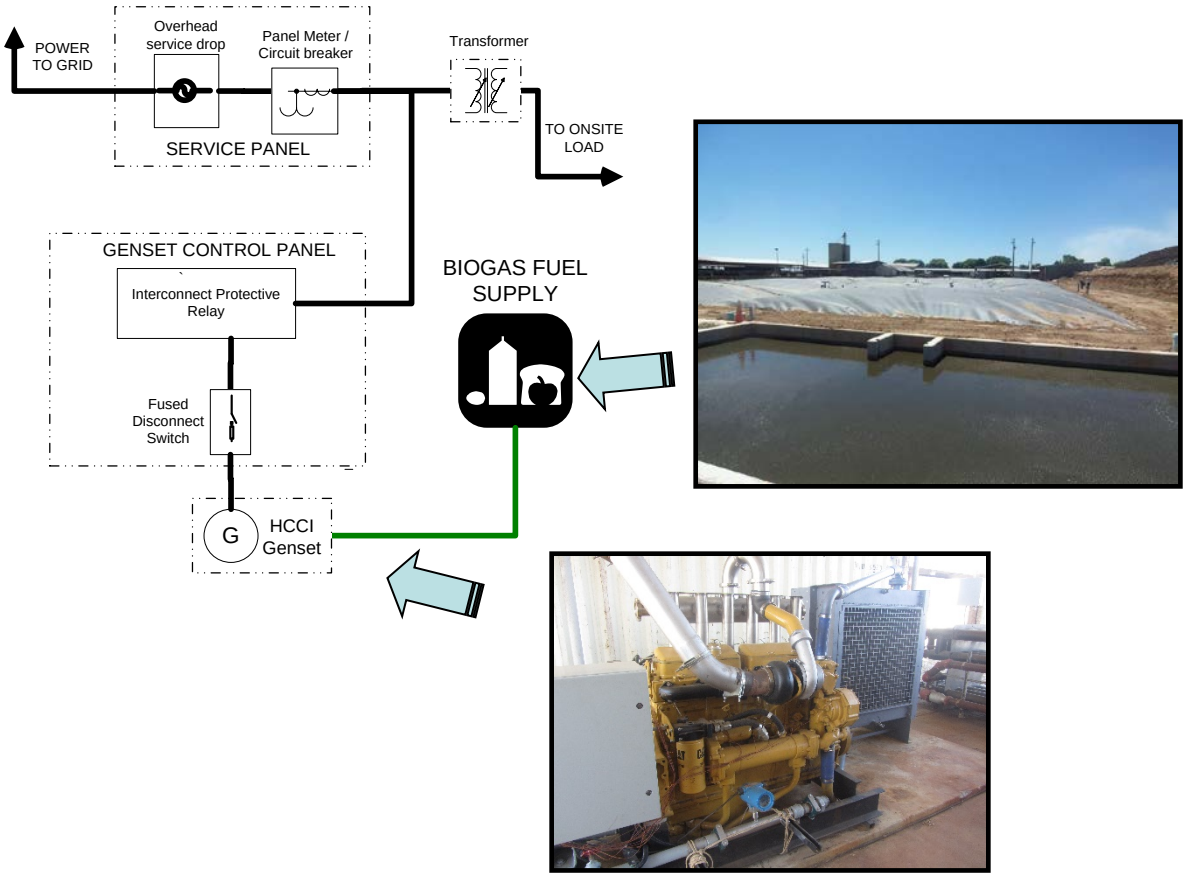
Estimated costs associated with the prime mover include: the cost of equipment summarized by the Bill of Materials, the cost of interconnection and the labor costs associated with assembling the genset. This system has an anticipated capital cost of less than $2000 / kW.

4.2 Design Overview

4.2.1 HCCI Site Installation

The HCCI genset was installed at the Tollenaar Dairy. A schematic of the installation is shown in Figure 4.

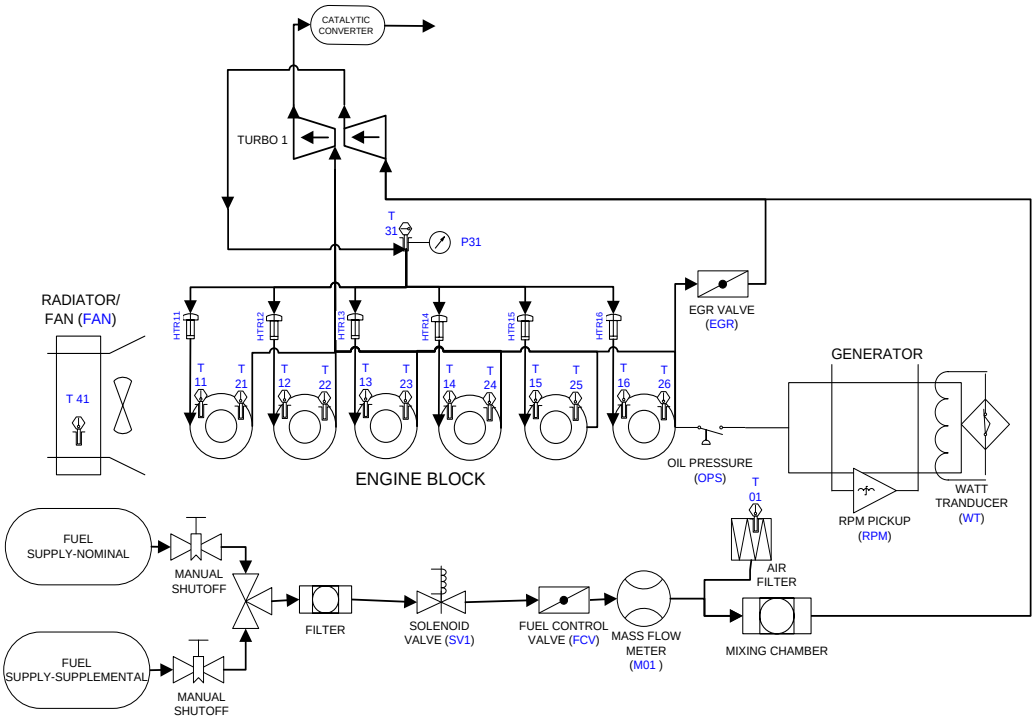
Figure 4: Site Integration Diagram



4.2.2 HCCI System Overview

The HCCI genset consists of several components including: a modified fixed displacement reciprocating engine, an electric generator, thermal conditioning system for the air-fuel mixture, instrumentation and actuators, and an automated control system. A process flow diagram is shown in Figure 5.

Figure 5: HCCI Genset Process Diagram



4.2.3 HCCI Engine and Generator

4.2.3.1 Prime Mover

MEI selected a large 14.6 L, CAT 3406 diesel engine block (shown in Figure 6) as the prime mover to be converted into operation in HCCI mode. Table 5 lists the prime mover's specifications. This prime mover was then coupled to an induction motor. Appropriate intake ducting for thermal conditioning of the intake charger was added. The major mechanical modifications consist of: coupling the engine block to a generator and mounting, installing a thermal conditioning intake system and replacing the stock turbocharger with a hybrid turbocharger.

Figure 6: CAT 3406 Engine Block

Table 5: CAT 3406 Specifications

Parameter	Specification
Cylinders	6 (In-line)
Compression Ratio	18 : 1
Displacement	14.6 L
Oil Sump Capacity	10.0 gal
Cooling	Air-Liquid (DEAC)
Turbocharged	~1.6 ATM
Engine RPM	1800 RPM
Maximum Output Power	125 kW
Generator	Induction 440 VAC, 3-phase, 60 Hz
Size	165″ X 44″ X 82″
Weight	6,200 lb

4.2.3.2 Induction Generator

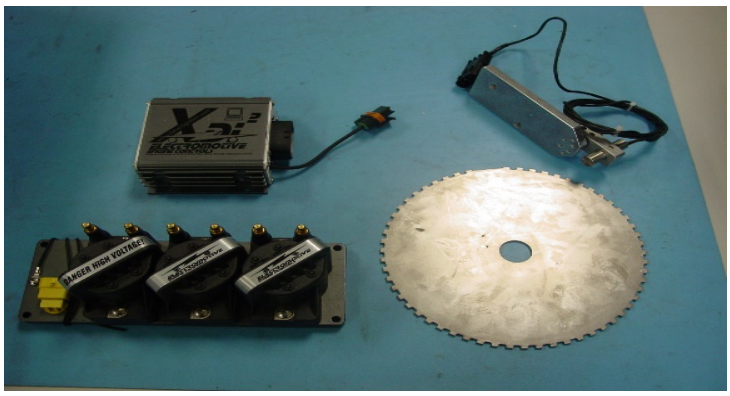
A Marathon Electric Primeline series 150kW (Part #:431ASL1415-shown in Figure 7) induction generator was selected to couple to the prime mover.

Figure 7: Marathon Induction Generator

4.2.3.3 Spark Ignited Startup

This engine starts in spark ignited mode using biogas. Then once the engine is warm hot, exhaust gas heats the charge incoming. Next the advanced control system allows for a transition into HCCI mode. The spark timing is controlled by an Electromotive direct fire unit model #XDI2 shown in Figure 8.

Figure 8: Electromotive Direct Fire Unit



4.2.4 Inlet Conditioning System

4.2.4.1 Thermal Conditioning

The thermal control of the HCCI system is the primary means to control ignition timing of the engine. The thermal control system controls the individual temperature of the cylinders (the ICTC manifold). The control of the individual cylinder is done via independent heaters. The control algorithm adjusts the duty cycle of the individual heaters as necessary, maintaining the target temperatures.

4.2.5 Instrumentation and Control

The genset is outfitted with appropriate instrumentation including temperature and pressure sensors, mass flow meters and a power output measurement device. All data is fed into the real-time data acquisition/control system. Detailed descriptions of the control system are provided in the following sections.

The three primary elements of the control system are: sensors, logic, and actuators. All of the other components function to support these three elements. The instruments provide operating point input and feedback to the control logic. The logic activates the actuators as appropriate in order to reach target operating conditions. The actuators are the actual hardware such as motors heater and valves. The control scheme is designed to provide autonomous operation of the control actuators with minimal operator input. In addition, a safety shutdown sequence is executed when the conditions are such that the engine may be potentially damaged or a hazardous operating condition exists. The paragraphs below describe each of the three primary control elements in greater detail.

4.2.5.1 Sensors

The sensors package includes thermocouples, pressure sensors, mass flow sensors, fuel quality sensors, engine speed sensors, power sensors, and environmental sensors. Table 6 lists the sensors and a description of each.

Table 6: List of Sensors

ID	Description
P31	Manifold absolute pressure
P01	Ambient pressure
H01	Ambient humidity
T01	2320 Air inlet
T11	2320 cylinder one inlet
T12	2320 cylinder two inlet
T13	2320 cylinder three inlet
T14	2320 cylinder four inlet
T15	2320 cylinder five inlet
T16	2320 K cylinder six inlet
T21	2320 cylinder one exhaust
T22	2320 cylinder two exhaust
T23	2320 cylinder three exhaust
T24	2320 cylinder four exhaust
T25	2320 cylinder five exhaust
T26	2320 cylinder six exhaust
T31	2320 pre-intake header
T41	2320 engine coolant temp
T51	2320 collective exhaust
WT	Watt Transducer
M01	Mass flow meter
FQS	Fuel quality sensor
RPM	Engine speed magnetic pickup
OPS	Oil pressure sensor
ES	Emergency stop

4.2.5.2 Actuators

The actuator package includes solenoid valves, proportional butterfly valves, heater elements, switches, and motor speed controllers. Table 7 below lists each actuator and a description of its function.

Table 7: List of Actuators

ID	Activation	Control Method	Description
HTR11 – HTR16	Relay	Cylinders 1 - 6 trim heaters	(ON-OFF) / PWM
V11	Proportional current	Pre and post ATA intake mixing val	Driver converts proportional input current to a valve position
SV1	Relay	Biogas cut-off valve 1	OPEN-CLOSE
SV2	Relay	Biogas cut-off valve 2	OPEN-CLOSE
FCV	Proportional current	Primary control for Air / Fuel mixing and setting equivalence ratio (PHI)	Driver converts proportional input current to a valve position
FAN	Proportional voltage	Regulates the temperature of the engine coolant	Driver converts input voltage to a fan motor speed
MS	Relay	Begins the startup sequence of the power generation system	ON-OFF
SYNC	Relay	Activates the grid sync motor controller for system spool-up	START-OFF
GRID	Relay	Connects or disconnects the power generation system from the electrical grid	OPEN-CLOSE
DFU	Relay	Activates the direct fire spark plug unit	ON-OFF

4.2.5.3 Control System

The control system uses predefined set points for the bulk manifold, and individual cylinder temperatures as the target operating conditions. The electronics portion consists of an electronic control module (ECM), an MEI core logic module, a signal conditioning module and an output module. Thermocouples on each cylinder intake port and the bulk manifold connect to the input module where the signals are conditioned and input to the ECM. The output module sends control signals to the relays that drive the heaters and control valves as dictated by the MEI core logic. A PC can be optionally connected in order to monitor operation, or modify control set points.

4.2.5.4 Logic

The control logic is provided by a programmable electronic control module (ECM) with add-on modules to digitally read all of the sensor inputs, implement simple PID control commands, and convert logic level outputs to relay and proportional drive outputs. MEI core logic provides advanced calculations capability and proprietary multiple input, multiple output control schemes for successful HCCI operation. It is implemented by a separate microcontroller system that communicates via digital and analog channels to the ECM. The ECM acts as the gateway between the MEI core logic and the control signals that drive the actuators. The ECM also provides digital connection to a PC for real-time monitoring or configuration of process variables.

4.2.5.5 Control Loops

There are six control loops necessary for successful operation of the system. Each loop is intended to produce a change in only one operating condition but it may include several inputs. Table 8 summarizes the inputs, feedback, and outputs from the point of view of the controlling electronics. The subsequent sections below describe control loop in detail.

Table 8: List of Control Loops

ID	Description	Input	Feedback	Output
BULK	Bulk manifold Temperature control	Manually set bulk inlet temperature	T31	V1 is dithered blending pre ATA air with post ATA air
TRIM	Trim inlet temp	Manually set inlet temperature	T11-T16	Trim heater (HTR11 to HTR16) temperature is varied by adjusting the duty cycle
RAD	Coolant Temp	Manually set Coolant temperature	T41	Fan speed on Radiator is controlled to maintain desired set point
FUEL	Fuel flow control	Manually set Φ	M01, FQS, T31, MAP & RPM used to compute Φ	Fuel control valve (FCV) is adjusted to maintain desired Φ
START	Starter engage, Spark system engage, VFD engage, grid disconnect	Manually set thresholds	RPM, PHI	Spark ignition on (DFU), engine starter (MS) engaged, SYNC engaged
SAFE	Safety shutdown	Hard coded trigger points	Oil Pressure, RPM, all T, Mass flow meter	Fuel Cutoff, Heater cutoff, Grid disconnect

4.2.6 Fuel Flow during Operation

The method for maintaining reduced NO_X levels during operation is to run at equivalence ratios less than 0.40. Equivalence ratio (Φ) is computed in Equation 3.

Equation 3:**Equivalence Ratio** $$\phi = \frac{(A/F)_s}{(A/F)}$$

Where $(A/F)_s$ is defined as the ratio between air to fuel ratio at stoichiometric combustion and (A/F) is the actual air to fuel ratio of the engine. The stoichiometric air to fuel ratio for methane $(A/F)_s$ is 17.19. An actual (A/F) of 43:1 corresponds to Φ=0.40 and an actual (A/F) of 57:1 corresponds to Φ=0.30. For HCCI engine operation, the equivalence ratio is controlled by limiting the amount of fuel the engine receives.

The fuel control system monitors fuel flow; power generated, manifold pressure, exhaust temperatures, fuel quality, and ambient environmental conditions such as relative humidity, temperature and pressure. The MEI core logic calculates the current Φ operating point and makes determinations based on the multiple sensor inputs and predefined algorithms to adjust the fuel control valve in order to achieve the target operating conditions. The commands flow from the MEI core logic to the output module, from the output module to the relays or proportional control of the fuel flow valve. The fuel control system also switches the fuel flows during start and warm-up sequences.

CHAPTER 5:
HCCI Genset System Assembly Tracking and Bench Test

5.1 Assembly Activities

MEI implored three mechanisms for tracking the HCCI genset assembly: bill of materials (BOM) tracking, photo-documentation and CAD modeling. The intention of this recording exercise was to document and track the assembly activities during the fabrication of the HCCI genset. Given the nature of this research, it was recognized that modifications to the design would occur as results were obtained and if deemed necessary to further explore individual characteristics. The tracking mechanisms in place ensured that the development process was chronicled appropriately.

5.1.1 Bill of materials tracking

The BOM was generated as part of the design process. The "status" column of the BOM indicated where a component was in the assembly process. All components are in one of the following five states:

1. Design (D)
2. Procurement (P)
3. Acquired (A)
4. Fabrication (F)
5. Installed (I)

As a component transitions from one state to the other, it was indicated as such on the master BOM. It was possible that the design for a specific component to change as MEI decided to further explore individual operating characteristics. For instance, a component status might have changed from "I" installed back to "D" design if another iteration of the design was required. The current status BOM list is available in MEI Document # MEI-PIR01-IR5.

5.1.1.1 Design

Components marked with "D" in the BOM status column were in the design stage. Hardware and necessary components of the HCCI genset were selected and/or designed as indicated in Task 3.1—Retrofit Design Documentation. This package was continually evolving as the genset was assembled and testing takes place. Modifications to the design document continually occurred as testing results were obtained.

5.1.1.2 Procurement

Once the design of a component was reviewed and accepted, a requisition form (MEI form OP-002A) was submitted to MEI's procurement officer. The components status was marked with "P" in the BOM status column.

5.1.1.3 Acquisition

Once a component had been received by a vendor, it was relocated to the appropriate handler by MEI's procurement officer. Components status was marked with "A" in the BOM status column meaning that it was on premises and ready for the next step in assembly.

5.1.1.4 Modification/Fabrication

Hardware that required fabrication and/or modification was marked with "F" in the BOM status column meaning that it was currently out for fabrication or being fabricated on site.

5.1.1.5 Installation

Whenever a component was physically assembled to the HCCI genset, and that specific component was added to the tracking CAD model, it was marked with an "I" in the BOM status column. For most components this was the last stop; however for components requiring further modification, their status could have been changed back to a "D" for design.

5.1.2 Photo documentation

As components were installed, digital images of the components were compiled in Appendix III of MEI Document # MEI-PIR01-IR5. Photo documentation served the purpose of assisting with tracking and verification of installation. Photos also served the purpose of monitoring equipment wear and tear as MEI proceeded with testing. For instance, the condition of the cylinder walls of the engine block prior to any testing were photo documented to compare with images of the walls after testing.

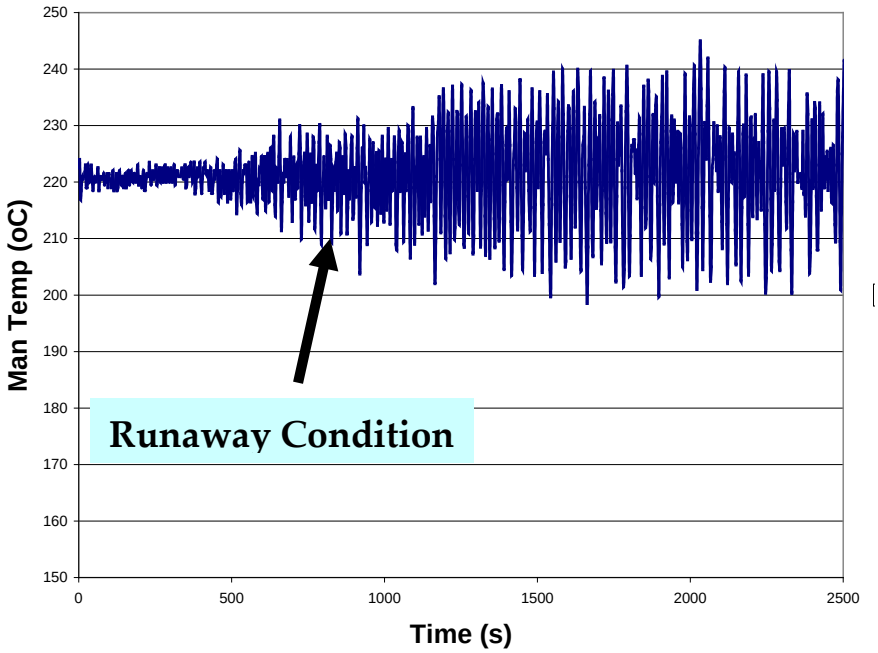
5.1.3 CAD documentation

Whenever a component was physically assembled to the HCCI genset, that specific component was modeled in CAD and added to the tracking CAD model. The inclusion of the tracking CAD model allowed for MEI to compare the as-built engine to the as-designed CAD model.

5.2 Automated Control System Issues and Resolutions

One of the key design elements was to have industrial control system with minimal human to machine interface in order to control the HCCI combustion. During this project, MEI moved towards a more rugged, industrial control system that did not required attended operation. The original HCCI control system was Windows based. This solely computer based control system relied on attended operation. The Windows system was often overtaxed resulting in unstable operation. MEI first attempted to adapt the HCCI control code to a programmable logic controller (PLC). There were challenges associated with transitioning control code from a computer to PLC and getting stable operation. Figure 9 shows a resulting runaway temperature control condition that MEI encountered when attempting to transition the HCCI control code to a PLC.

Figure 9: Runaway Condition When Attempting to Use PLC



Runaway were resolved by taking a hybrid control system approach. As shown in Figure 10, individual controllers monitor the thermal manifold and block temperatures, genset electronic control unit (ECU) controls grid sync and safety shutdowns and a PC controls startup, fuel transition and remote monitoring. Additionally, MEI added capability to remotely monitor, control, start and stop the genset. The resulting hybrid control system resulted in stable HCCI operation. As shown in Figure 11, the manifold temperature was able to be controlled to less than 33.8° F (1°C) (an improvement of more than eight times over the PLC attempt). Stable inlet temperature control resulted in stable power output. Also shown in Figure 11, the power output varied less 0.5 kW with the hybrid control system.

Figure 10: Hybrid Control System Diagram for the HCCI System

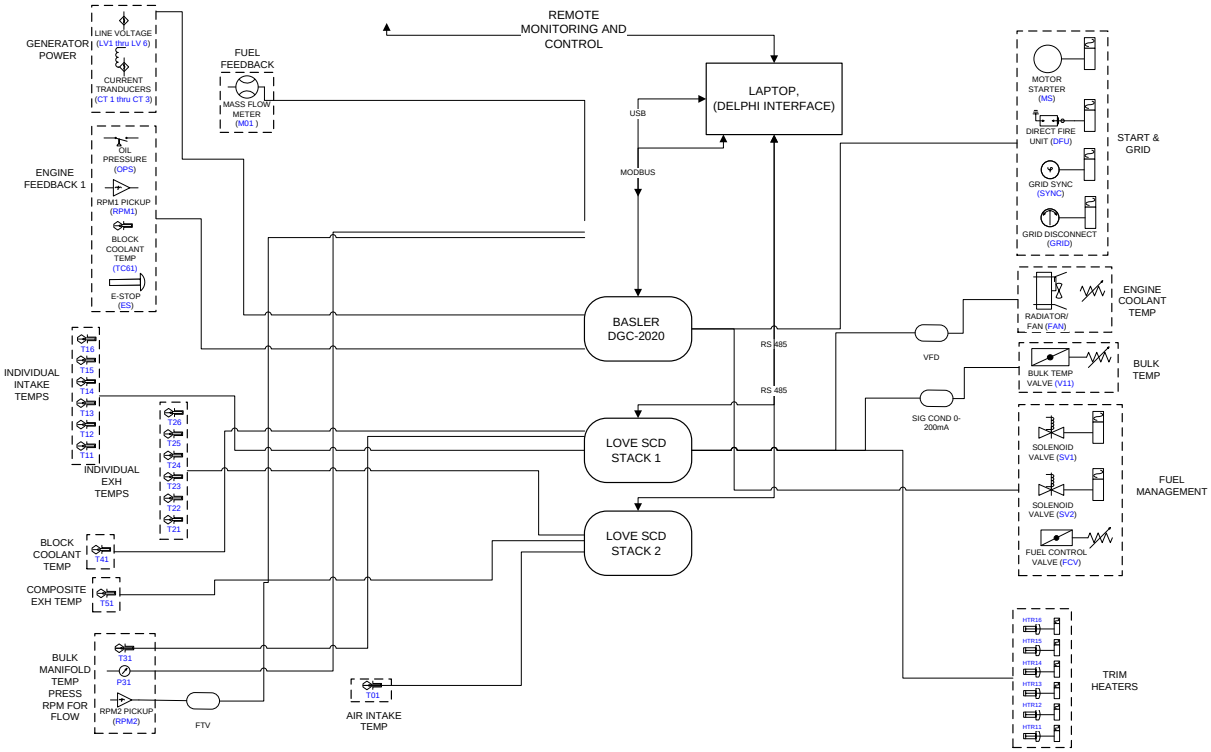
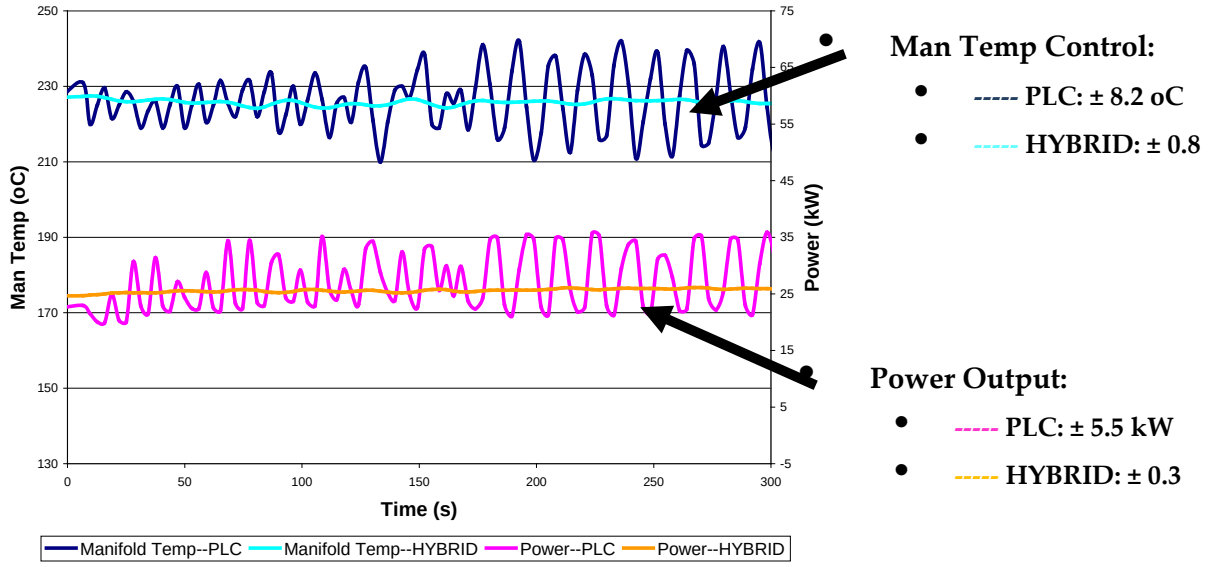


Figure 11: Improved Stability using the Hybrid Control System for the HCCI System



5.3 Hardware Challenges and Resolutions

5.3.1 Custom Camshaft

MEI designed and installed a modified camshaft in the engine block shown in Figure 13(left). The modified design allowed up to 45 percent internal exhaust gas recirculation (EGR) as shown by the position of the exhaust valve relative to top dead center in Figure 12. This eliminated need for external heat exchanger, driving overall system costs down. The modified camshaft was abandoned because it produced unstable operation and did not meet performance targets. Spark ignition to transition HCCI was challenging with the modified camshaft in place. Efficiencies in the 25 to 30 percent range were achieved missing the project target of greater than 30 percent. Additionally, this configuration was prone to increased backfire events leading to failed engine components (see Figure 13). MEI discontinued the use of the modified camshaft.

Figure 12: Modified Camshaft Valve Position as a Function of Crank Angle

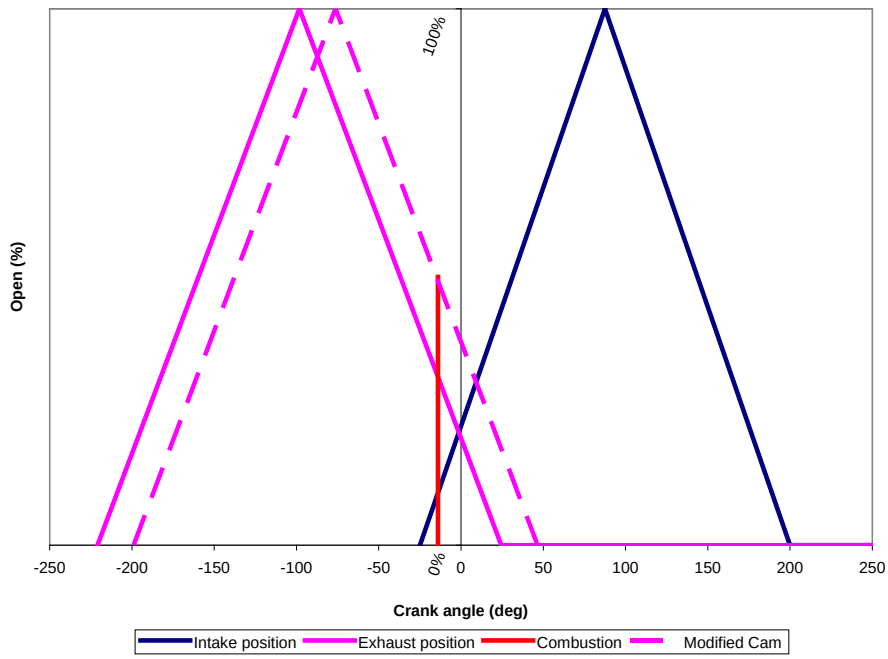
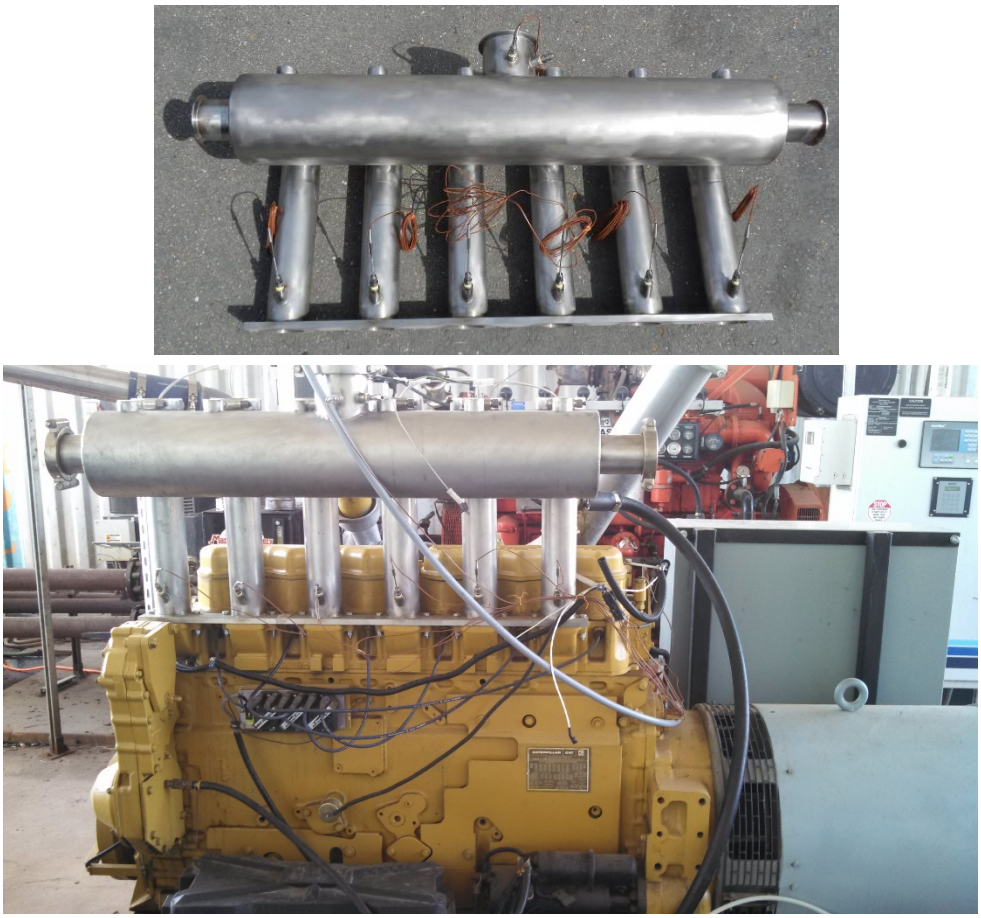


Figure 13: Modified Camshaft (left) and Failed Valve Cover (right)

5.3.2 Thermal Control Manifold

MEI designed and developed a thermal control manifold shown in Figure 14. This manifold is capable of adding up to 3 kW per cylinder. This design also eliminated the need for external air-to air (ATA) heat exchanger. MEI successfully achieved efficiencies in the 32 to 36 percent range with this design.

Figure 14: Thermal Control Manifold



CHAPTER 6:
Baseline Testing

The goal of baseline testing activities was to perform initial checkout testing of the HCCI genset. Initial testing was carried out as prescribed in the Baseline Test Plan (task 2.3B). Testing was conducted in three phases: control system tests, system checkout tests and steady state operation tests. All tests that were conducted are listed in summary Table 9. The following sections detail the results of specific tests as conducted on the HCCI genset.

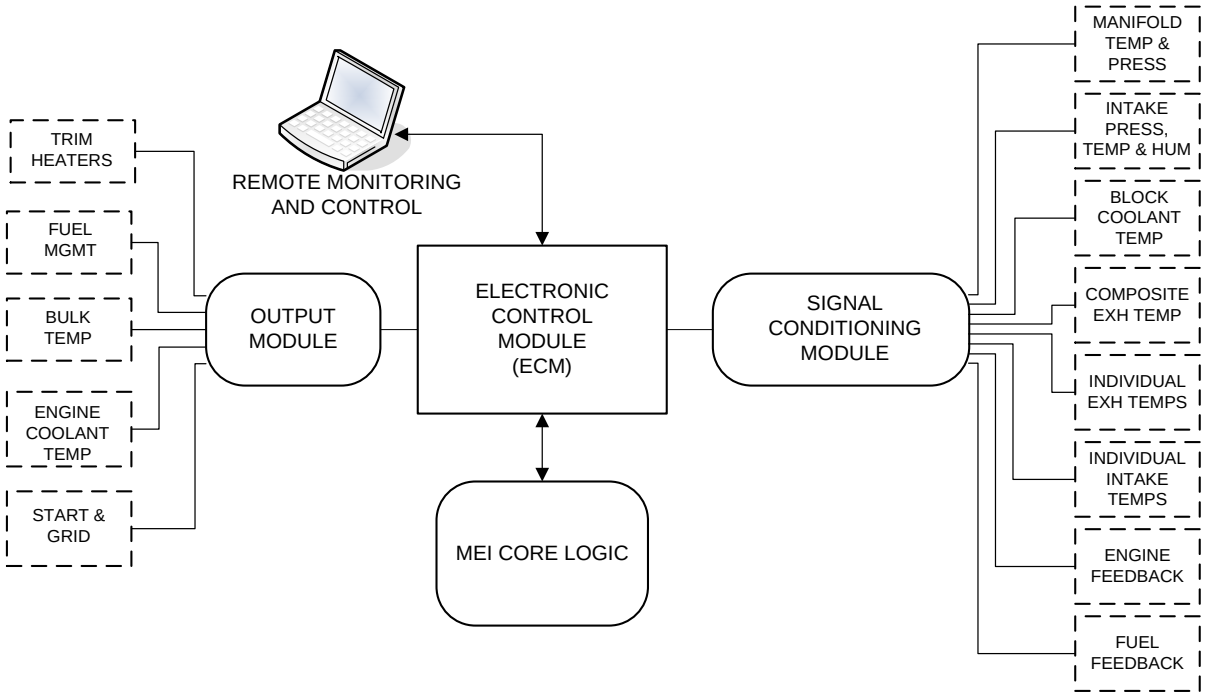
Table 9: Testing Overview

Test
4.1 Control system tests
4.1.1 Communication tests
4.1.2 Safety shutdown tests
4.2 System checkout tests
4.2.1 Fuel flow characterization
4.2.2 Startup sequence characterization
4.2.3 SI to HCCI characterization
4.3 Steady state operation & optimization
4.3.1 Equivalence Ratio -- Temperature -- Boost Characterization Matrix

6.1 Control system tests

The control system uses predefined set points as the target operating conditions. The electronics portion consists of an electronic control Module (ECM), an MEI core logic module, a signal conditioning module and an output module. Figure 15 illustrates the main areas of the control system.

Figure 15: Control Schematic



6.1.1 Communication test results

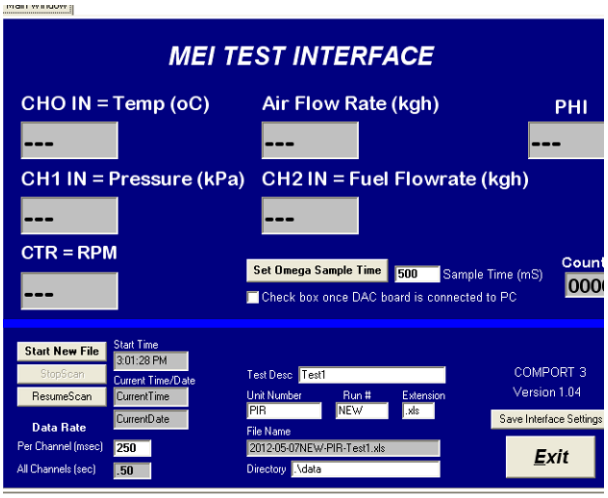
6.1.1.1 Purpose

This test was used to confirm system communications and validate the systems fundamental logic.

6.1.1.2 Results

The HCCI ECM input channels log data consistent with the HCCI interface. Output channels communicate with their associated devices, for example, the fuel relay shuts down when it is supposed to. The HCCI ECM provides autonomous on board programming of the control system. Figure 16 shows a screen capture of the computer interface for remote monitoring and control.

Figure 16: HCCI Interface for Remote Monitoring and Control



6.1.2 Safety shutdown test results

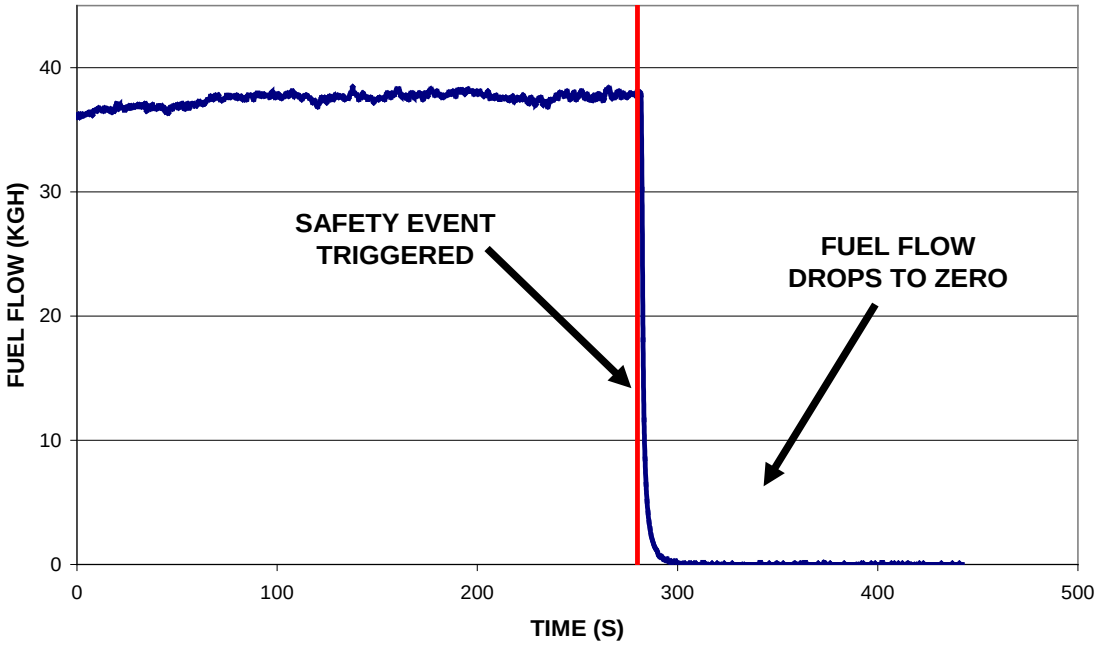
6.1.2.1 Purpose

This test ensured the safety of the equipment and operator when potentially hazardous conditions are present. This test would demonstrate the physical interruption of the system's fuel supply, grid connection and heater power in response to a hazardous condition. Ten different safety conditions were tested.

6.1.2.2 Results

The fuel did not flow to flow through the fuel line when the appropriate safety condition was exercised. Figure 17 shows the response of the fuel flow when a safety condition is triggered.

Figure 17: Fuel Flow Response When a Safety Condition is Triggered



The contactor on the grid connection opens when the appropriate safety condition is exercised. Heater power disengagement was tested when the installation trim heating circuit was completed. A summary of safety conditions and their test results are listed in Table 10.

Table 10: Safety Shutdown Conditions

#	Condition	Parameter	Action	Test Result
1	Manual Kill	User Activated	Close Fuel Solenoid, Open Grid Disconnect	*Fuel ceases to flow and contactor signal recognized*
2	Low oil pressure	< 2000 kPa	Close Fuel Solenoid, Open Grid Disconnect	*Fuel ceases to flow and contactor signal recognized*
3	High Coolant Temp	> 257°F (125°C)	Close Fuel Solenoid, Open Grid Disconnect	*Fuel ceases to flow and contactor signal recognized*
4	High Engine Speed	> 2200 RPM	Close Fuel Solenoid, Open Grid Disconnect	*Fuel ceases to flow and contactor signal recognized*
5	Low Engine Speed	< 300 RPM	Close Fuel Solenoid, Open Grid Disconnect	*Fuel ceases to flow contactor signal not present in 300 RPM condition*
6	High Exhaust Temp	> 932°F (500 °C)	Close Fuel Solenoid, Open Grid Disconnect	*Fuel ceases to flow and contactor signal recognized*
7	Low Air Flow	< TBD	Close Fuel Solenoid, Open Grid Disconnect	*Will be tested in steady state testing*
8	Low Inlet Temp	< 257°F (125°C)	Close Fuel Solenoid, Open Grid Disconnect	*Fuel ceases to flow and contactor signal recognized*
9	Phi	> 0.45	Close Fuel Solenoid	*Fuel ceases to flow*
10	High Heater Temp	572°F (300°C)	Disconnect Heater Power, Open Grid Disconnect	*Will be tested in steady state testing*

6.2 System checkout tests

6.2.1 Fuel flow characterization

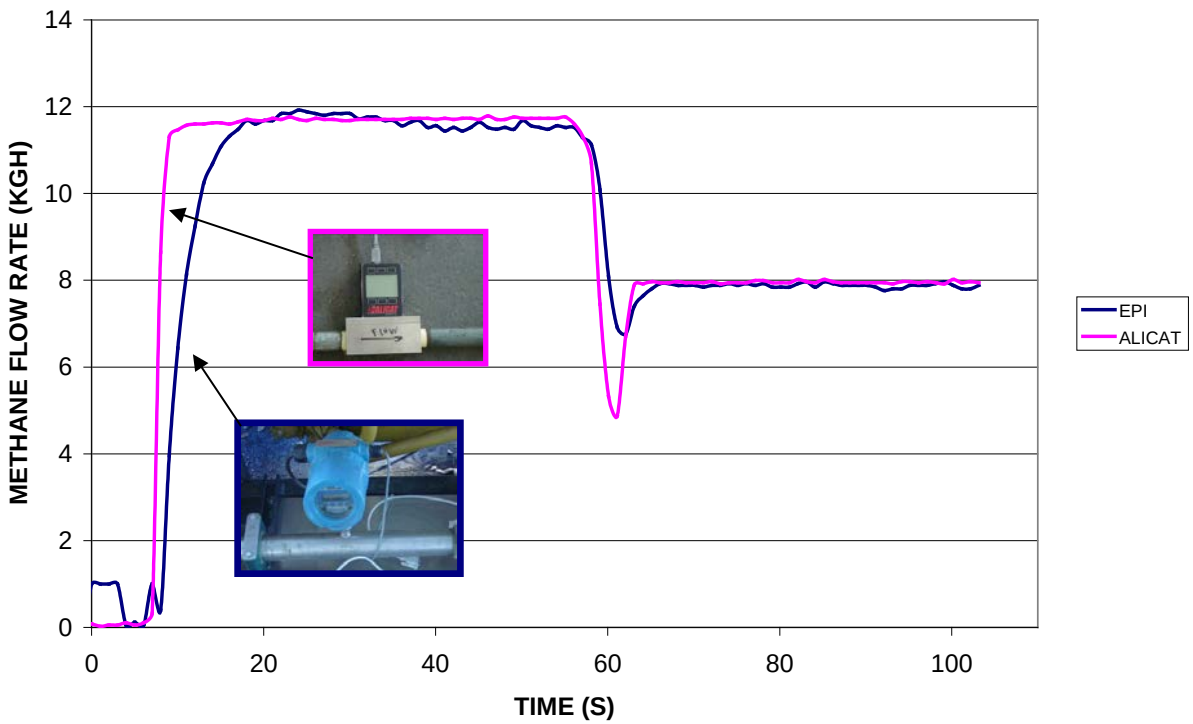
6.2.1.1 Purpose

Testing the mass flow meter system would verify that flow meter inputs are correctly recorded. These inputs were used to develop the control algorithm for setting target equivalence ratios. The results from this test were used to verify that the mass flow meter was sensing mass flow rates comparable to the published data.

6.2.1.2 Results

This HCCI system used an 8716MP series Eldridge Products, Inc. (EPI) mass flow meter to log and control fuel flow rates. To verify that the EPI mass flow meter was reading correctly, MEI installed a precision ALICAT M500S mass flow meter in series with the EPI flow meter. Methane was flowed thru the flow meters and flow rates were recorded. The recorded response of each flow meter (see Figure 18) indicated that EPI flow meter was recording accurately. The recorded flow rates from the EPI flow meter were then used to compute equivalence ratio.

Figure 18: Mass Flow Meter Correlation



6.2.2 Startup sequence characterization

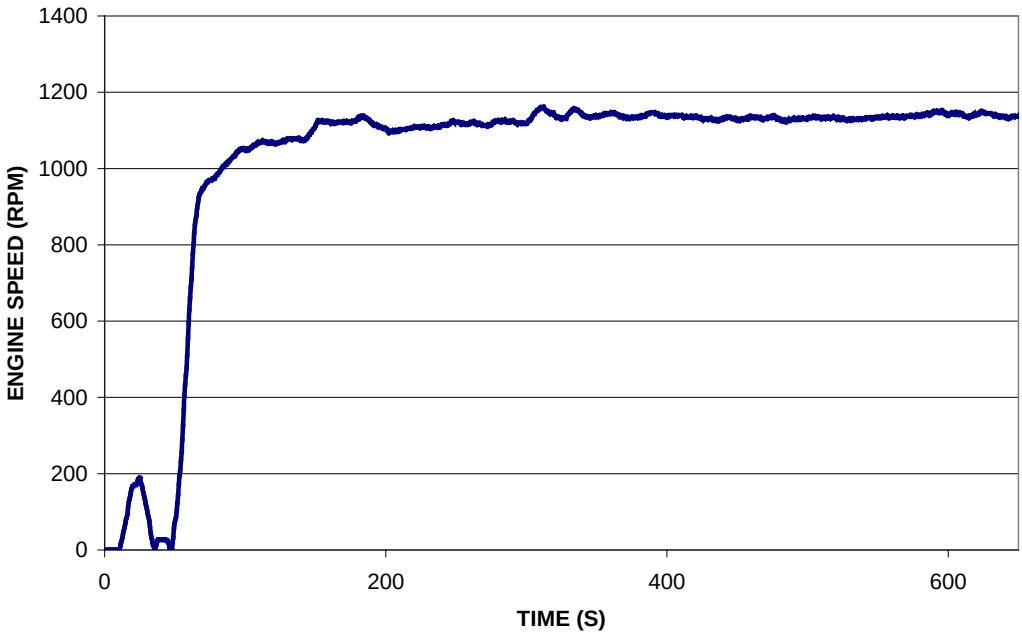
6.2.2.1 Purpose

This test was used to verify the startup sequence. It allowed for necessary modifications in the sequence to be implemented.

6.2.2.2 Results

The HCCI system starts up in spark ignited mode. The engine speed steadies in less than one minute of warm-up time. Figure 19 shows the typical engine speed during startup. The next step in this testing was to characterize the automated grid synchronization. Additional startup characterization would take place during steady state testing.

Figure 19: Engine Speed During Start Sequence



6.2.3 SI to HCCI characterization

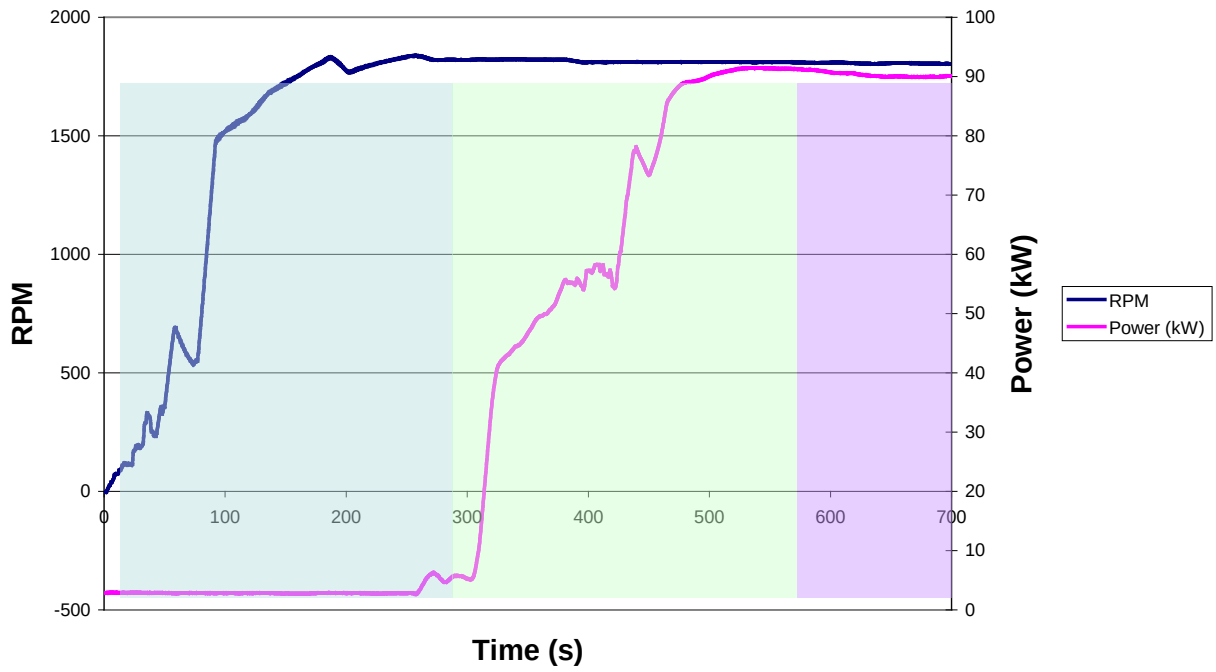
6.2.3.1 Purpose

This test was used to verify the startup sequence and the transition from SI to HCCI mode.

6.2.3.2 Results

The HCCI system starts up in spark ignited mode. After grid synchronization and appropriate operating conditions for HCCI are reached, the engine transitions from SI mode to HCCI mode. Proper startup allowed for the spark ignition to HCCI transition. Figure 20 shows the engine speed and power output during the SI to HCCI transition. The genset controller allows for the system to start and sync to the grid shown as the blue region on plot. The spark ignition to HCCI transition is illustrated in the green region on the plot. Finally, HCCI operation is achieved, show in the purple region on the plot.

Figure 20: Engine Speed and Power Output During Start SI to HCCI Transition



6.3 Steady state operation & optimization

6.3.1 Equivalence Ratio — Temperature — Boost Characterization Matrix

6.3.1.1 Purpose

This test was used to generate an equivalence ratio versus temperature data which was then used to determine the optimal engine inlet temperature, equivalence ratio and boost. Efficiency and NO_x values were be tabulated and compared to project goals.

6.3.1.2 Results

MEI tested both the modified camshaft and the thermal manifold configurations during this phase of baseline testing. The focus was to map the operating conditions that lead to optimal emissions and efficiency. MEI compared the emissions, power output, efficiency and equivalence ratio of these two configurations to the original MEI model 300 genset. MEI model 300 genset has a range of efficiencies of 32 to 39 percent with corresponding emissions shown in blue in Figure 21. While both configurations had low NOx emissions, the modified camshaft had less than 30 percent efficiency shown in red in Figure 21. The thermal manifold configuration (shown in green in Figure 21) has both low NOx emissions and has efficiencies in the 32 to 36 percent range.

MEI's model 300 genset has a power output of about 30kW with corresponding emissions shown in blue in Figure 22. While both MEI model 302 configurations had low NOx emissions, the modified camshaft only produced about 80 kW shown in red in Figure 22. The thermal

manifold configuration (shown in green in Figure 22) had both low NOx emissions and produced close to 100kW of electrical power.

Model 300 was operated over a wide range of equivalence ratios with corresponding emissions shown in blue in Figure 23. Both configurations had low NOx emissions when operated with the equivalence ratios in the 0.31 to 0.33 range. Figure 23shows the comparison of the two model 302 configurations compared to the MEI model 300 system.

Figure 21: NOx Emissions and System Efficiency During HCCI Operation

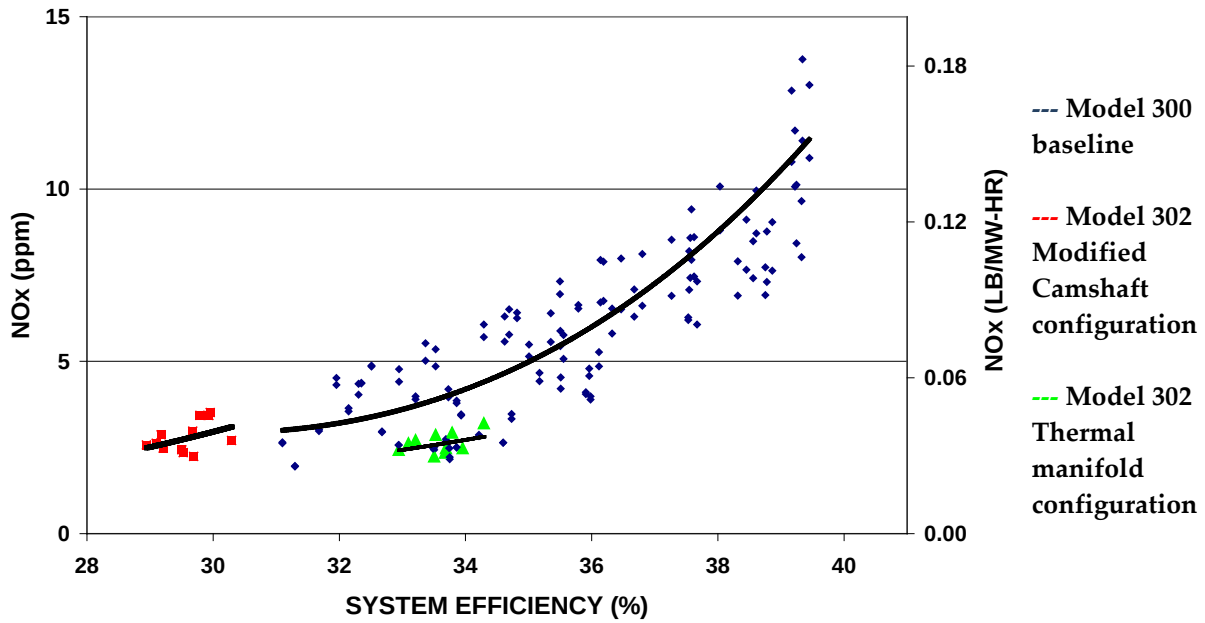


Figure 22: NOx Emissions and Power Output During HCCI Operation

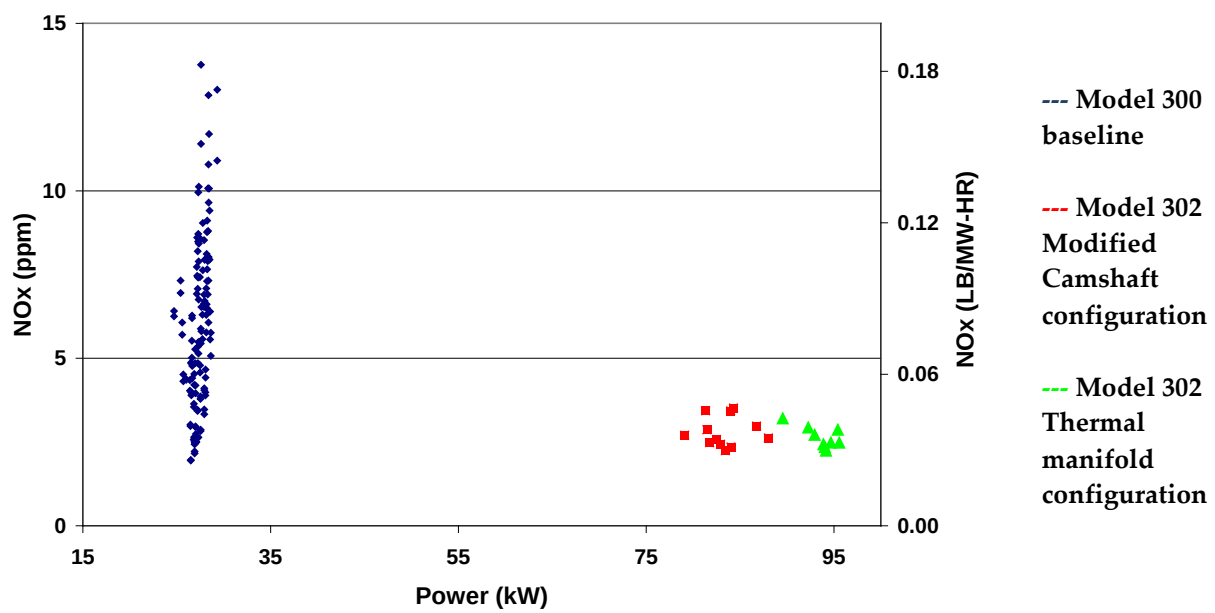
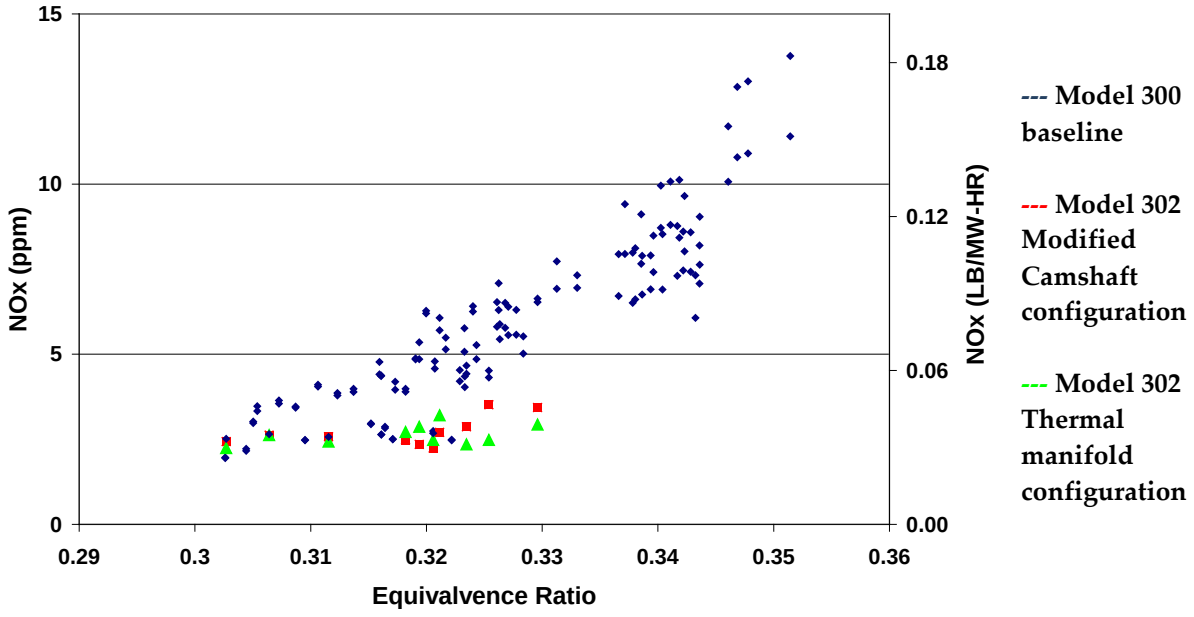


Figure 23: NOx Emissions and Equivalence Ratio During HCCI Operation



6.4 Summary of Bench Results

Initial testing was used to verify genset operation and identify any major design modifications that would need to occur prior to deployment into the field. The control system tests verified that control system and safety system are functional. The fuel flow rate was verified and the engine starts in spark ignited mode. The engine transitioned form SI to HCCI mode allowing for HCCI characterization. The test results summary can be found in Table 11. The HCCI system was ready for field testing.

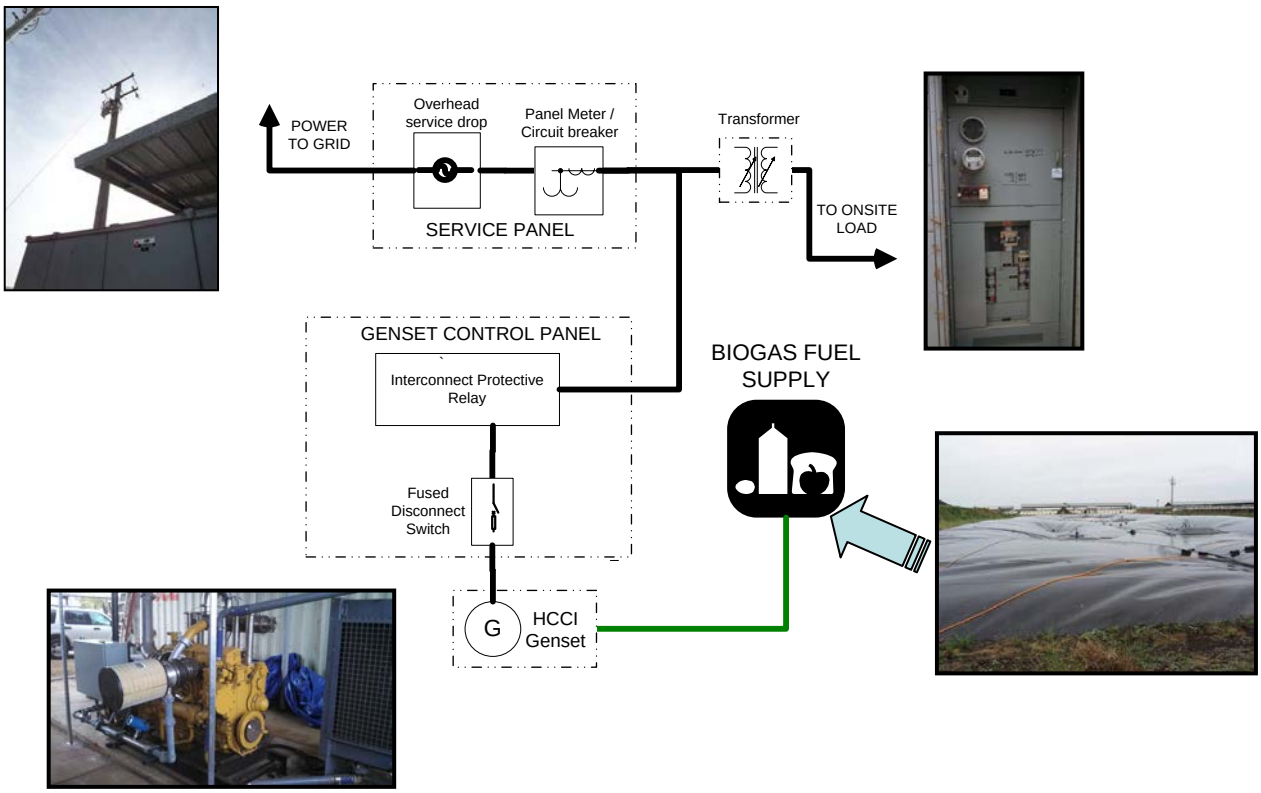
Table 11: Testing Results

Test	Result
Control system tests	
Communication tests	Verified data consistent with the HCCI interface
Safety shutdown tests	Safety sequences were functional
System checkout tests	
Fuel flow characterization	Fuel flow rate is accurate
Startup sequence characterization	Engine started in SI mode
SI to HCCI characterization	Engine transitions to HCCI mode
Steady state operation & optimization	
Equivalence Ratio -- Temperature -- Boost Characterization Matrix	Maps created for operation with the thermal manifold configuration

CHAPTER 7:
Site Development, Installation and Initial Field Testing

MEI generated a series of questions to ask the site owner in order to determine what activities could be performed prior to the relocation of the genset. The site owner's answers allowed for a smooth transition from MEI's test facility to the field test site. Prior to the genset being re-located, the site was pre-wired for the electrical connections and pre-plumbed for the fuel delivery. Figure 24 show an overview of the integration of the HCCI genet to the test site.

Figure 24: Overview of Site Integration



7.1 Installation Activities

7.1.1 Pre-wiring

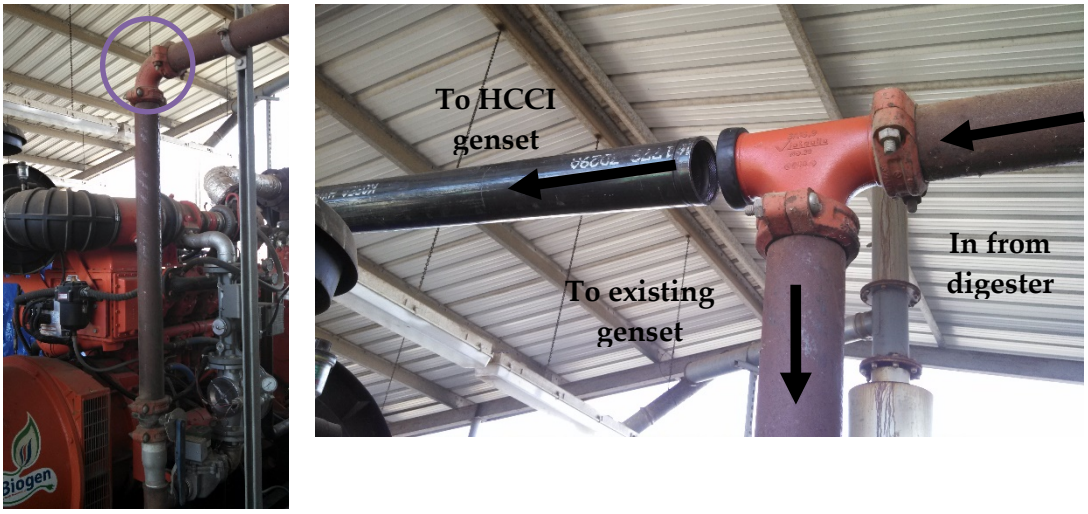
The 480 electrical system was wired from the grid connection through a three way switch (Figure 25 left) to a 200 A safety switch (Figure 25 middle). The safety switch was then tied to the genset soft start and main breaker box shown in Figure 25 right. This box serves as the grid interconnection point for the genset.

Figure 25: 480 VAC Wiring

7.1.2 Pre plumbing

The existing fuel line was extended to accommodate the HCCI genset. The 3" elbow (shown in Figure 26 left) was replaced with a tee (shown in Figure 26 right) and the fuel was hard plumbed over to the pad where the HCCI genset would go.

Figure 26: The Existing Fuel Line Was Extended



7.1.3 Re-location

The genset was loaded up from MEI testing facility (see Figure 27) and transported to the Tollenaar Holsteins Dairy. The final electrical connections were made to the grid as shown in

Figure 28. The exhaust ducting was installed (see Figure 29). The HCCI genset was ready for Phase I Field Testing as shown in Figure 30.

Figure 27: Genset Relocated to Tollenaar Dairy

Figure 28: Final Electrical Connections Were Made

Figure 29: Exhaust Ducting was Installed

Figure 30: Genset Installed and Ready for Field Testing

CHAPTER 8:
Field Test Plan

8.1 Overview

The goal of field testing the HCCI genset was to generate data sets that validated HCCI operation parameters including: power output, efficiency, emissions profile and stability. Field testing was conducted in three phases: Phase I, pre-preparation/system checkout, attended operation, extended operation.

Phase I, pre-preparation tests assed the functionality of the communication system and safety shutdown systems during potentially harmful conditions once the genset was grid connected plumbed to the biodigester gas fuel source. Part of Phase I testing included system checkout tests which verify fuel flow control and ensured that the automated systems (start, grid synchronization and SI to HCCI transition) are functional.

After confirming that all of the sub-systems within the HCCI genset were operational and the genset was performing as expected, attended operation took place. During the Phase II attended operation tests, the HCCI genset was operated for short test runs while continually monitoring power output, efficiency, emissions profile and stability.

Phase III, extended operation tests consisted of several 12 to 24 hour test runs. The system was remotely monitored for power output, efficiency, emissions profile and stability. MEI personnel visited regularly to perform appropriate checkups including visual inspections and gathering oil samples for analysis.

8.2 Field Test Plan Detail

A summary of field tests are summarized in Table 12.

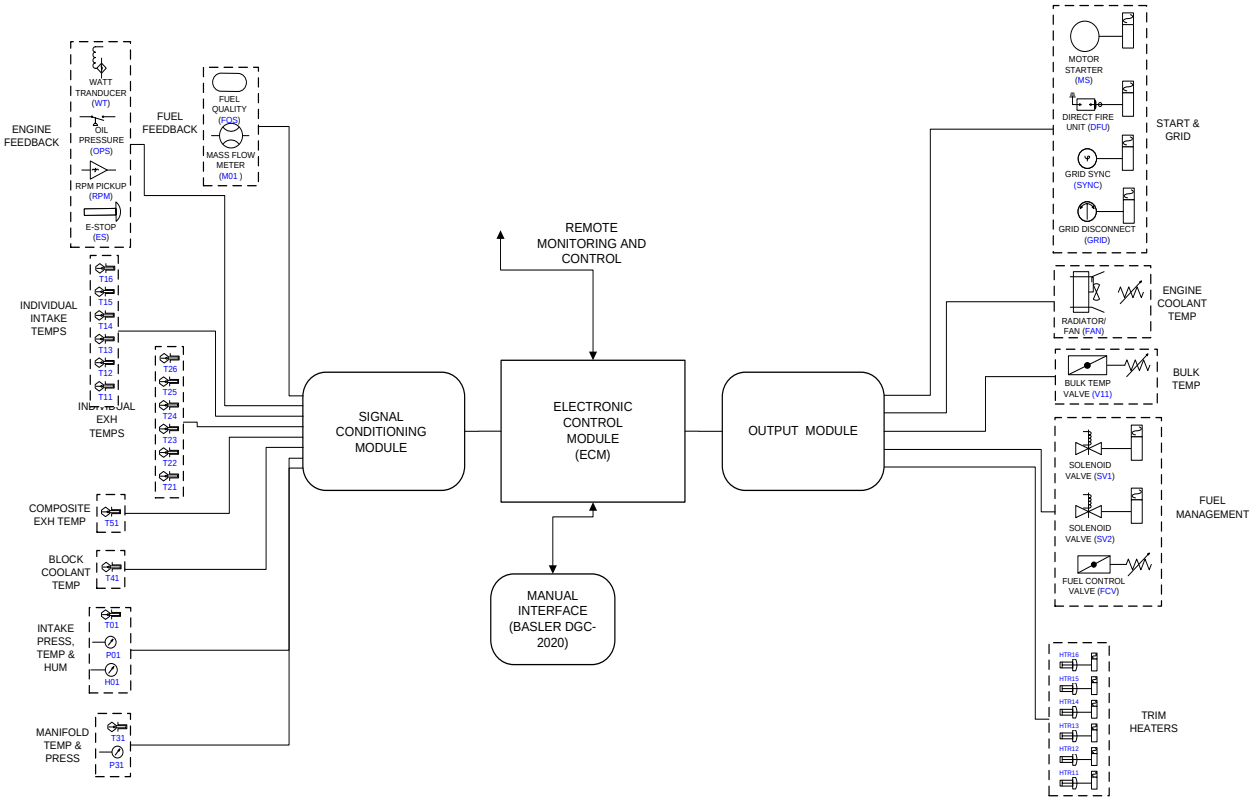
Table 12: Field Testing Overview

Test
Phase I: Pre-prep / System checkout
Communication tests
Fuel Safety shutdown tests
Startup sequence verification
Phase II: Attended Output Monitoring
Equivalence Ratio -- Temperature -- Boost -- Emission Validation Matrix
Remote operation verification
Emissions Testing
Phase III: Field Test / Extended Operation
Extended Operation with Remote Monitoring
Inspections

8.2.1 Control system tests

The control system used predefined set points as the target operating conditions. The electronics portion consists of an electronic control Module (ECM), an MEI core logic module, a signal conditioning module and an output module. Figure 31 illustrates the main areas of the control system.

Figure 31: Control Schematic



Testing the HCCI ECM communication verified that the incoming signals channels match the devices they were associated with. The HCCI ECM output signals needed verification that they were associated with the correct channel and that their performance was adequate for control purposes. The ECM is responsible for monitoring and adjusting system performance during operation including A/F mixture, inlet temperature, and all other system parameters. Basic system health and operation is prerequisite to all other operating scenarios.

8.2.2 System checkout tests

Check out tests were intended to ensure the safety of the equipment and operator when potentially hazardous conditions are present. These tests exercised safety shutdown conditions 1 through 10 listed in Table 13.

Table 13: Safety Shutdown Conditions

#	Condition	Parameter	Action
1	Manual Kill	User Activated	Close Fuel Solenoid, Open Grid Disconnect
2	Low oil pressure	< 2000 kPa	Close Fuel Solenoid, Open Grid Disconnect
3	High Coolant Temp	> 125°C	Close Fuel Solenoid, Open Grid Disconnect
4	High Engine Speed	> 2200 RPM	Close Fuel Solenoid, Open Grid Disconnect
5	Low Engine Speed	< 300 RPM	Close Fuel Solenoid, Open Grid Disconnect
6	High Exhaust Temp	> 500 °C	Close Fuel Solenoid, Open Grid Disconnect
7	Low Air Flow	< TBD	Close Fuel Solenoid, Open Grid Disconnect
8	Low Inlet Temp	< 125°C	Close Fuel Solenoid, Open Grid Disconnect
9	Phi	> 0.45	Close Fuel Solenoid
10	High Heater Temp	300°C	Disconnect Heater Power, Open Grid Disconnect

8.2.3 Startup and synchronization test

Starting and synchronizing testing were necessary to verify the startup and grid synchronization process is functional.

8.2.4 Short duration testing

Short duration testing allowed for basic system health and operation to be monitored.

8.2.5 Extended duration testing

Data collected during extended testing of the genset was used to validate HCCI technology as a viable, reliable technology for distributed generation applications. Key results from this testing will be shared with appropriate industry partners and policy makers.

CHAPTER 9:
Field Testing

The goal of field testing the HCCI genset was to generate data sets that validated HCCI operation parameters including: power output, efficiency, emissions profile and stability. Field testing was conducted in three phases: Phase I, pre-preparation/system checkout, attended operation, extended operation. Phase I, pre-preparation tests assed the functionality of the communication system and safety shutdown systems during potentially harmful conditions once the genset is grid connected plumbed to the biodigester gas fuel source. Part of Phase I testing included system checkout tests which verified fuel flow control and ensure that the automated systems (start, grid synchronization and SI to HCCI transition) were functional. After confirming that all of the sub-systems within the HCCI genset were operational and the genset was performing as expected, attended operation testing would take place. During Phase II attended operation tests, the HCCI genset was operated in several short test runs while continually monitoring power output, efficiency, emissions profile and stability. MEI's emission monitoring equipment was temporarily relocated to the Tollenaar test site to verify emissions. Phase III, extended operation tests, will took over an extended period in several 12 to 24-hour test runs. The system was remotely monitored for power output, efficiency, emissions profile and stability. MEI personnel visited regularly to perform appropriate check-ups including visual inspections and gathering oil samples for analysis. A summary of field tests that were conducted are summarized in Table 12.

9.1 Phase I, Pre-Prep / System Checkout

The following sections detail the results of specific tests as conducted on the HCCI genset during Phase I field testing. The HCCI genset successfully completed all Phase I testing. All communication for the data acquisition were operational. The genset passed all of its safety checks and was safe to operate. The engine started and synchronizes to the grid.

9.1.1 Communication Tests

9.1.1.1 Purpose

Confirm system communications and validate the system's fundamental logic.

9.1.1.2 Result

All input channels had appropriate signals on the interface that match the inputs to the data acquisition board. All of the output channels communicated with their corresponding devices. The HCCI ECM via a laptop, provided autonomous on board programmable system control.

9.1.2 Safety Shutdown Tests

9.1.2.1 Purpose

Ensure the safety of the equipment and operator when potentially hazardous conditions are present. A series of ten safety shutdown conditions were executed.

9.1.2.2 Result

This testing successfully demonstrated the physical interruption of the system's fuel supply, grid connection and heater power in response to one or more of the hazardous safety shutdown conditions 1 through 10 listed in Table 14. All safety shutdown conditions worked as expected.

Table 14: Safety Shutdown Conditions

#	Condition	Parameter	Action	Result
1	Manual Kill	User Activated	Close Fuel Solenoid, Open Grid Disconnect	PASS
2	Low oil pressure	< 2000 kPa	Close Fuel Solenoid, Open Grid Disconnect	PASS
3	High Coolant Temp	> 257°F (125°C)	Close Fuel Solenoid, Open Grid Disconnect	PASS
4	High Engine Speed	> 2200 RPM	Close Fuel Solenoid, Open Grid Disconnect	PASS
5	Low Engine Speed	< 300 RPM	Close Fuel Solenoid, Open Grid Disconnect	PASS
6	High Exhaust Temp	> 752°F (400 °C)	Close Fuel Solenoid, Open Grid Disconnect	PASS
7	Low Air Flow	< TBD	Close Fuel Solenoid, Open Grid Disconnect	PASS
8	Low Inlet Temp	< 257°F (125°C)	Close Fuel Solenoid, Open Grid Disconnect	PASS
9	Phi	> 0.45	Close Fuel Solenoid	PASS
10	High Heater Temp	572°F (300°C)	Disconnect Heater Power, Open Grid Disconnect	PASS

9.1.3 Startup Sequence Verification

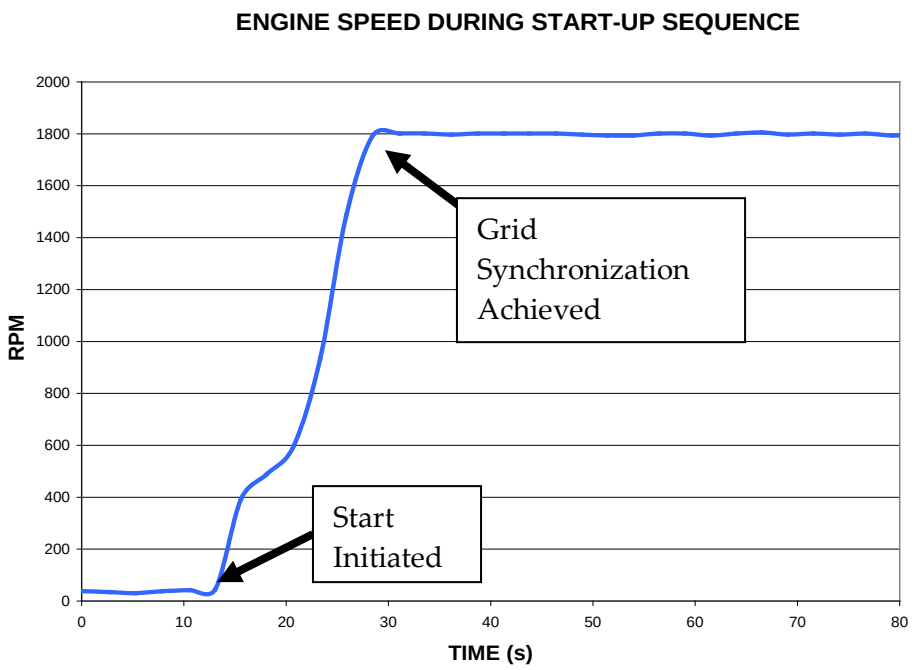
9.1.3.1 Purpose

Verify the genset startup sequence. This test was used to verify that the genset undergoes the proper sequence of events for starting and synchronizing to the grid.

9.1.3.2 Results

When initiated, the genset starts and synchronizes to the grid as intended. Figure 32 shows a typical plot of time versus engine speed. This plot indicates that the startup sequence and grid synchronization are functional.

Figure 32: Engine Speed during Startup and Grid Synchronization



9.1.4 Additional tests

9.1.5 Biogas Quality

The biogas flow was consistently in the 60 to 80 CFM range at 30"Hg. MEI verified that the methane concentration was between 70 to 75 percent, with carbon dioxide levels in the 25 to 30 percent range. There was some concern about H2S levels. Summers Consulting, Inc. developed and installed an air injection system. After the addition of air injection to the digester, H2S levels below 100ppm have been recorded. MEI continued to monitor the biogas for methane, carbon dioxide and H2S levels during operation.

9.2 Phase II, Attended Output Monitoring

9.2.1 Equivalence Ratio — Temperature — Boost — Emission Validation

9.2.1.1 Purpose

Generate an equivalence ratio versus temperature data which validated the optimal engine inlet temperature, equivalence ratio and boost determined during bench testing. Efficiency and NO_x values were tabulated and compared to project goals.

9.2.1.2 Results

Phase II testing required 30 hours of testing to allow for mapping of emissions, power and efficiency. The HCCI genset was operated over a range of operating conditions to find optimal operational conditions. MEI mapped the system efficiency and resulting NOx emissions as shown in Figure 33. The HCCI genset consistently has emissions levels below 10 ppm NOx and system efficiencies as high as 35 percent. A map of NOx emissions and power output was generated as well. Shown in Figure 34, the HCCI genset produces up to 100kW of electrical power using actual biogas as fuel. The genset was operated at several different equivalence ratios in order to map the emissions profile as a function of how rich or lean the engine was operated. Higher equivalence ratios resulted in higher electrical power output, but had slightly elevated NOx emission levels. Figure 35 is a map of NOx emissions and equivalence ratio for MEI's model 302 genset.

Figure 33: NOx and Efficiency Mapping

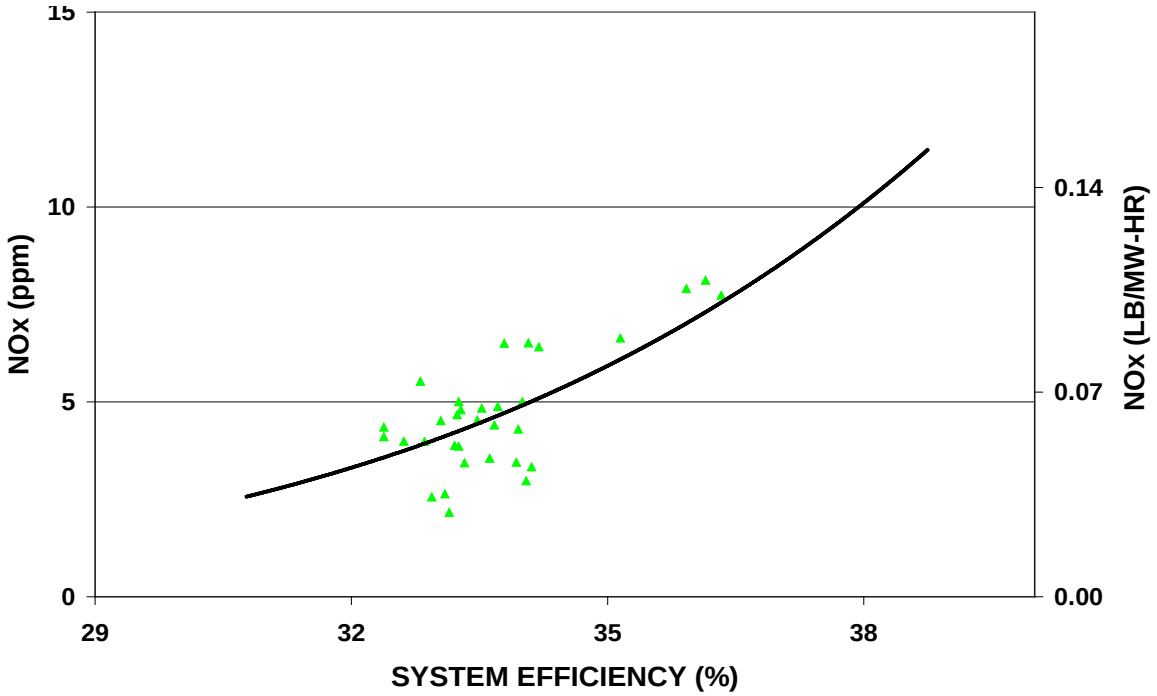


Figure 34: NOx and Electrical Power Output mapping

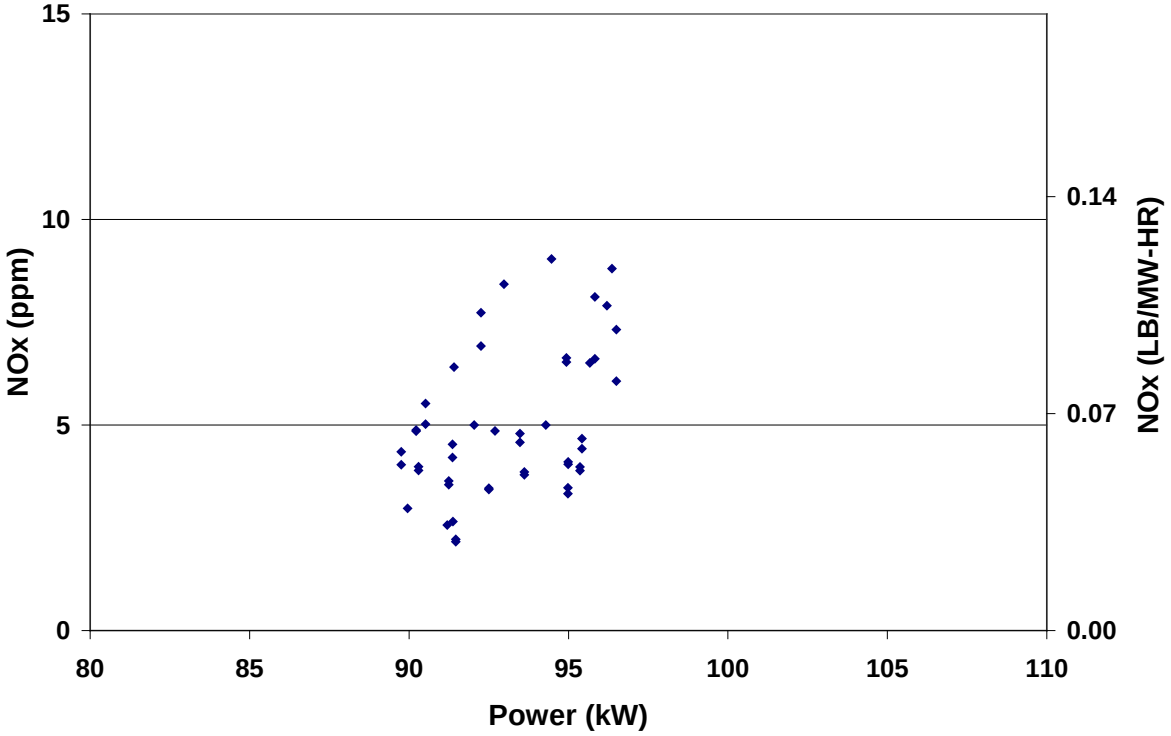
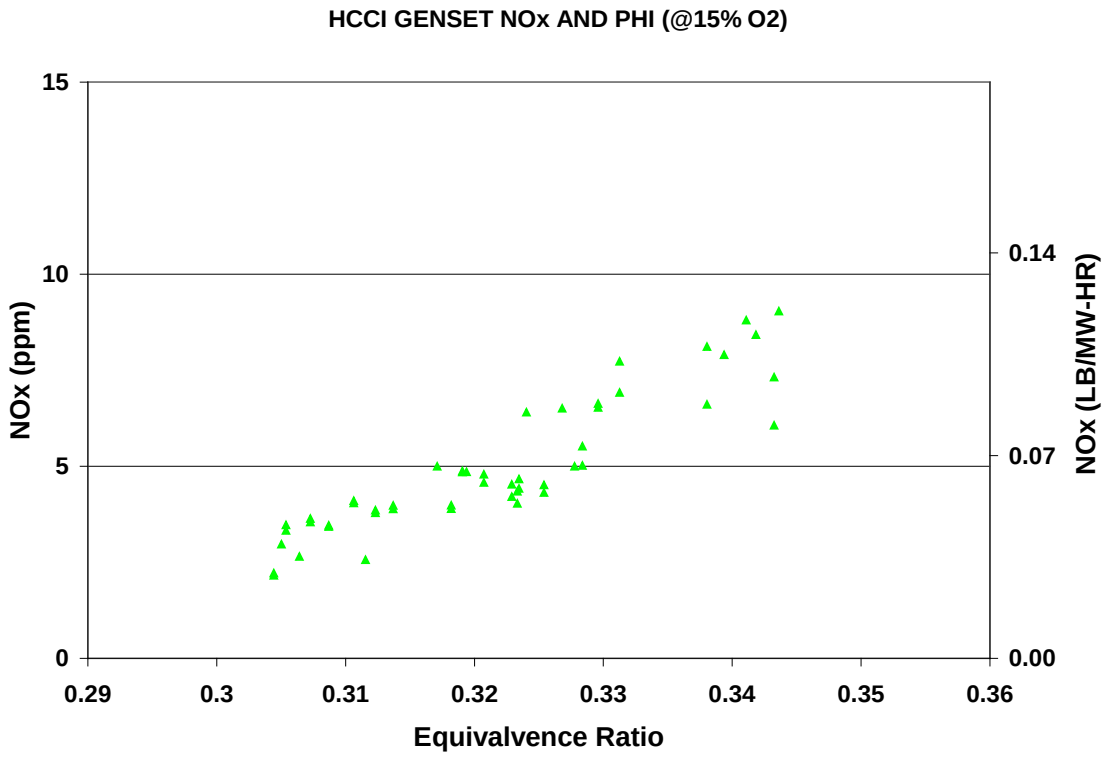


Figure 35: NOx and Equivalence Ratio Mapping



9.2.2 Remote Operation Verification

9.2.2.1 Purpose

Confirm system communications, safety and remote operations can be remotely monitored and controlled

9.2.2.2 Results

Utilizing an internet connection, MEI successfully started, stopped and changed appropriate operating parameters via a specialized interface within the HCCI's ECM control system.

9.2.3 Emissions Testing

9.2.3.1 Purpose

Confirm emissions were within permitted levels.

9.2.3.2 Results

The research team measured the concentrations of reactive organic compounds (ROC) and carbon monoxide (CO) in addition to the concentration of nitrogen oxides (NOx). Testing indicated that the NOx concentration is about 5ppm, the ROC concentration is about 42 ppm and the CO concentration is about 75 ppm as summarized by Table 15. At these emissions levels, the model 302 HCCI genset was ready for permitting.

Table 15: Summary of Emission Levels for HCCI Operation

Pollutant	Concentration (ppm @ 15% O2)	Mass emission rate (g/hp-hr)	Mass emissions rate (lb/MW-hr)
Reactive Organics Compounds	42	0.16	0.47
Nitrogen Oxides	4	0.03	0.07
Carbon Monoxide	75	0.58	1.87

9.3 Phase III, Extended Operation with Remote Monitoring

Once the HCCI genset was mapped for optimal operation, MEI operated for an additional 270 hours under these optimal operating conditions. The hybrid control system allowed for these conditions to be maintained while remote monitoring allowed for real time data to be gathered remotely. Typical data recorded includes: cylinder inlet temperature, power output, manifold pressure, fuel flow rate and block temperatures. The data recorded during a typical test run are shown in Figure 36. Stable manifold temperature resulted in stable power output during testing as indicated in Figure 37.

Figure 36: Manifold Absolute Pressure and Power Output for Typical Test Run

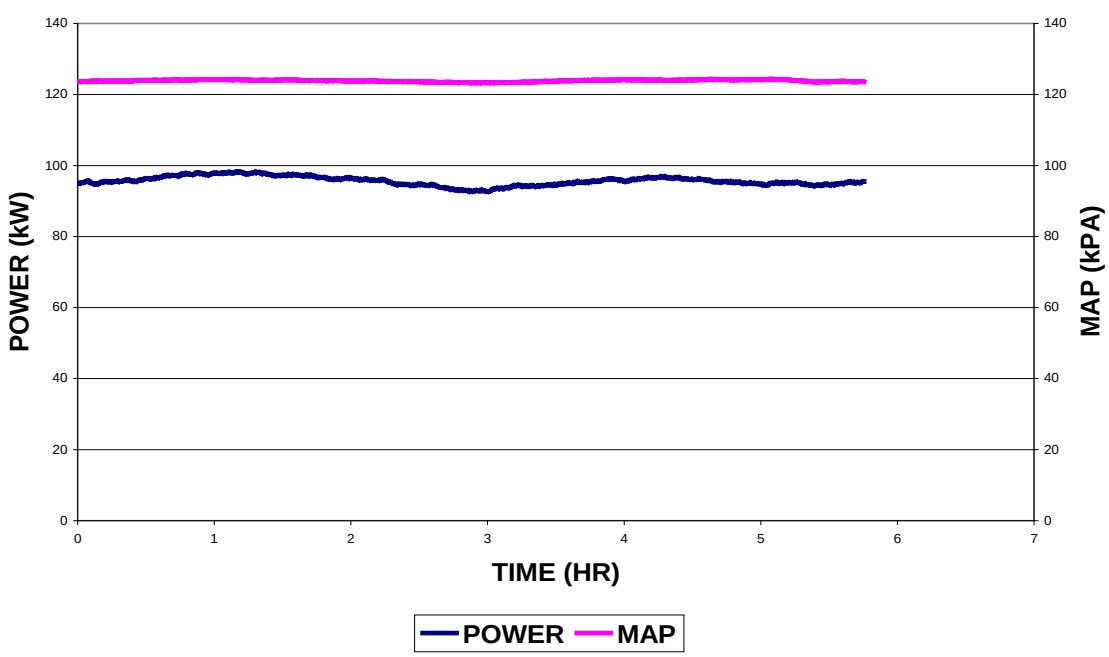
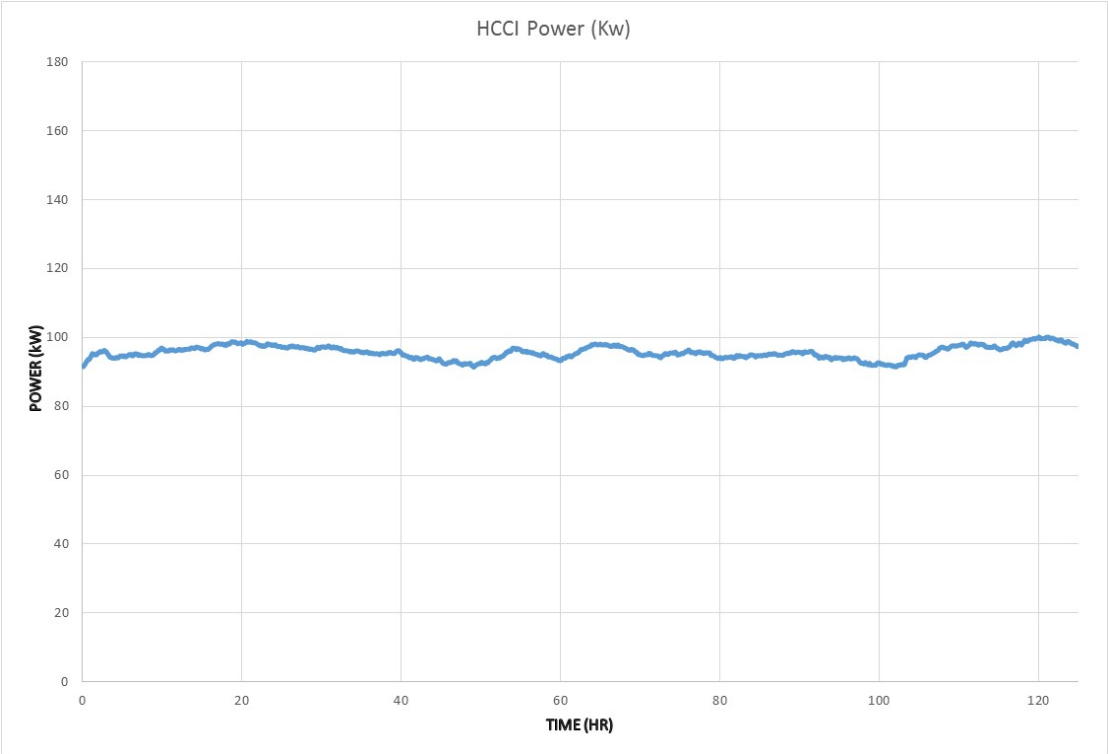


Figure 37: Power Output During Several Days of Testing



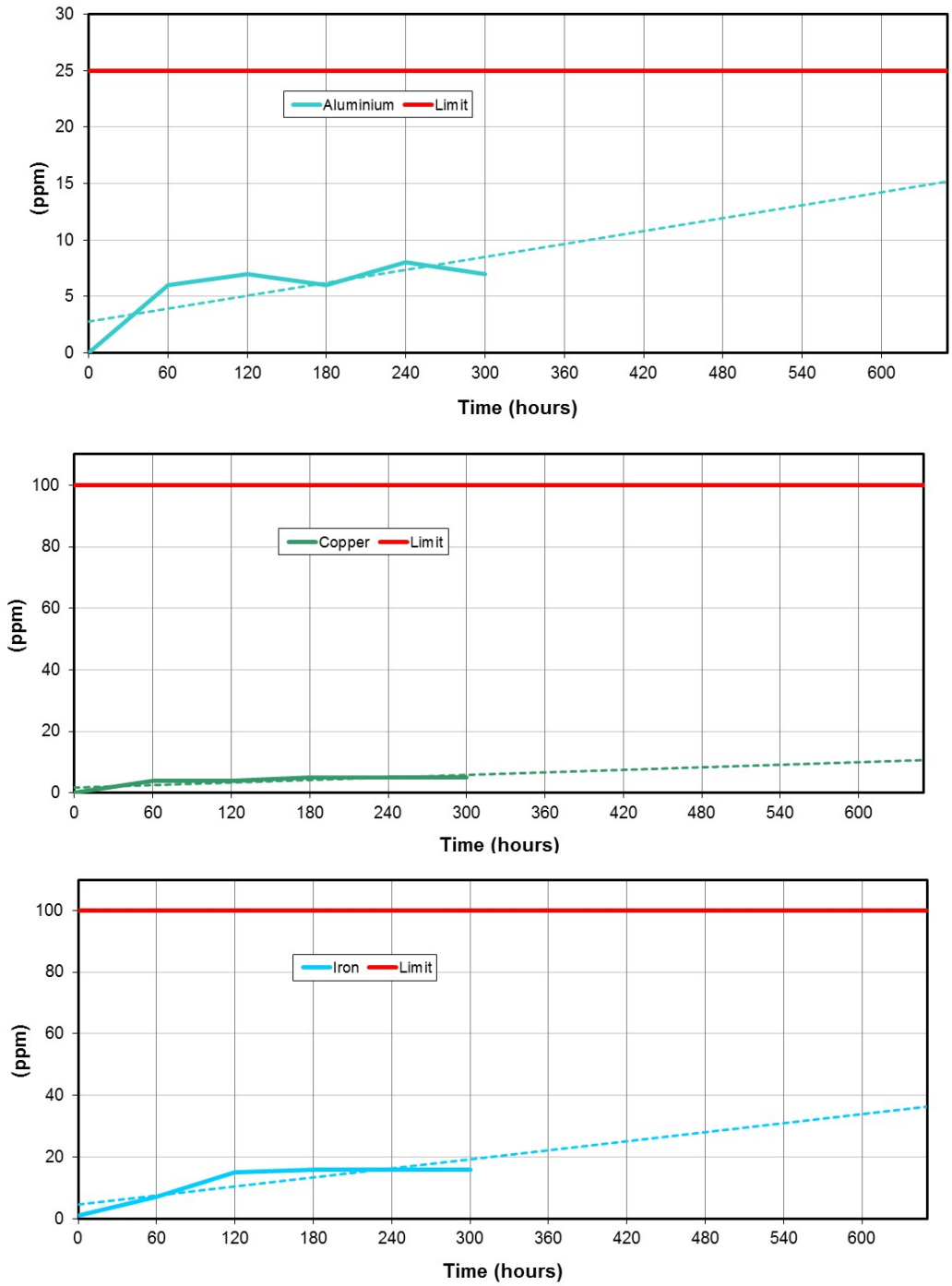
9.3.1 Maintenance Inspections

MEI operated the HCCI genset for one full maintenance cycle, or 300 hours. MEI inspected thirty different components listed in Table 21 for unusual wear included in Appendix B. None of the components showed signs of potentially catastrophic failure of the engine components.

9.3.2 Oil Analysis

Oil quality was monitored every 60 hours for signs of degradation. An eight ounce sample was pulled from the engine oil sump and send to Oil Analyzers, Inc. The normal oil change interval for a CAT 3406 engine is 250 hours. MEI has operated the model 302 HCCI genset for longer than CATERPILLAR suggested oil sample change interval *without* abnormal oil sampling results. Figure 38 shows plots for the iron, copper and aluminum levels in the engine oil over the 300 hour period. The corresponding dashed indicates the projected level of these metals up to 800 hours of operation. When the ppm level of these metals reaches the alarm limit, an oil change is recommended. According to the analysis performed, even after 300 hours of use, the oil is still considered suitable for continued use. From this analysis, it is concluded that the engine is not operating outside of recommended operation conditions. Furthermore, the recommended engine oil change interval for the HCCI genset is every 600 hours of operation.

Figure 38: Metal Wear During 300 Hours of Operation



9.4 Summary of Test Results

The Model 302 HCCI genset has an efficiency of about 33 percent while producing less than 0.07 lb/MWh NOx emissions. The NOx emissions and efficiency were plotted for the phase III field

testing as shown in Figure 39. MEI's model 302 HCCI genset generates 95kW of electrical power. Table 16 summarizes field testing results compared to the program goals. The HCCI genset achieved all emission levels it was permitted for within the SMAQMD as summarized by Table 17.

Figure 39: NOx and Efficiency Summary

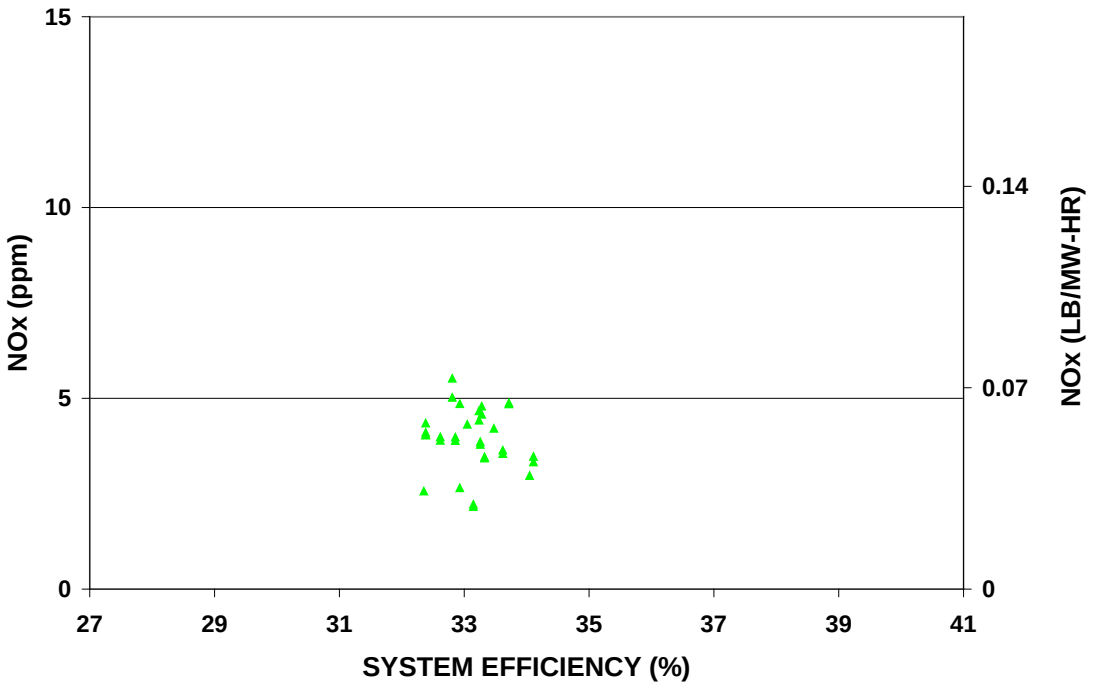


Table 16: Testing Results Compared to Program Goals

Target Parameter	CEC Program Goal	HCCI
Power Output (kW)	>100	100
System Efficiency—BTE, LHV (%)	>30	30-35
Emissions: NOx (lb/ MWh)	< 0.07	0.05 -0.07
Emissions: NOx (lb/ MWh)	<0.10	1.68-1.72
Capital Cost ($/kW)	< 1500	1350 - 1500
Affordability - LCOE ($/kWh)	<0.14	.101

GOAL*:* Achieve greater than 30 percent brake thermal efficiency (LHV)

RESULT: Achieved 33 to 35 percent Efficiencies

GOAL: Generate electric power while meeting or exceeding current and future California atmospheric emissions requirements.

RESULT: Achieved 100kW output while meeting emission levels

GOAL: Operate at an active dairy during a 12 month period, including a minimum of 300 hours of continuous operation utilizing biogas as fuel

RESULT: Achieved 300 hours of operation using biogas

Table 17: Summary of Emission Levels

Source	Pollutant	Concentration (ppm @ 15% O2)	Mass emission rate (g/hp-hr)	Mass emissions rate (lb/MW-hr)
MEI HCCI LEVELS	Reactive Organic Compounds	42	0.16	0.47
	Nitrogen Oxides	4	0.03	0.07
	Carbon Monoxide	75	0.58	1.87
PERMITTED LEVELS	Reactive Organic Compounds	41	0.2	0.59
	Nitrogen Oxides	11	0.15	0.44
	Carbon Monoxide	250	2.0	5.89
PROGRAM TARGETS	Reactive Organic Compounds	N/A	N/A	N/A
	Nitrogen Oxides	5	0.03	0.07
	Carbon Monoxide	6	0.05	0.1

CHAPTER 10: Commercialization

10.1 Technology Transfer Activities

In order to make the findings of MEI's developments available to the public, MEI provided information to both SMUD and the CEC. The following technology transfer activities took place during this program:

1. April 2010—25th Annual Bio-Cycle West Coast Conference in San Diego, California
    a. Overview presented by Marco Lemes SMUD
2. September 2010—Pacific Southwest Organic Residuals Symposium in Sacramento, California
    a. Overview presented by Marco Lemes SMUD
3. January 2012—Pacific West Biomass Conference in San Francisco, California
    a. Overview presented by Val Tiangco SMUD
4. February 2012—CEC IEPR Combined Heat Power in Sacramento, California
    a. Presented by Brandon Blizman
5. September 2012—Fact Sheet prepared and distributed internally at SMUD
    a. Prepared by MEI
6. February 2014—Fact Sheet prepared and distributed internally at CEC
    a. Prepared by MEI

For the entire presentations and fact sheets see MEI Document #: MEI-PIR01-IR8 (Technology Transfer Activities). The following technology transfer activities will be executed in the near future:

1. Planned Paper at upcoming a Renewable/Biomass Conference TBD with full project results
2. Post Summary Final Report on MEI website http://www.makelengineering.com/hcci.htm
3. Post Technical Brief on MEI website http://www.makelengineering.com/hcci.htm
4. Plan to maintain unit at test site for next several months for further testing and demonstration

10.2 Production Readiness Plan

MEI has identified the following steps as a plan to make HCCI technology a viable commercial product:

1. Genset Performance Targets Defined
2. Hardware Supply Chains
3. Genset Testing Adequate
4. End User Acceptance of Cost Analysis
5. Service and Maintenance Contracts
6. Implementation Steps

The critical production processes, equipment, facilities, personnel resources and support systems necessary to produce a commercially viable product will be identified. Cost projections for production thresholds will be determined as well as the development necessary to achieve these cost targets.

Makel Engineering will deliver value through the design, development, and licensing of HCCI engine technologies. Partnerships will be sought with companies having a strong history of distributing to and serving the customers who will be the end-users for its products.

Makel Engineering's value resides in its intellectual property complimented by capable engineering, prototyping skills and also low-volume manufacturing capabilities. This value will be leveraged through marketing partnerships with companies who have established sales and distribution channels.

10.2.1 Product Development

The production HCCI genset will be based upon readily available diesel engines. During the MEI manufacturing process, these engines will be modified to operate in HCCI mode. Materials can be purchased at commodity prices from outside vendors. Production CHP HCCI Gensets will be either skid mounted for permanent installations or trailer mount for temporary applications.

MEI has identified the following steps working towards the development of a commercial product:

- Feasibility Prototype Demonstrated
- Further Product Development Needed
    - Control System and Instrumentation – Custom Electronics and Firmware
    - Intake and Exhaust System – Design Modifications To Reduce Cost
    - BG Cleanup System

    - Develop Standardized Installation/Interconnect Design
- Manufacturing Process Development
    - Establish key supplier agreements
    - Production Process Development
    - Capitalize Production Facility
- Business Model Development
    - Purchase, Lease, Contract for Operation Options

10.2.2 Production Readiness Status

Supply chains have been identified for the following major purchased components:

- Engine Components – Caterpillar
- Generator – Marathon
- Control Interface – Basler
- Turbo Charger –Comp Turbo
- Major Custom Fabricated Parts – Northern California Machine Shops (Advanced Building, Pro2Pro, Iron Tree Solutions)
    - Thermal manifold
    - ATA
    - Covers
    - Frame
- Assembly and Fabrication Manufacturing – assumes work conducted in California

10.2.3 Capital costs

Table 18 below summarizes the HCCI genset's capital costs. The target sales price (excluding shipping and tax) is $119,840 or $1289/kW at 93 kW. Service and maintenance contract is not included and would be at a separate cost. MEI is in discussions with digester system integrators to be generator supplier for complete systems.

Table 18: Cost Analysis Summary

Capital Cost	Value	Units
Power rating	93	kW
Number of units	100	units
Purchased/Subcontracted Material Cost:	57,620	$ / unit
Direct Labor Cost including fringe:	9,392 (320 hr @ $29.35/hr)	$ / unit
Operating Overhead & Profit:	52,832	$ / unit
Target Sales Price (excluding shipping and tax)	119, 840 ($1289/kW at 93 kW)	$ / unit

10.2.4 Levelized Cost of Energy

The levelized cost of energy (LCOE) was determined using the Cost of Generation model found on the California Biomass collaborative website. Basic assumptions include a 5 percent interest rate on a 20 year loan, a 20 year straight depreciation schedule, an engine efficiency of 30 percent, a $0.0247 / kWh cost for fuel, a capacity factor of 85 percent and a combined tax rate of 40.75 percent. The capital cost for this genset will be $119,840. A levelized cost of energy of $0.101/kWh was determined for a commercial HCCI genset. Table 19 below summarizes the HCCI genset's costs and assumptions which lead to a $0.101/kWh LCOE.

Table 19: HCCI Genset Costs and LCOE

HCCI Prime Mover Inputs	Value	Units
Engine Power Output	93	kW
Efficiency	35	%
Prime Mover Cost (BOM)	119,840	$
Emission Control System	0	$
Prime Mover Capital Costs	1,289	$/kW
NOx Emissions		
min	0.05	lb /mW-hr
max	0.07	lb /mW-hr
Total Present Worth	415,146	$
Capital Recovery Factor	0.17	--
Annual Net Electricity Generation	692,478	kWh / yr
LCOE	$0.101	$ / kWh

CHAPTER 11:
Conclusions and Recommendations

11.1 Conclusions

At the beginning of this project, most HCCI engines had been operated primarily in laboratory environments. Field testing of this HCCI demonstration engine has allowed for optimization of an engine control system to allow for operation in HCCI mode using dairy biogas as fuel. The HCCI genset meets project goals for efficiency power and emissions. This project met program objectives prompting Makel Engineering, Inc. to ramp up its efforts to produce HCCI gensets as commercial gensets. In addition, the authors have formed the following conclusions:

- The development of a rugged automated industrial control system for controlling HCCI combustion proved to be a huge undertaking. The resulting hybrid HCCI control system allowed for unattended, stable HCCI operation. Additionally, the control system has the capability of remote monitoring and control of the genset. These control system developments will help MEI with long term deployment of units in the field.
- This scaled-up model 302 HCCI genset proved that HCCI technology is scalable; leading the authors to believe that a larger class of HCCI engines capable of greater than 100kW electrical output is feasible. MEI intends to keep the HCCI genset installed at the Tollenaar Dairy and continue to gather valuable longer term data.
- Power generation from HCCI technology has proven that distributed generation technologies exist that can to meet the strict air quality guidelines in California.
- This model 302 HCCI genset has an efficiency of about 33 percent while producing less than 0.07 lb/MWh NOx emissions and generating up to 100 kW of electrical power.

11.2 Recommendations

11.2.1 Technical/Design Recommendations

While the HCCI genset meets project goals while operating on dairy biogas as fuel, MEI recognizes that a few design modifications could enhance engine performance and commercial adoption. Potential improvements to the HCCI genset include

1. Larger diameter intake ducting
    - A large diameter on the intake ducting would reduce pressure drop resulting in higher electrical power output
2. Instrumented engine head
    - The addition of in-cylinder instrumentation (ION SENSING) would allow for a more accurate determination of cylinder firing
3. Higher compression ratio (16.7:1 currently)

- Developing a piston/head arrangement that allowed for a higher compression ratio would improve efficiency.

11.2.2 Recommendations towards Commercialization

Successfully demonstration of the HCCI genset using biogas, marks the next step in MEI's long term goal towards a commercial HCCI gensets. As part of the commercial development of this HCCI genset, MEI recommends that other similar facilities install and perform testing to demonstrate the viability of this technology for specific sites. MEI intends to keep the HCCI genset developed during this project installed at the Tollenaar Dairy and is actively seeking other potential demonstration sites to install other HCCI gensets. MEI is in the process of making this size genset (100kW) commercially available as a demonstration engine. Initially these sites will benefit from electrical power savings by offsetting some of their electrical usage, but as the technology continues to develop, large power purchase agreements will be made between site owners and utilities. Future systems will be deployed to residential subdivisions to medium size cities and include university campuses, business parks, public agency operations, and other localized groupings of energy users. The scaled up HCCI system will be deployed in 100kW packages. Each unit will have the capability to stand alone or be coupled.

11.3 Benefits to California

Commercial implementation and market adoption of the HCCI technology demonstrated in this project, has the following immediate as well as long term benefits:

- Improving air quality
  - Emissions levels that do not require SCR cleanup
  - Prevents GHG emissions to the atmosphere by destroying methane in biogas
  - Prevents smog formation by destroying ROGs and reducing NOx emissions.
- Reducing operational costs
  - Offsetting the cost of electricity for the end users
  - Increase revenue for end user from electricity sales
- Reduces regulatory penalties
- Improving site quality (at dairies, for example)
  - Odor and fly reduction
  - Improved soil nutrient management.
  - Digested solids are pathogen free and can be sold for animal bedding or compost
  - Effluent liquid can serve as crop fertilizer, reducing need for inorganic fertilizers

According to a recent PIER Collaborative Report by the California Biomass Collaborative, it is estimated that there is an additional 2,850 MWe of technical electrical capacity from biomass

resources on top of the already installed 968 MWe in the state of California[8] . 80 MW of HCCI power systems are projected to be deployed over the next three to five years. In the subsequent 10 years, an additional 300 MWe or more are projected to be deployed as more biomass conversion sites mature.

Implementing HCCI power systems instead of BACT spark ignited gensets equipped with selective catalytic reduction (SCR) will result in reduced annual operating costs, higher income potential and reduced annual emissions. Operating cost reduction comes from the lower maintenance costs (no SCR system to maintain). The high efficiency nature of HCCI combustion translates to more income for the user (HCCI ~ 35%, SI ~ 28%). The NOx emissions a SI engine with SCR are on the order of 0.15-0.61 g/bhp-hr (11-40 ppmv)[9] [Table 20]. The NOx emissions from the HCCI engine are 0.024-0.054 g/bhp-hr (2-4 ppmv), critically important in non-attainment regions of California.

If 80 MWe of SI SCR engines are deployed, 142 to 567 tons per year of NOx would result. If 80 MWe of HCCI engines are deployed, 22 to 50 tons per year of NOx would result.

The estimated annual emissions reduction of up to 517 tons of NOx could be achieved if 80 MWe of HCCI technology was deployed instead of BACT SI-SCR technology.

[8] Williams, R.B., M. Gildart, and B.M. Jenkins, 2008, An Assessment of Biomass Resources in California, 2007. California Biomass Collaborative: CEC PIER Contract 500-01-016

[9] SJVAPCD PERMIT NO: S-7767-2-0, AUTHORITY TO CONSTRUCT Permit San Joaquin Valley Air Pollution Control District

Table 20—Emission benefits HCCI versus BACT SI with SCR of 80 MWe deployed

HCCI Prime Mover Outputs	Value	SI + SCR Prime Mover Outputs	Value		Units
NOx Emissions		NOx Emissions			
min	0.070	min	0.450		lb / MW-hr
max	0.160	max	1.800		lb / MW-hr
Power output	80	Power output	80		MW
Efficiency	35	Efficiency	28		%
90% capacity factor	7872	90% capacity factor	7872		hr /yr
Annual Net Electricity Generation	787,200	Annual Net Electricity Generation	787,200		kWh / yr
Annual NOx Emissions		**Annual NOx Emissions**			
min	**22**	**min**	**142**		**ton / yr**
max	**50**	**max**	**567**		**ton / yr**

GLOSSARY

Term	Definition
AD	Anaerobic Digestion
A/F	Air to Fuel
AQMD	Air Quality Management District
ARB	Air Resources Board
BACT	Best Available Control Technology
BTE	Brake Thermal Efficiency
BTU	British Thermal Unit
CHP	Combined Heat and Power
CO	Carbon Monoxide
DG	Distributed Generation
η_t	Brake thermal efficiency
EPI	Eldridge Products, Inc.
η_c	Combustion efficiency
°C	Degrees Centigrade
HCCI	Homogenous Charge Compression Ignition
ICE	Internal Combustion Engine
ICTC	Individual cylinder temperature control
kgh	Kilograms per hour
kPA	Kilopascal
kW	Kilowatt
lb/MWh	Pound per Megawatt-hour
LCOE	Levelized Cost of Energy
LHV	Lower Heating Value
MAP	Manifold Absolute Pressure
MEI	Makel Engineering, Inc.

Term	Definition
MW	Megawatt, electrical
NG	Natural Gas
NO_X	Nitrogen Oxides
O_2	Oxygen
ppm	Parts per million
Φ	Phi (Equivalence ratio)
RPM	Revolution Per Minute
SI	Spark Ignition
VDC	Volts, direct current
UHC	Unburned hydrocarbon

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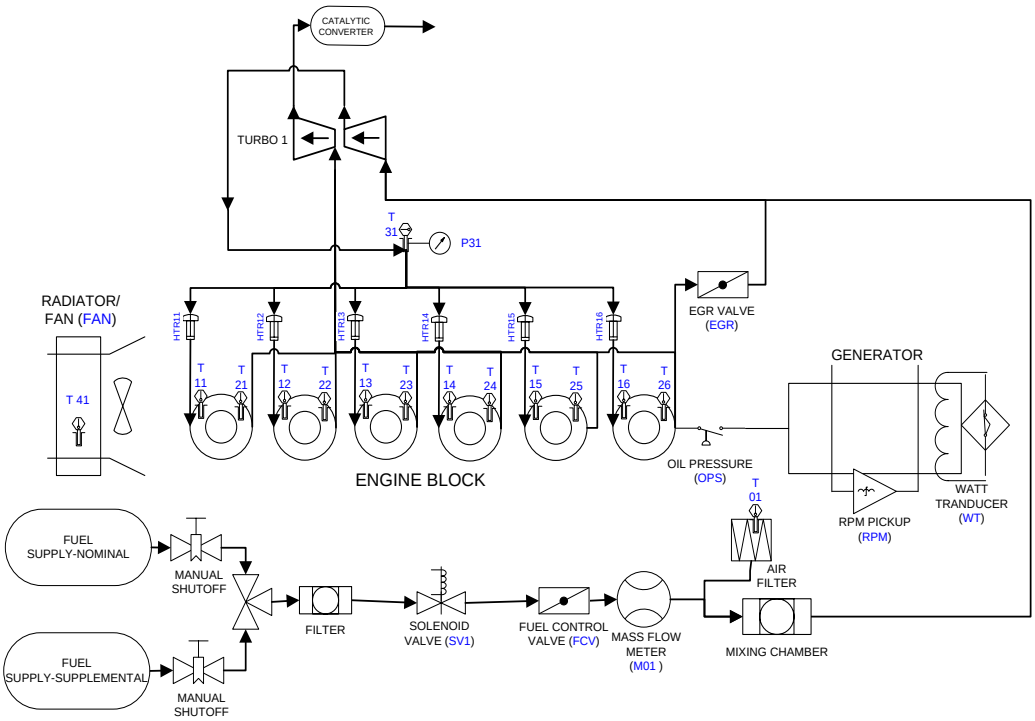
APPENDIX A:
Process Flow Diagram

Figure 40: HCCI Genset Process Diagram



Nominal Operating Conditions:

Location/ Measure	Φ	MAP	Power	BTE	Inlet Temp	NOx
Value	0.33	148	100.0	35.0	240	0.07
Unit		kPa	kW	%	oC	lb/ MWh

APPENDIX B:
Inspected Components

Table 21: HCCI Components for Inspection

Item #	Component:	Specification:	By:	Method	Int. (hrs)
1	Battery	12 Volt 1200 CCA	MEI	Meas	300
2	Main Bearing Set	Orig. Journal Size 3.5433 Undersize 3.5335 = .010 Undersize 3.5335 = .020	MEI	Meas	300
3	Rod Bearing Set	Original Journal Size 2.7559 Undersize 2.7461=.010 Undersize2.7362=.020	MEI	Meas	300
4	Pistons	Piston Skirt=5.3299 Orig.Clr.=.0049 Limit=.0090	MEI	Meas	300
5	Rings Set	Ring Gap =.0300 RingLandClr.=.003	MEI	Meas	300
6	Wrist Pins	Pin Dia.= 1.5748 WearLimit=.0010	MEI	Meas	300
7	Rebuilt Head/Valves/Guides	Pitting/excess clr=.005	Peterson	Meas	300
8	Crank Seals	3.533 i.d.	Petersen	Visual	300
9	Cylinder Sleeves	Orig. Bore = 5.4015 Max.wear=.0040	Peterson	Visaul/Meas	300
10	Crankshaft Regrind	Orig. Journal Size=2.7759	Peterson	Meas	300
11	Oil Filter	N/A		N/A	300
12	Turbo inspection/repair	Shaft play spec. N/A	MEI	Visaul/Meas	300
13	Starter	Shorting or open circuits		Meas	N/A

Item #	Component:	Specification:	By:	Method	Int. (hrs)
14	Water Pump	Shaft playgood to .005	MEI	Visaul/Meas	300
15	Intake System Flex Hose	Good physical condition	MEI	Visual	300
16	Intake Tubing Couplers	good mech. Condition	MEI	Visual	300
17	Water Pump Belt	Sign of cracks or wear	MEI	Visual	300
18	Engine Oil	Std oil testing	OAI Testing	Meas	30
19	Oil Cooler	Clean--no sludge or scaling	MEI	Visual	300
20	Coolant	Spec. gravity / ph	MEI	Meas	300
21	Coolant level	Level	MEi	Visual	24
22	Valve Adjustment	.015 int. .025 exh	MEI	Meas	250
23	Valve Guides	Valve Stem clr.= .0035 max.	MEI	Visaul/Meas	300
24	Air to Air HXR	Inspect for abnormal fouling	MEI	Visual	300
25	ECM	Ensure ECM is reporting tremotely	MEI	Check	24
26	Air Filter	Excess Contamination	MEI	Visual	300
27	Radiator Hose Set	Signs of leakage or Swelling	MEI	Visual	300
28	Compression Test	350 psi	MEI	Meas	300
29	Intake Heaters	Nominal resistance 30 OHM in Parallel	MEI	Meas	30