Santa Clara County Planar Solid Oxide Fuel Cell Demonstration Project

Final Scientific Report

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End Date: October 2009

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Abstract

The Santa Clara County Planar Solid Oxide Fuel Cell (PSOFC) project demonstrated the technical viability of pre-commercial PSOFC technology at the County 911 Communications headquarters, as well as the input fuel flexibility of the PSOFC. PSOFC operation was demonstrated on natural gas and denatured ethanol.

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Executive Summary

The Santa Clara County Planar Solid Oxide Fuel Cell (PSOFC) project goals were to acquire, site, and demonstrate the technical viability of a pre-commercial PSOFC technology at the County 911 Communications headquarters. Additional goals included educating local permit approval authorities, and other governmental entities about PSOFC technology, existing fuel cell standards and specific code requirements.

The project demonstrated the Bloom Energy (BE) PSOFC technology in grid parallel mode, delivering a minimum 15 kW over 8760 operational hours. The PSOFC system demonstrated greater than 81% electricity availability and 41% electrical efficiency (LHV net AC), providing reliable, stable power to a critical, sensitive 911 communications system that serves geographical boundaries of the entire Santa Clara County.

The project also demonstrated input fuel flexibility. BE developed and demonstrated the capability to run its prototype PSOFC system on ethanol. BE designed the hardware necessary to deliver ethanol into its existing PSOFC system. Operational parameters were determined for running the system on ethanol, natural gas (NG), and a combination of both. Required modeling was performed to determine viable operational regimes and regimes where coking could occur.

Report Details: PSOFC Demonstration

EXPERIMENTAL METHODS

Planning stages for the PSOFC installation at Santa Clara's 911 Center began in 2007, and formal design and permitting process began in June 2007. During this phase BE and Santa Clara County's Facility and Fleet Department reached out to the authorities having jurisdiction to educate them about fuel cell technology, applicable codes, and the safety features designed into BE's systems. Site construction to prepare for system delivery began in 2008, following successful design review and permitting.

Figure 1A: Photo of construction in progress

The PSOFC system was installed, tested and commissioned in October, 2008. The system was operated and maintained from October 2008 through October 2009, the duration of the demonstration period. The system was monitored remotely and maintained onsite.

Figure 1B: Photo of final fuel cell installation

RESULTS AND DISCUSSIONS

The following represent results of the 12 month operation of the PSOFC at Santa Clara's 911 Center:

10/10/08 - 10/9/09		
Average AC Efficiency	41.9	%
Total Energy Output	160,877	kWhrs
Total Fuel Consumption	38,356,136	L
Peak AC Power	25.6	kW
Peak AC Eff	51.4	%
Hrs On-Site	8748	Hrs
Uptime	8556	Hrs
Load Hrs	8304	Hrs
Availability at 15.0kW+	81.1	%
Grid Faults	18	
System Faults	8	

Table 1: PSOFC Operating Statistics

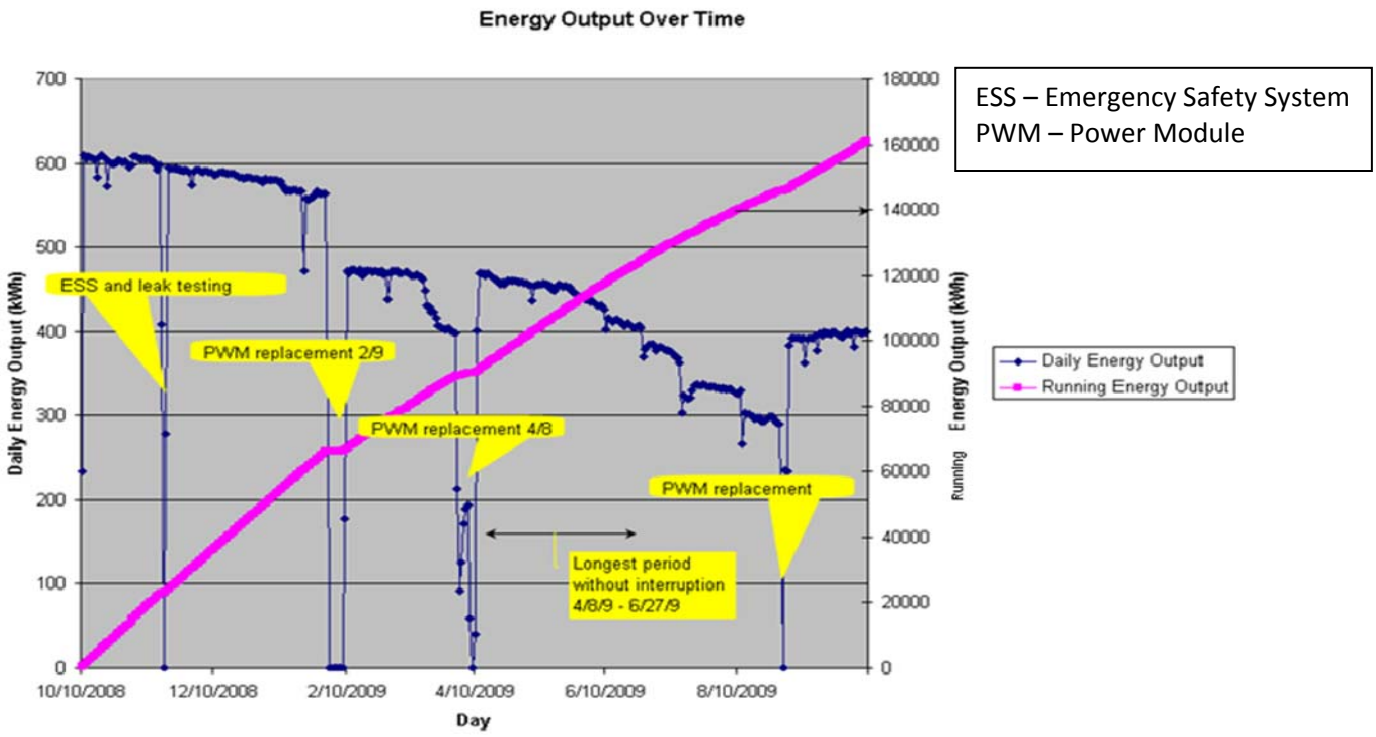

Figure 2: Graph of PSOFC Energy Output over Time

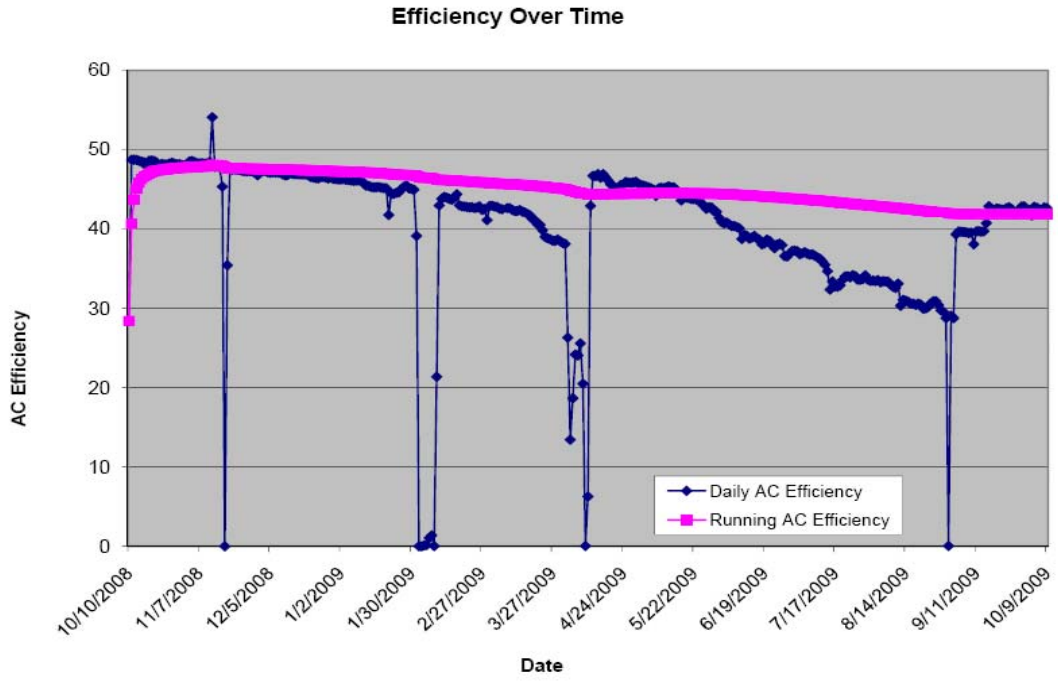

Figure 3: Graph of PSOFC Efficiency over Time

The following eight PSOFC system faults were noted and addressed:

- Three anode recycle blower failures, replaced
- Power module failure, replaced
- Two Catalytic Partial Oxidation (CPOx) air blower failures, replaced
- Gas solenoid valve failure, replaced
- Mass flow control valve failure, replaced

Santa Clara 911 Center facility personnel were trained, and good communication between facility personnel and BE Central Monitoring and Field Services teams allowed system faults to be addressed in a timely manner, facilitating the system to function at 81% capacity.

Mean Time Between Failure: Mean Time Between Failure (Point Estimate) was 2,040 hours MBTF for the system. The system level MTBF numbers improve in a full 4-PWM installation, due to modularity.

Cost Parameters

- Total Fuel Cell Plant Capacity: 25kW
- Total Fuel Cell Plant Cost: $2,055,000
- Fixed Operating Cost: Negligible (Internet connection)
- Variable Operating Costs: 77.87 mills/kWh
- Heat Rate: 8,725 Btu/kWh
- Local Area Average Electricity Price: 12.38 cents/kWh

Capacity Factor: 76%

Fuel Price: $9.00/MMBtu (million BTU)

Thermal Output: Not applicable

Site Parameters Prior to Installation:

Date of Usage		Total Site Electrical Usage (kWh)	Peak Site Electrical Usage (kW)
FROM	TO		
9/2/2008	10/1/2008	116,800	235
8/1/2008	9/2/2008	132,640	235
7/2/2008	8/1/2008	124,160	246
6/3/2008	7/2/2008	113,760	251
5/2/2008	6/3/2008	111,680	222
4/2/2008	5/2/2008	95,200	186
3/4/2008	4/2/2008	92,480	190
2/4/2008	3/4/2008	86,560	178
1/5/2008	2/4/2008	86,240	160
12/4/2007	1/5/2008	89,440	163
11/3/2007	12/4/2007	99,520	179
10/4/2007	11/3/2007	105,440	195

Table 2: Electrical Usage Prior to Installation

Note: Fuel usage data prior to installation is not available.

Site Parameters During Year of Operation:

Date of Usage		Total Site Electrical Usage (kWh)	Peak Site Electrical Usage (kW)
FROM	TO		
10/1/2009	10/21/2009	99,680	192
9/1/2009	10/1/2009	108,160	205
8/3/2009	9/1/2009	101,120	226
7/3/2009	8/3/2009	109,440	227
6/3/2009	7/3/2009	101,120	206
5/4/2009	6/3/2009	109,120	206
4/3/2009	5/4/2009	96,160	210
3/4/2009	4/3/2009	84,320	181
2/2/2009	3/4/2009	36,320	155
12/31/2008	2/2/2009	94,880	160
12/2/2008	12/31/2008	72,320	174
10/30/2008	12/2/2008	94,880	174
10/1/2008	10/30/2008	96,960	202

Table 3: Electrical Usage During Year of Operation

Date of Usage		Total Site Fuel Usage (MMBtu)
FROM	TO	
10/1/2009	10/30/2009	660
9/1/2009	10/1/2009	1,089
8/3/2009	9/1/2009	983
7/3/2009	8/3/2009	1,119
6/3/2009	7/3/2009	1,124
5/4/2009	6/3/2009	1,083
4/3/2009	5/4/2009	973
3/4/2009	4/3/2009	1,043
2/2/2009	3/4/2009	847
12/31/2008	2/2/2009	1,543
12/2/2008	12/31/2008	1,357
10/30/2008	12/2/2008	1,489
10/1/2008	10/30/2008	987

Table 4: Fuel Usage During Year of Operation

Date of Usage		Total Fuel Cell Electrical Output (kWh)	Total Fuel Cell Fuel Usage (MMBtu)
FROM	TO		
10/1/2009	10/30/2009	7,949	1,870,060
9/1/2009	10/1/2009	11,475	2,835,271
8/3/2009	9/1/2009	8,498	2,721,575
7/3/2009	8/3/2009	10,780	3,104,695
6/3/2009	7/3/2009	12,263	3,166,688
5/4/2009	6/3/2009	13,495	3,071,300
4/3/2009	5/4/2009	11,434	2,770,968
3/4/2009	4/3/2009	12,941	3,184,402
2/2/2009	3/4/2009	10,365	2,557,132
12/31/2008	2/2/2009	18,733	4,118,264
12/2/2008	12/31/2008	17,020	3,627,559
10/30/2008	12/2/2008	18,633	3,914,660
10/1/2008	10/30/2008	11,669	2,537,659

Table 5: Fuel Cell System Output/Usage During Year of Operation

CONCLUSION

The PSOFC demonstration highlighted the importance of communication through the course of the design, permitting, construction and system operation phases. Permitting of the new technology requires outreach and coordinated training of authorities having jurisdiction. Also critical to success was outreach and training with facility personnel. Communication during the demonstration process was important to ensure access for timely repair and replacement of parts causing system failures.

In conclusion, the PSOFC system demonstration was a valuable effort for the Federal, County and commercial partnership, proving technical viability of PSOFCs, and valuable lessons for the installation process.

Report Details: PSOFC Operation on Denatured Ethanol

EXPERIMENTAL METHODS

The objective for the task is the operation of a PSOFC system on denatured ethanol. The standard Bloom Energy system was designed primarily for operation on natural gas and serves as a baseline platform for operation on ethanol. In preparation for operation, several adaptations to the system design were required.

Fuel

Due to the complications in obtaining pure ethyl alcohol, a denatured mix of 90% ethanol, 5% methanol, and 5% isopropyl alcohol was used. The chemical properties are shown in Appendix 1.

Subsystem Design

The addition of liquid fuel requires various design changes prior to beginning any system testing. Primary concerns include coking tendencies and control algorithms to handle fuel transitions. Extensive modeling work optimized the conceptual design and primary operating parameters in preparation for system testing.

System P&ID

The Piping and Instrumentation Diagram (P&ID) offers a detailed look at the fuel delivery system design. Abbreviations of the P&ID tags are described in Table 6.

GPR – Gas Pressure Regulator
FFM – Fuel Flow Meter
FLT – Filter
NRV – Non Return Valve
NTC – N Type Thermocouple
MBV – Manual Ball Valve
MNV – Manual Needle Valve
PMP – Pump
PSW – Pressure Switch
QDC – Quick Disconnect
REG – Pressure Regulator
TCO – Thermal Cutout
WFM – Liquid Flow Meter
WSV – Solenoid Valve

Table 6: P&ID Tags

Liquid Fuel Delivery

The foundation of the liquid fuel delivery system is based on the current water system, which has been proven to work reliably during system operation. The major components of the system include the variable speed pump, which regulates flow, and the flow meter for control system feedback. The P&ID for the water system is shown below in Figure 4 in conjunction with the ethanol delivery system. Both the water and ethanol mix prior to entering the hotbox through the water inlet where it flows through some heat exchangers to create a fuel-steam mixture. This fuel-steam mixture is then flowed into the anode inlet where it is used as fuel.

From previous experience with corrosive fuels, the fuel filter FLT521 (analogous to FLT501 on the water line) was removed from the design to prevent the filter media from travelling down and damaging the down stream fuel cell. Very little risk was posed with the removal of this filter as the filter is redundant to the filters that provide de-ionized water to the system.

An additional check valve, NRV-522 was added to the system to prevent any back flow of water into the ethanol delivery system from the water's higher pressure. TCO-521 was added due to the flammable nature of ethanol, shutting down the entire PSOFC system if the TCO senses 230°C.

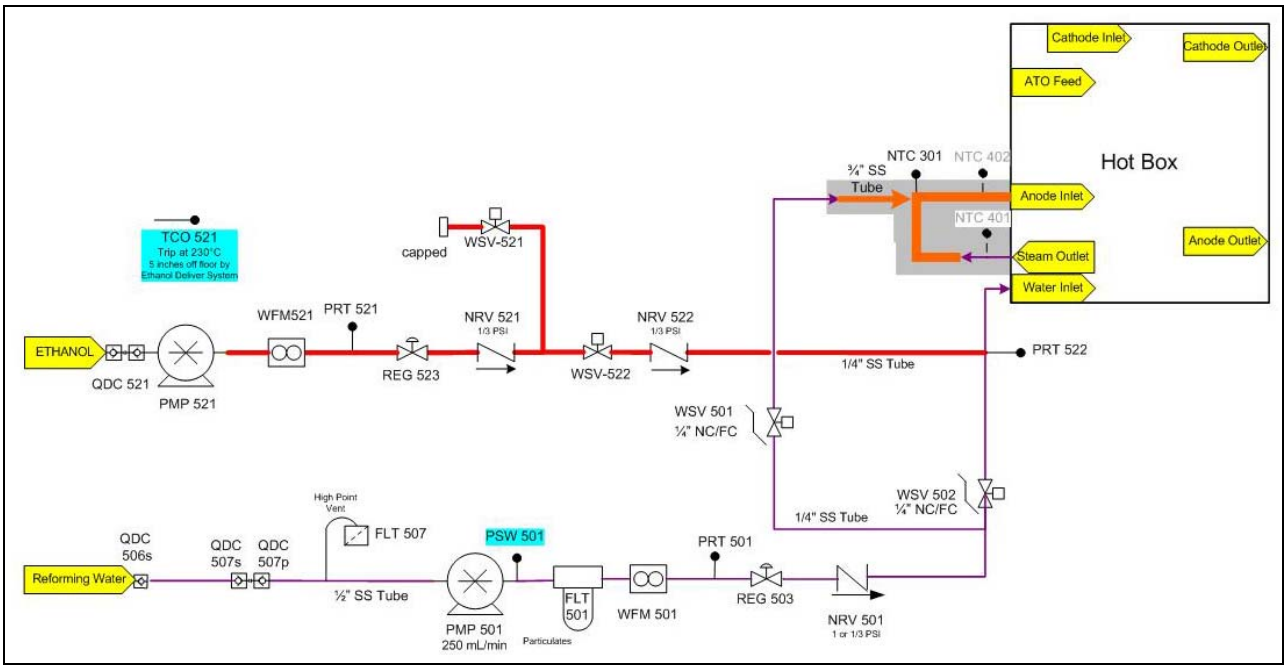

Figure 4: HB_B P&ID Diagram

Fuel Supply

Previous testing with other types of liquid fuels using the existing water system exposed priming issues which needed to be addressed before operation. This was accomplished by designing a pressurized fuel supply which allows uninterrupted fuel feed from storage drums to the PSOFC system at constant pressure and without introducing air into the lines. The upstream fuel delivery infrastructure was built as shown below in Figure 5. Permits for storage and double wall plumbing had to be obtained from the City of Sunnyvale to set up the infrastructure.

Given the flow rates at full rated power, each drum requires refill at 36 hour intervals. The procedure followed for this refill can be seen in Appendix 3. This procedure was tested and proved effective prior to startup. No loss of prime was experienced by the pump during the test and steady fuel flow rates were achieved.

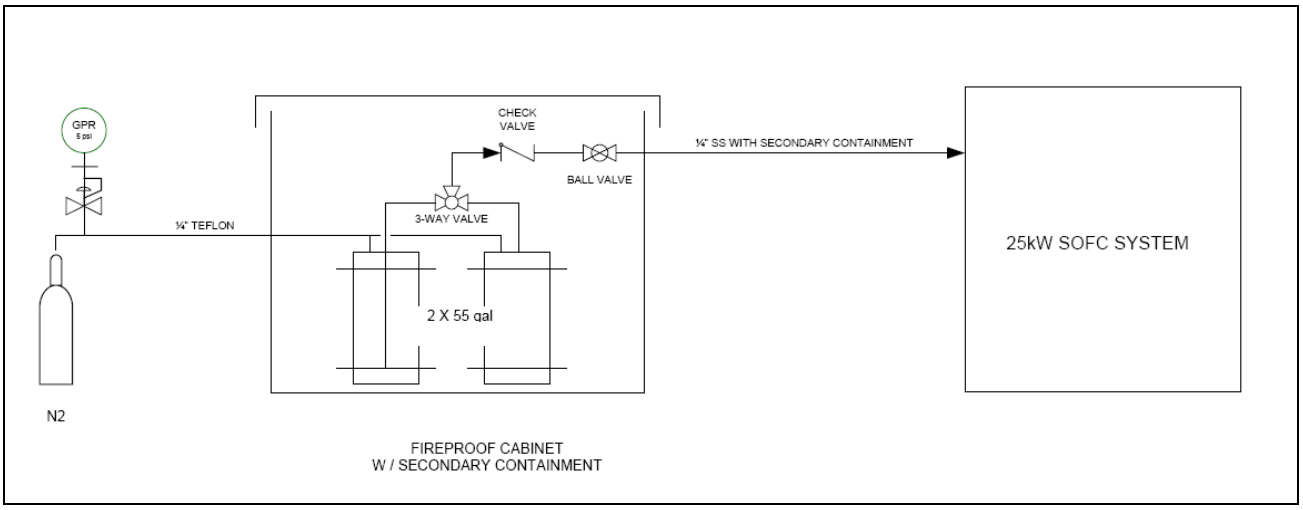

Figure 5: Liquid Fuel Delivery Infrastructure

Reforming Reaction Stoichiometry

Natural gas (Methane)	$CH_4 + H_2O$	<->	$CO + 3H_2$
Ethanol	$C_2H_5OH + H_2O$	<->	$2\ CO + 4H_2$
Methanol	CH_3OH	<->	$CO + 2H_2$
Isopropyl Alcohol	$C_3H_7OH + 2\ H_2O$	<->	$3CO + 5H_2$

PSOFC cells utilize CO and H_2 in the electrochemical reaction to produce CO_2 and H_2O. The calculations below are assuming 25kW DC system operation at 80% fuel utilization and S:C of 3.0. Water flow has to be higher when operating on ethanol as compared to natural gas due to the higher carbon content of the fuel, and the variability of both the water and ethanol flow.

Methane atomic weight	16.043	g/mol
Methane Density (gas)	0.68	g/L
H2 flow equivalent	311.425	slpm
H2 flow equivalent	13.894	mol/min
CH4 flow	3.474	mol/min
CH4 flow (gas)	**77.856**	**slpm**
CH4: Water flow required (liquid)	**187.780**	**ml/min**

Table 7: Methane and water requirements for 25kW at 80% fuel utilization

Ethanol atomic weight	46.08	g/mol
Ethanol density (liquid)	789.3	g/L
Methanol atomic weight	32.05	g/mol
Methanol density (liquid)	791.8	g/L
Isopropyl alcohol atomic weight	60.1	g/mol
Isopropyl alcohol density (liquid)	780	g/L
H2 flow equivalent	315.914	slpm
H2 flow equivalent	14.094	mol/min
Ethanol flow	2.114	mol/min
Methanol flow	0.235	mol/min
Isopropyl alcohol flow	0.078	mol/min
Denatured ethanol flow	2.427	mol/min
Denatured ethanol flow (liquid)	**141.772**	**ml/min**
Denatured ethanol: Water flow required (liquid)	**172.426**	**ml/min**

Table 8: Denatured ethanol and water requirements for 25kW at 80% fuel utilization

Thermodynamic CO Decomposition Modeling

Coke formation during fuel cell operation is highly undesirable. The thermodynamic potential to form coke at chemical equilibrium is a function of atomic composition (%C, %H, %O) and temperature. Experience in the industry indicates that coke has the potential to form in piping, heat exchangers, reformers, or stacks.

Bloom Energy has a history of being able to operate its fuel cell systems with natural gas without evidence of coking. Due to the lower intrinsic H:C ratio in ethanol relative to natural gas, the potential for coking is increased. For this reason, simulations were developed to quantify the conditions under which coke formation is thermodynamically feasible at chemical equilibrium.

Fuel	H:C ratio
Methane	4
Ethanol	3
Propane	2.667

Thermodynamic coking potential of methane under steam reforming conditions is well known. Figure 6 shows simulation results for the fractional thermodynamic conversion of methane to coke as a function of temperature at various steam:carbon ratios. Simulation calculations show excellent agreement with published literature. Figure 7 shows simulation results for the fractional thermodynamic conversion of ethanol to coke as a function of temperature at various steam:carbon ratios. Thermodynamics dictates that ethanol can be reformed at a lower steam:carbon ratio than methane to avoid coking.

Fuel	Minimum S:C ratio to avoid thermodynamic coke formation (no anode recycle)
Methane	1.5
Ethanol	1.4

Note that thermodynamic conversion to coke does not mean that coke will necessarily form in real life; it is only an indication that coke formation is thermodynamically possible at chemical equilibrium. Whether or not coke forms in real life depends on the kinetics of coke formation, which is not well understood.

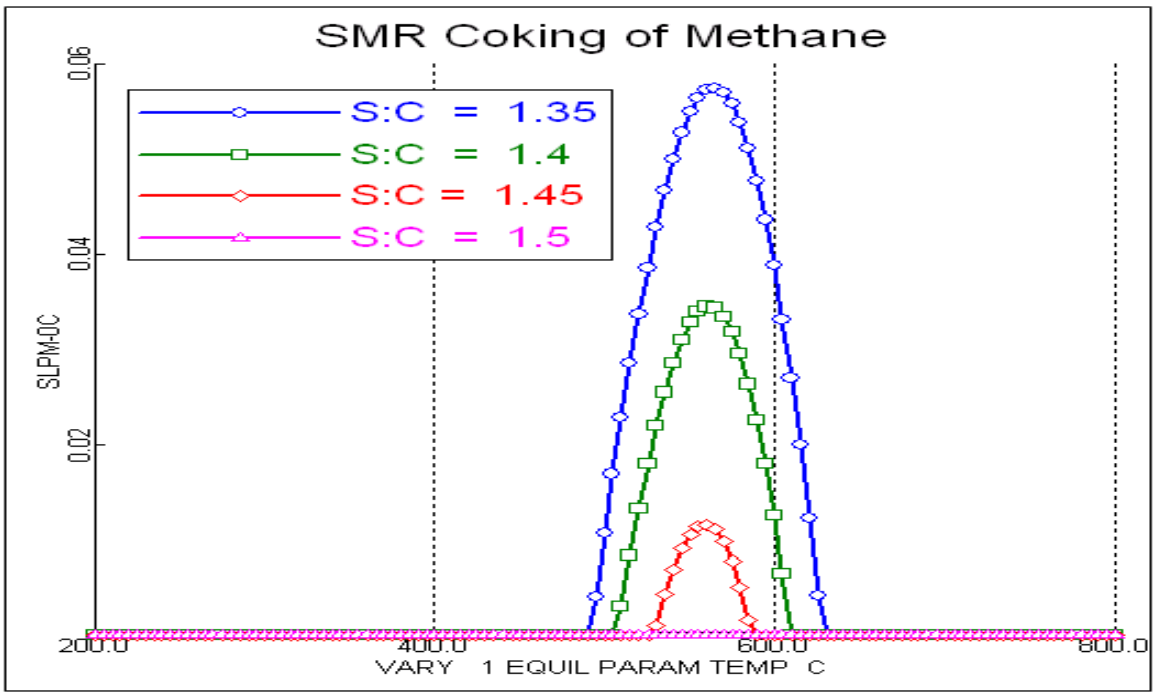

Figure 6: Thermodynamic conversion of methane to coke under single pass steam reforming conditions

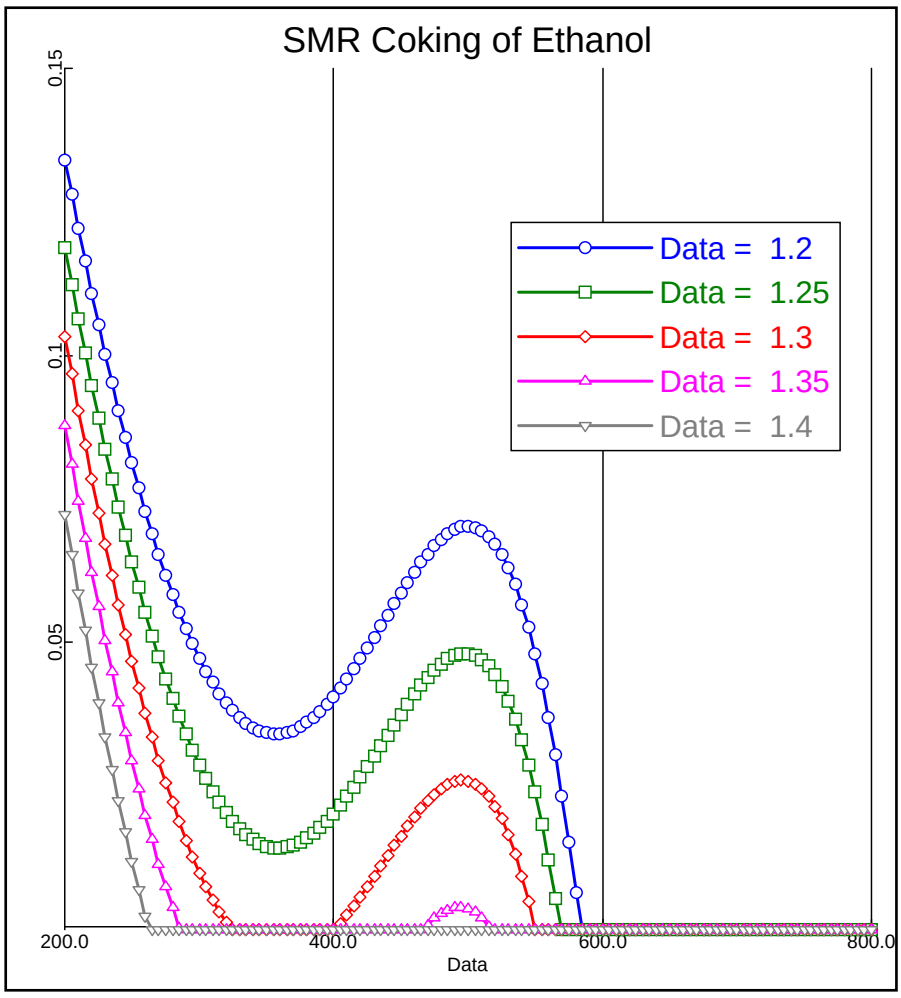

Figure 7: Thermodynamic conversion of ethanol to coke under single pass steam reforming conditions

Solid oxide fuel cells do not operate at 100 % fuel utilization. Therefore, the anode exhaust stream contains unreacted fuel (H2, CO, CH4) in addition to the byproducts of stack operation (H2O, CO2). As indicated in Figure 7, Bloom Energy segregates a portion of the anode exhaust and recycles it to mix with fresh fuel and water.

Anode recycle offers the following conceptual advantages:

- Raises fuel utilization
- Lowers fresh fuel requirement
- Raises process efficiency
- Provides a portion of the water required to prevent coking

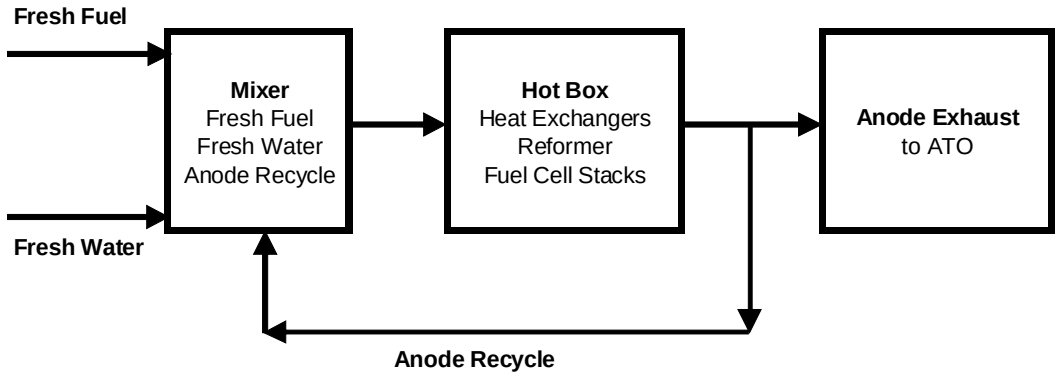

Figure 8: Schematic of Bloom Energy Fuel Cell System

Evaluation of the thermodynamic tendency to form coke in Bloom Energy fuel cell systems is not as straight forward due to the presence of anode recycle. The amount of fresh water required to stay out of the region where coking is thermodynamically possible depends on the fuel utilization and the percentage of anode exhaust recycled. Since the anode recycle stream contains CO and CO2, the concept of a steam to carbon ratio is potentially ambiguous.

For this analysis, steam to carbon ratios have been defined as follows:

$$\text{S:C from fresh water} = \frac{\text{Molar flow rate of Fresh Water}}{\text{Molar flow rate of carbon atoms in the Fresh Fuel}}$$

$$\text{S:C from anode recycle} = \frac{\text{Molar flow rate of Water in the anode recycle stream}}{\text{Molar flow rate of carbon atoms in the Fresh Fuel}}$$

S:C Final = S:C from fresh water + S:C from anode recycle

Potential modes of system operation have been characterized by:

- Fuel (natural gas, propane or ethanol)
- Overall Fuel Utilization (65 % or 85 %)
- S:C ratio from anode recycle (1.7, 2.0, 2.25, or 2.5)
- S:C ratio Final (2.5, 3.0 or 3.5)

Due to the presence of CO in the anode recycle stream, all simulations indicate that coke formation is thermodynamically possible at low temperatures. For each case, there is an upper temperature, above which coke formation is not thermodynamically feasible at equilibrium.

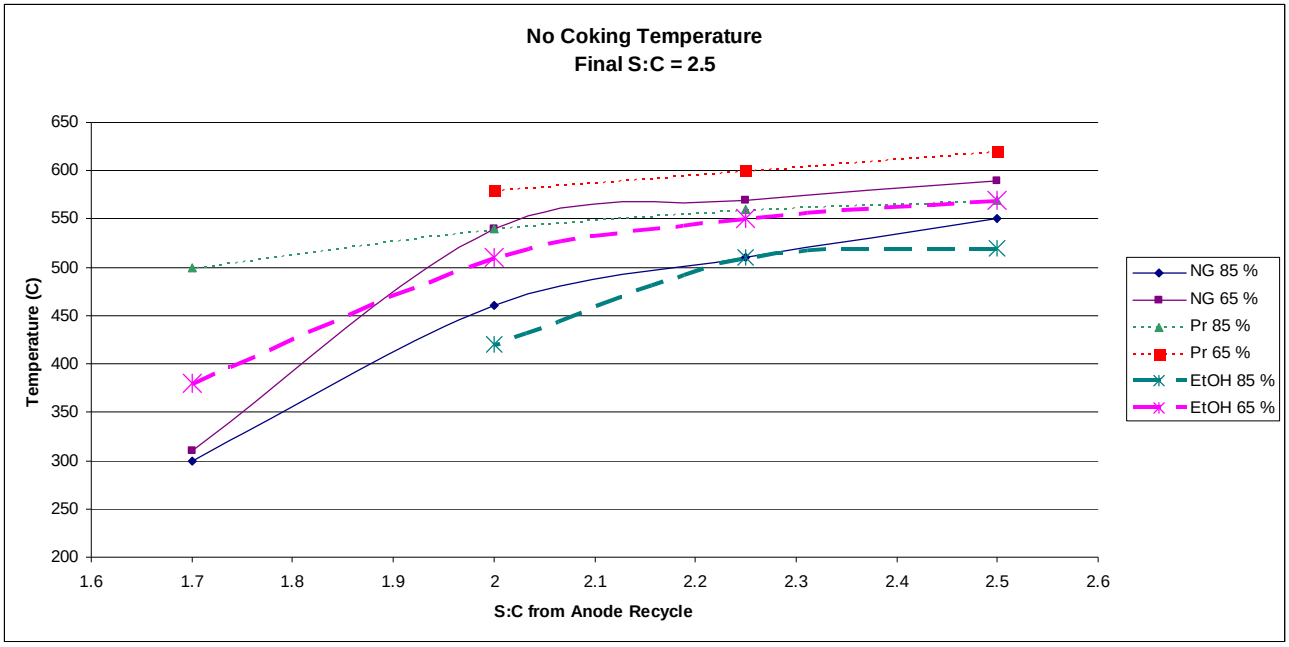

Figure 9: Temperature Required to Avoid Thermodynamic Potential of forming Coke - Final S:C = 2.5

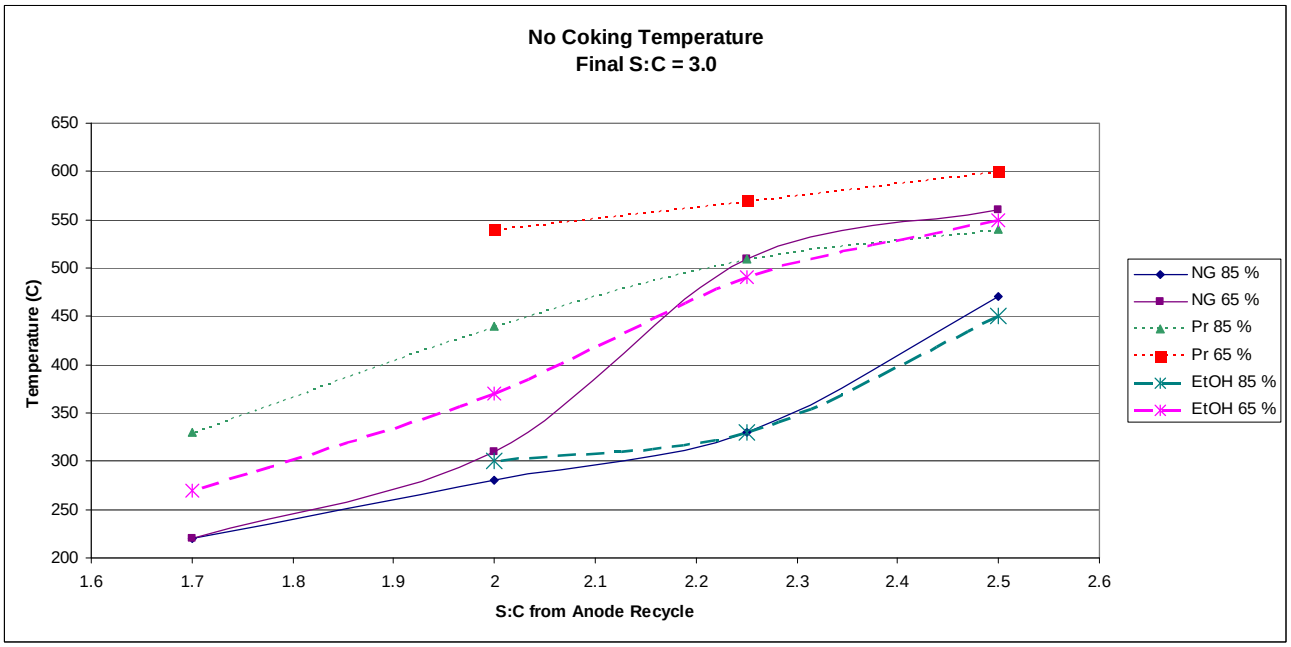

Figure 10: Temperature Required to Avoid Thermodynamic Potential of forming Coke - Final S:C = 8.0

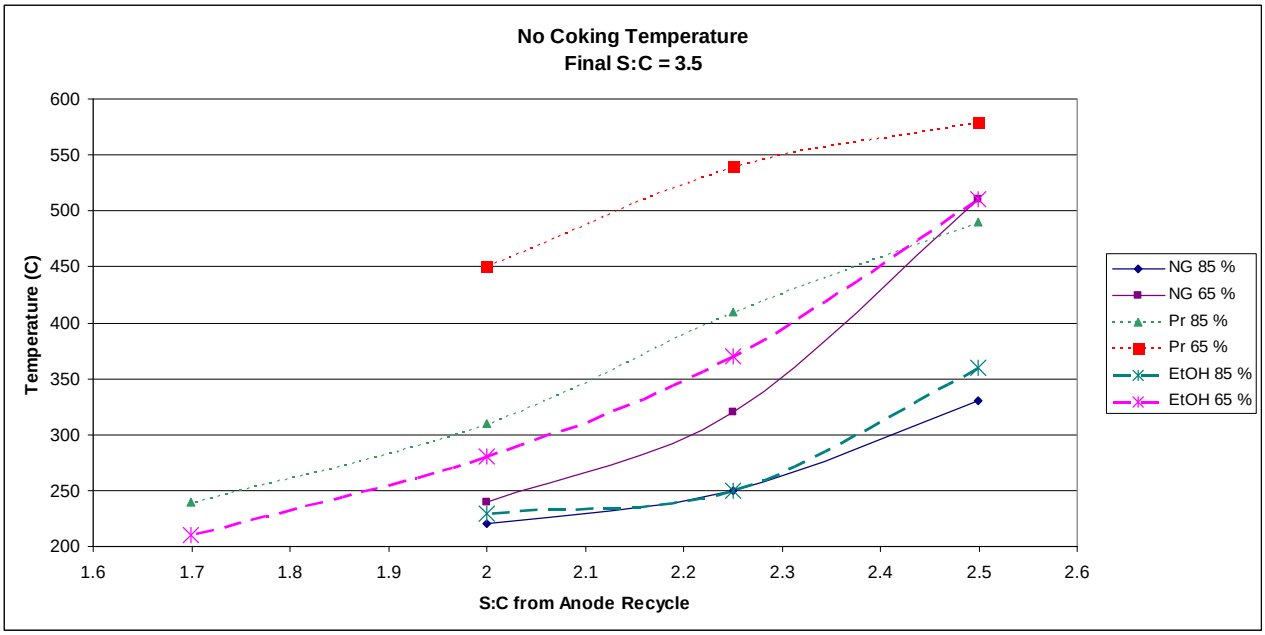

Figure 11: Temperature Required to Avoid Thermodynamic Potential of forming Coke - Final S:C = 3.5

The plots above (Figures 9-11) indicate that the coking potential of ethanol is similar to natural gas and significantly less than propane. For a fixed final S:C ratio, decreasing the S:C ratio from anode recycle decreases the coking potential. For fixed fuel and S:C ratios, raising the overall fuel utilization decreases the coking potential.

Modeling results seem to suggest that to avoid coking, it may be possible to run at similar S:C ratio as with natural gas. However, in a practical sense, the ability to run at a lower S:C will ultimately depend on the stability and quality of the fuel delivery system, including the interaction of the ethanol fuel system and water system. Given the noise in the fuel flow delivery system and the noise in the water delivery system, it was decided to run the system at a conservative S:C ratio value of 3.0.

RESULTS AND DISCUSSIONS

Subsystem Testing

Liquid Fuel Delivery System

The liquid fuel delivery system, shown in Figure 4 above, was completed in June 09 and underwent fuel compatibility testing for approximately 1 week. This testing included verifying the accuracy of the denatured ethanol volume pumped and ensuring that the response time was adequate for system performance. Volume was verified by both weight and graduated cylinder to ensure that the pump's performance was satisfactory despite the lower density of the ethanol compared water. The response times during the initial testing showed satisfactory results (less than 2 seconds to achieve setpoint) when compared to the existing water system.

System Fuel Transition

The transition of NG to ethanol required various controls changes to ensure system stability. The following modifications were incorporated into the controls logic to handle fuel transitions.
Flow control for ethanol with ramp function

- Ability to automatically open/close WSV521
  - Open when WFM521 SP > 0 or PMP521 SP > 0
  - Closed when WFM521 SP = 0 and PMP521 SP = 0
- Modify fuel utilization control to work on the sum of NG flow + ethanol flow
- Modify fuel utilization control to specify which fuel is the swing fuel.
- Modify the anode recycle composition estimate to be based on operating calculations.
- S:C calculation takes the maximum value of PMP521_SP and WFM521
- Fuel Utilization calculation takes the minimum value of PMP521_SP and WFM521

The following alarms were added to monitor the liquid fuel flow.

- Ethanol flow deviation from SP
- Ethanol pump failure
  - Included a corrective action to emergency transition to NG
- Very low Steam Temp Alarm – if NTC301 or 401 drop below 90, begin emergency transition to NG.

System Testing

System testing was performed on HB_B, a BE owned hotbox. BOP modifications consisted of a liquid fuel delivery system feeding the standard steam generator. The BE owned hotbox was exactly similar to the hotbox operated at the Santa Clara site to include:

- 100% Same stack enclosure (including stacks, fuel reformer, heat exchangers, catalytic reactors, insulation package, etc)
- 100% Same balance of plant components (including blowers, valves, flow controllers, fans, controller cards, etc)
- Same power conversion (including DC/DC converters, inverter, central control unit, etc)

- Ethanol system had additional ethanol delivery system that site did not. Ethanol delivery system consisted of standard water delivery system with inlet filter removed because of media compatibility concerns

Pre-ethanol Baseline

The hotbox, HB_B, was initially heated and conditioned with natural gas to establish a baseline performance evaluation. The system was held 11.85 AC kW for 1000 hours to ensure system stability. At this power level, the anode tailgas oxidizer (ATO) still required a small amount fuel to sustain the heat of the stacks. Natural gas, and not ethanol was used as this fuel.

Fuel Transition Procedure

The controls code was setup to facilitate the following procedure to transition from natural gas to ethanol:

- **Normal Stop** the system.
- Turn on **Ethanol Fuel** flag
- Click **Start** to perform a Hot Restart
- Hot Restart will be the same as a NG system up until SS8.3 (NG fuel delivery to the stacks via CPOx reactor, and NG fuel delivery to the ATO, prior to loading the stacks)
- In SS8.3/Temp range 4; the CPOx will turn off. Wait for operator intervention to proceed.
- To start ethanol, click on **Start Ethanol Fuel**. This will not begin until Cpox turns off
    - WSV-522 will open.
    - Ethanol pump SP will be set to 20ml/min
- SS9.1 (stack stabilization at temperature) will continue after a 5min timer completes for the ethanol pump to stabilize.
- SS10 will draw power up to 5A and turn on the inverter as usual.
- Turn off NG will be done manually by clicking on **Stop NG** after drawing BOP load.
- Ramp up to rated power.

For transition from ethanol to NG, the following occurs:

- Emergency transition from ethanol to NG
    - Drop load to BOP only.
    - Set NG as the swing fuel
    - Ignore ethanol flow rate in fuel utilization calculation
    - Ramp PMP521 speed to zero in 30 seconds
    - Turn off ethanol flow rate in fuel utilization calculations
    - Close WSV521
    - Turn off Alarm added to trigger if NTC301 drops below 210C.

Validation Testing

HB_B was first transitioned to ethanol on 22 Sept 2009. During the initial system run, two items of concern arose: 1) Extreme oscillations with the fuel delivery system and 2) Difficulty maintaining the

anode inlet temperatures above dew point. The extreme oscillations are illustrated in Figure 12 with a constant 35 mL/min setpoint. At one moment, flow momentarily reached 70 mL/min, a 100% error in flow. The oscillations would eventually result in the pump seizing and required venting the inlet of the pump to restore function.

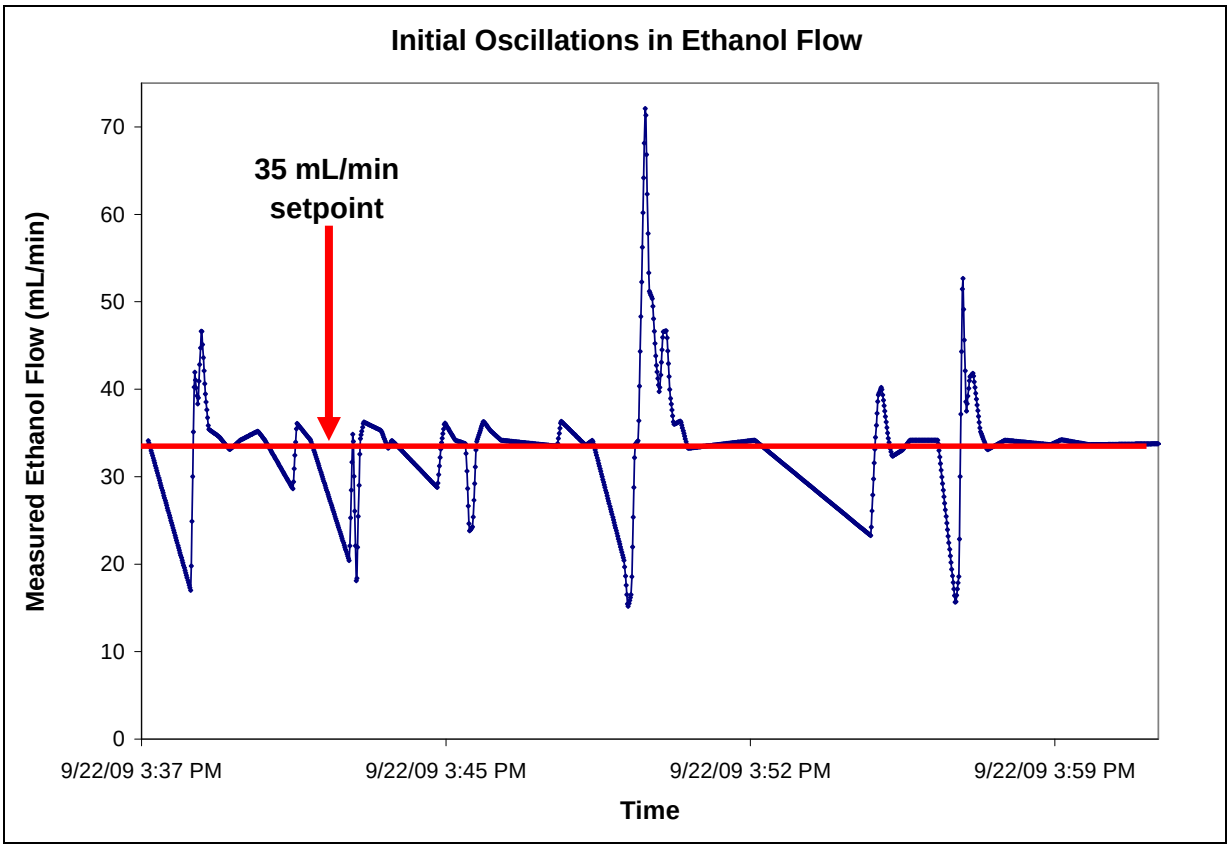

Figure 12: Oscillations in ethanol flow of up to 100% error

There were several factors affecting the oscillations. A period of lengthy investigation was required to determine the various factors.

The first factor addressed was cavitation in the pump. The pump, originally for water, was never adapted for ethanol. Micropump, the manufacturer for the pump, verified that they have experienced cavitation when attempting to pump lower density fluids such ethanol with pumps designed for water. This cavitation could either be from the transition of liquid ethanol to a gas at the edges of the gears in the pump or promoting the dissolution of dissolved air in the ethanol. The manufacturer suggested increasing the fuel pressure to mitigate the issue. The pressure was subsequently increased from 2.5 psig to 6 psig. This increased the endurance of the pump at lower flow rates up to 45 mL/min, however, at greater flow rates, the pump would still seize and require venting of the inlet to continue.

To investigate the issue further, clear tube was attached to outlet of the pump and the flow was monitored during operation. Air was discovered while observing the clear tubes. The quantity of air

would increase as the flow setpoint of the pump was increased. A leak of air was suspected in the ethanol delivery system. As the ethanol delivery system was being removed, deterioration of the Teflon tape used to seal the threads throughout the system was discovered. An improper grade of Teflon tape was left in place when adapting the water system for ethanol. Although designed to the same standard, Industrial grade Teflon tape was used to replace all the inferior grade tape. The industrial grade tape is thicker and is advertised to perform in corrosive environments.

Figure 13 below illustrates the fall of inlet fuel temperature over night. As liquid fuel, the desire was to maintain the hot steam and ethanol mixture between the heat exchangers for the fuel inlet. The system was programmed with an alarm to automatically switch back to natural gas if the ethanol/water feed temperature dropped below 110 C. The limit was set to 110 C to provide margin above the dew point of the mixture.

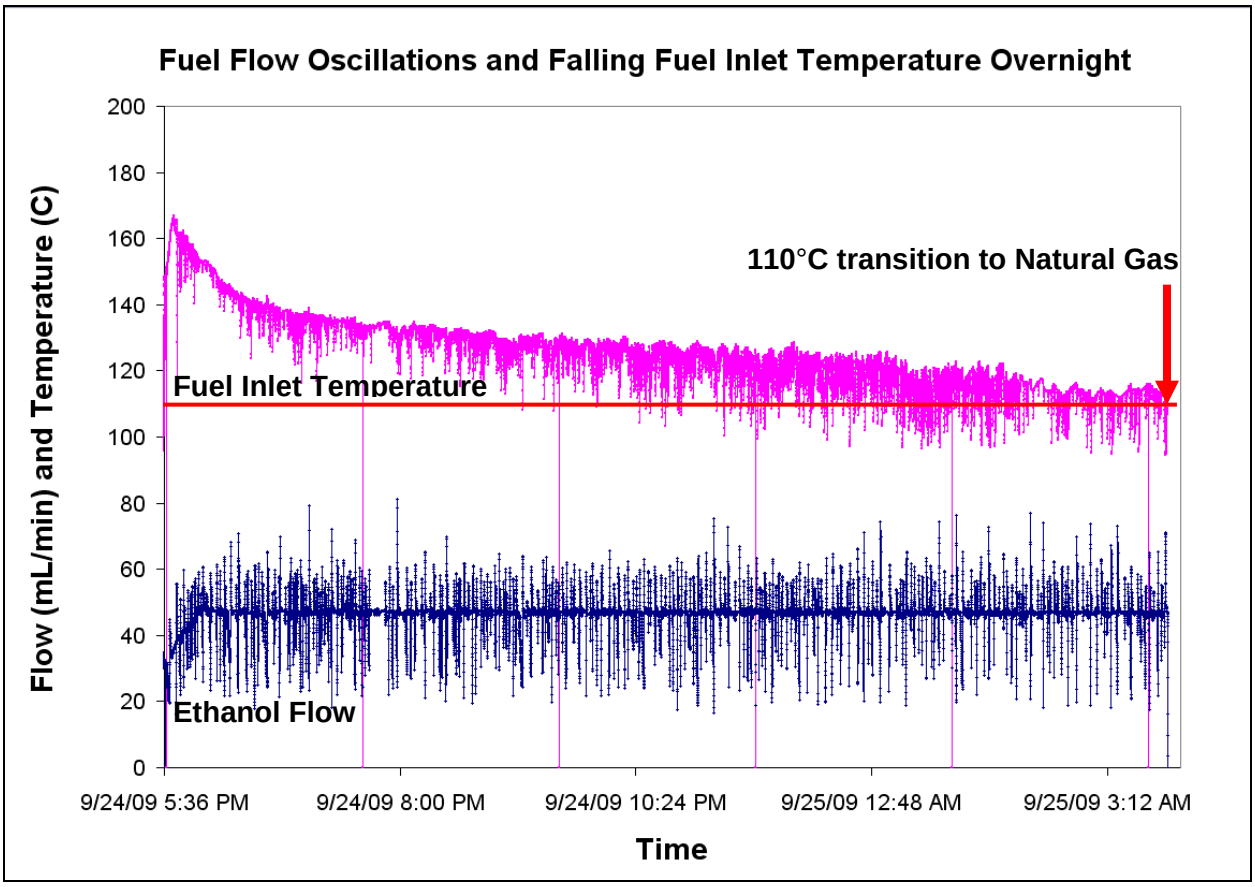

Figure 13: Fuel inlet temperature falling below the original 110°C limit forcing transition back to natural gas

When the system reverted to natural gas, the system was held at the same current, and the S:C ratio was automatically decreased to 2.25. During this time, cell voltages increased by approximately 9 %. The higher voltages on natural gas is expected, as the total concentration of reformed fuel seen by the cells is significantly higher on natural gas at a S:C ratio of 2.25, compared to Ethanol at a S:C ratio of 3.0. As the ethanol molecule contains an oxygen atom, the carbon and hydrogen in the ethanol molecule are already partially oxidized.

The first action taken to prevent the system transitioning back to natural gas was to lower the transition limit to 90°C. However, temperatures continued to fall below the new limit, therefore 2 new actions were taken: 1) Minimum fuel utilization was raised to 70% from 66% and the maximum fuel utilization was raised from 80% to 81%. Higher fuel utilizations translate to less fuel flow, which lowered the amount of fuel and water that needed to be vaporized, thereby decreasing the amount of heat required for vaporization.

These changes allowed the commencement of a 100 hour endurance test. A summary of the endurance test is below.

Elapsed time	Ethanol Fuel	ATO Fuel (NG)	Power Produced	Overall Efficiency
105.67 hours	515.66 L	31629.85 L	1094.30 kW-hr	32.72 %

Table 9: Summary of 100 hour endurance test

Efficiency is calculated through the following equation:

$$\eta_{\underline{AC}} = \frac{\left[AC\ PowerOutpu\quad t\right]}{(F_{ATO} * LHV_{CH\ 4}) + (F_{Ethanol} * LHV_{Ethanol})}$$

where,

$ACPowerOutput$ is the actual AC power out transmitted to the grid.

F_{ATO} is the ATO fuel flow. This fuel flow is measured by a mass flow meter.

$F_{Ethanol}$ is the Ethanol fuel flow. This fuel flow is measured by the Ethanol flow meter.

LHV_{CH4} is the heating value of natural gas, which is derived from Pacific Gas and Electric. That value is 0.600 kw/slm.

$LHV_{Ethanol}$ is the heating value of the denatured ethanol, a constant with the value of 0.3525 kW-min/ml.

The 100 hour test was only limited by the fuel remaining in stock. Both fuel flows and power remained relatively stable throughout the run as shown in Figure 14 below.

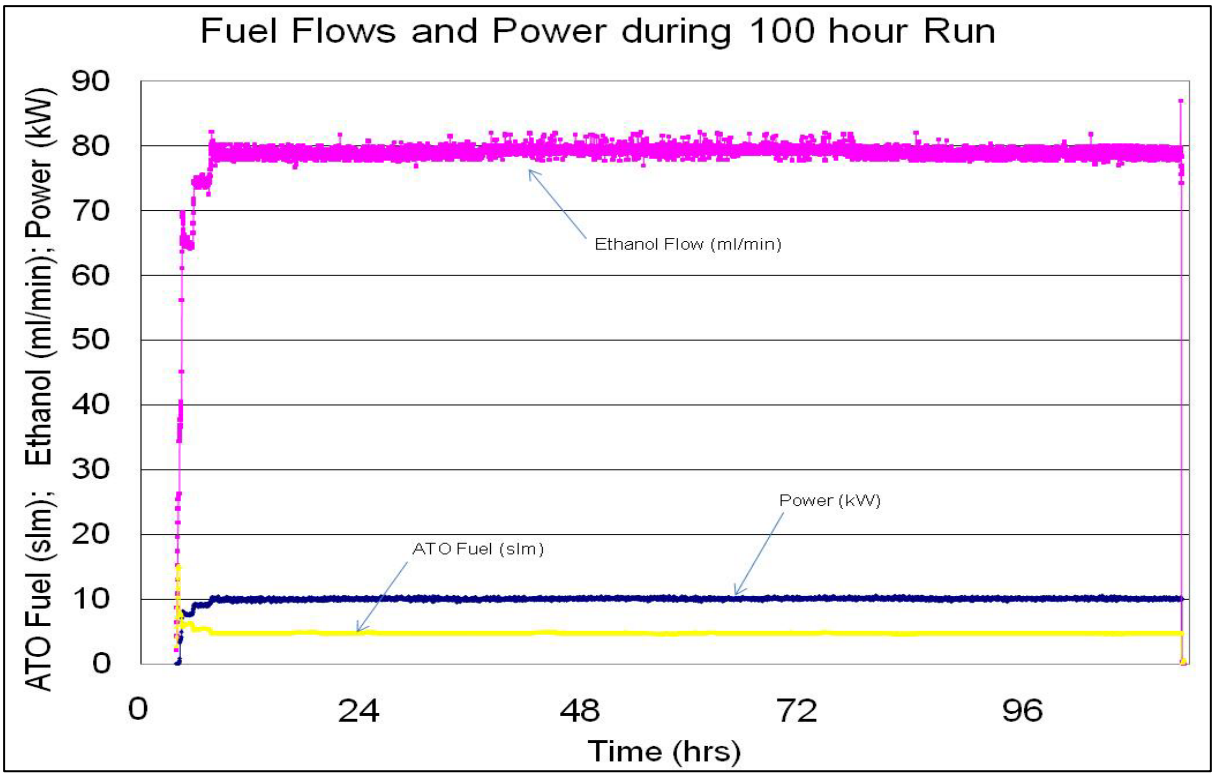

Figure 14: Steady fuel flows and power during 100 hour run

CONCLUSION

Successful operation of a PSOFC system was achieved using denatured ethanol as the primary fuel. Extensive modeling work identified coking tendencies and defined the necessary operating parameters for successful system operation. The standard reformation catalyst used in the system was validated on ethanol, with operating parameters defined by the coking model.

The liquid fuel delivery system was designed and demonstrated on the standard PSOFC system. Removal of a redundant fuel filter and use of industrial tape was required to prevent air from entering the fuel lines. The controls logic received several modifications to handle the delicate fuel transitions along with the new alarm indications.

The PSOFC system proved to operate successfully on ethanol, remaining stable throughout the initial 10 kW holding period. Operation at higher power was not feasible, due to the insufficient heat transfer in the heat exchanger used to vaporize the ethanol/water mixture. Cell voltages indicated that the cells could have run at significantly higher power operation on Ethanol. The heat exchange network employed was adapted from the equipment designed for operation on natural gas. The shortcomings of the existing fuel/water vaporizer could certainly be addressed if the system was fundamentally redesigned for full time operation on ethanol.

This project provided an invaluable platform to develop Balance of Plant components required for operation on liquid fuel. Significant operational lessons were obtained and incorporated into control logic for future power production using PSOFC technology.

Graphic Materials List

LIST OF ACRONYMS & ABBREVIATIONS

ATO - Anode Tailgas Oxidizer
BOP – Balance of Power/Plant
CPOx – Catalytic Partial Oxidation
ESS – Emergency Safety System
FFM – Fuel Flow Meter
FLT – Filter
GPR – Gas Pressure Regulator
IPA – Isopropyl Alcohol
MBV – Manual Ball Valve
MNV – Manual Needle Valve
MTBF – Mean Time Between Failure
NG – Natural Gas
NRV – Non Return Valve
NTC – N Type Thermocouple
P&ID – Piping and Instrumentation Diagram
PMP – Pump
PSW – Pressure Switch
PWM – Power Module
QDC – Quick Disconnect
REG – Pressure Regulator
S:C – Steam to Carbon Ratio
TCO – Thermal Cutout
WFM – Liquid Flow Meter
WSV – Solenoid Valve

Appendix 1: Denatured Ethanol Properties

THE POWER OF THREE[3]
PHARMCO-AAPER
AND COMMERCIAL ALCOHOLS

PRODUCT SPECIFICATION SHEET
REAGENT ALCOHOL / 200 PROOF (ANHYDROUS)
ACS GRADE
(ETHANOL DENATURED WITH METHANOL AND ISOPROPANOL)

Main Catalog #: 241000200 Alt. Catalog #: 241ACS200, R200-Size Code*

Available in the following sizes:

*Refer to the Master Price List – Individual package sizes have unique size codes

Test	Specification	Typical Result
Assay (by GC) (v/v)	89.5 – 91.5% Ethanol 4.0 – 5.0% Methanol 4.5 – 5.5% IPA	90.65% Ethanol 4.53 Methanol 4.82% IPA
Assay: Methanol and Ethyl Alcohol (SDA 3A 200 proof) (v/v) Isopropyl Alcohol (2-Propanol) (v/v)	 94.0 – 96.0% 4.0 – 6.0%	 95.18 % 4.82 %
Water, max	0.2%	0.05%
Residue After Evaporation, max	10ppm	<10ppm
Appearance	Clear	Clear
Specific Gravity	0.7902 - 0.7912 @ 20C	0.7906
Color, Pt-Co	10 max	< 10
Odor	Pass	Pass
Titrable Acid	0.0003meq/g	0.0001meq/g
Titrable Base	0.00021meq/g	0.00005meq/g
Fluorescent Background	Pass	Pass
Identification	Pass	Pass
Substances Reducing $KMnO_4$	Pass	Pass
Solubility In Water	Pass	Pass
Refractive Index @ 25C	1.3580-1.3510	Pass

Form: Reagent Alcohol, 200, #201, Rev. 4.6, 6/08, SAK

Disclaimer: For Industrial, Pharmaceutical, Flavor & Fragrance or Lab Use. Not intended for use as an active substance in Food or Drug. Not to be considered a Medical Device. Not intended for use as a Disinfectant as defined by the EPA. The appropriate use of this product is the sole responsibility of the user. (Rev. # disclaimer only, rev 3.3 10/05/05 PD

An ISO 9001:2000 Certified Company

Pharmco Products Inc. 58 Vale Road, Brookfield, CT 06804 1-800-243-5360 www.pharmco-prod.com
Aaper Alcohol & Chemical Co., Inc. 1101 Isaac Shelby Drive, Shelbyville, KY 40065 1-800-456-1017 www.aaper.com

Appendix 2: Ethanol Refill Procedure

Ethanol Fill Procedure:

1. Bring a full barrel from the fuel storage area using the barrel truck.
2. Remove the ¾" polymer cap from the fresh barrel and install the fuel fill assembly provided in the fuel cabinet.
3. Note the current tank on service, and open the air pressurizing valve for the off service tank.
4. Shift the service tank selector valve to the off service tank placing it on service.
5. Close the air pressurizing valve on the off service tank, and connect the vent hose relieving the barrel pressure.
6. Place the other end of the vent hose into the fuel catch container provided.
7. Connect the fuel fill hose to the off service barrel.
8. Connect the Air pressure hose to the fill barrel and open the pressurizing valve.
9. Fill the off service barrel until fuel issues from the vent hose.
10. Disconnect the vent hose from the off service barrel.
11. Shut the Air pressurizing valve and disconnect the air pressure hose from the fill barrel.
12. Disconnect the fuel fill hose and remove the fill assembly from the fill barrel wiping up any residual Ethanol.
13. Re-install the polymer cap on the fill barrel and take it back to fuel storage.
14. This completes the re-fueling procedure