Final Technical Report

Project Title: Intergovernmental Advanced Stationary PEM Fuel Cell System Demonstration

Project Period: October, 2007 to May, 2010

Date of Report: August 31, 2011

Recipient: Plug Power Inc.
968 Albany Shaker Road
Latham, NY 12110

Award Number: DE-FG36-07GO17017

Working and Cost
Sharing Partners: None

Contact: Principal Investigator
Richard Chartrand
518-782-7700 x. 1938
rich_chartrand@plugpower.com

DOE Manager: Jason Marcinkoski
202-586-7466
jason.marcinkoski@ee.doe.gov

DOE Project
Officer: Reginald Tyler
720-356-1805
reginald.tyler@go.doe.gov

Executive Summary

A program to complete the design, construction and demonstration of a PEMFC system fuelled by Ethanol, LPG or NG for telecom applications was initiated in October 2007. Early in the program the economics for Ethanol were shown to be unfeasible and permission was given by DOE to focus on LPG only.

The design and construction of a prototype unit was completed in Jun 2009 using commercially available PEM FC stack from Ballard Power Systems. During the course of testing, the high pressure drop of the stack was shown to be problematic in terms of control and stability of the reformer. Also, due to the power requirements for air compression the overall efficiency of the system was shown to be lower than a similar system using internally developed low pressure drop FC stack. In Q3 2009, the decision was made to change to the Plug power stack and a second prototype was built and tested.

Overall net efficiency was shown to be 31.5% at 3 kW output. Total output of the system is 6 kW. Using the new stack hardware, material cost reduction of 63% was achieved over the previous Alpha design.

During a November 2009 review meeting Plug Power proposed and was granted permission, to demonstrate the new, commercial version of Plug Power's telecom system at CERL. As this product was also being tested as part of a DOE Topic 7A program, this part of the program was transferred to the Topic 7A program.

In Q32008, the scope of work of this program was expanded to include a National Grid demonstration project of a micro-CHP system using high-temperature PEM technology.

The Gensys Blue system was cleared for unattended operation, grid connection, and power generation in Aug 2009 at Union College in NY state. The system continues to operate providing power and heat to Beuth House. The system is being continually evaluated and improvements to hardware and controls will be implemented as more is learned about the system's operation.

The program is instrumental in improving the efficiency and reducing costs of PEMFC based power systems using LPG fuel and continues to makes steps towards meeting DOE's targets.

Plug Power would like to thank DOE for their support of this program.

Contents

Executive Summary	2
1.0 Descriptive Title.....	4
2.0 Name, Address and Background Information.....	4
3.0 Production Capability of the Manufacturer	4
4.0 Principal Investigator(s).....	5
5.0 Authorized Negotiator(s)	5
6.0 Past Relevant Performance Information	5
7.0 Task Schedule	6
8.0 Program Objectives, Barriers and Targets	6
8.1 Objectives	6
8.2 Technical Barriers	7
8.3 Technical Targets.....	7
8.0 Task Summary	7
8.1 Task 1 - Concept Development.....	7
8.2 Task 2 – System Definition.....	10
8.3 Task 3 – System Integration.....	21
8.4 Task 4 – Prototype Field Demonstration	27
8.5 Task 5 – Project Close Out	28
8.6 Task 6 – Project Management	29
8.7 Task 7 – National Grid Demonstration Project	29
9.0 Accomplishments	29
10.0 Conclusions/Summary	29
Appendix A	29

1.0 Descriptive Title

Intergovernmental Advanced Stationary PEM Fuel Cell System Demonstration

2.0 Name, Address and Background Information

Plug Power Inc.

968 Albany Shaker Rd.

Latham, NY 12110

(518) 782-7700

Data Universal Numbering System (DUNS) Number - 08-690-8444

Commercial and Government Entity (CAGE) Code - 2AAT3

Taxpayer Identification Number (TIN) - 22-3672377

Plug Power is a leader in fuel cell industry with over 1200 fuel cell systems built to date and operating experience worldwide. This project is focused on the development of Plug Power's third generation of a reformer-based, low-temperature, PEM stationary fuel cell system (*GenSys*), and involves the design, assembly, test, and demonstration of a flex-fueled, combined heat and power (CHP), grid-connected system. The resulting system will advance the state of the art toward the Department of Energy's (DOE's) program objectives of increased durability, reduced cost and improved efficiency.

3.0 Production Capability of the Manufacturer

Plug's fuel cell systems are manufactured at its Latham, NY manufacturing facility. This custom-designed facility, which opened in February 2000, has over 50,000 ft² of dedicated production and test facilities. Plug employs approximately 100 personnel in its production areas. Production processes are designed around the principles of lean manufacturing, and use the Toyota production system as a model. As such, planning and production is via a "pull system" (i.e., systems are produced only as orders pull demand for product through the production system.)

Dedicated test and laboratory facilities (at over 45,000 ft²) provide Plug with some of the most advanced capabilities in the fuel cell industry. These laboratories are capable of operating various configurations of fuel cell stacks, components, and subsystems. There are 110 test stations, 23 test rigs, and 16 fully instrumented test bays.

Plug has additional capacity in place in both indoor and outdoor settings to test up to 28 fully integrated fuel cell systems utilizing hydrogen, natural gas, and/or propane. Additional facilities are capable of mixing any composition of feed gas to duplicate any reformatted composition for cell, stack subsystem or system testing.

4.0 Principal Investigator(s)

Richard Chartrand
Plug Power, Inc.
O: (518) 738-0938
F: (518) 782-7914
rich_chartrand@plugpower.com

5.0 Authorized Negotiator(s)

Sharalyn Conner
Plug Power, Inc.
O: (518) 738-0136
F: (518) 782-7914
Sharalyn_Conner@plugpower.com

6.0 Past Relevant Performance Information

Table 1 Relevant Project History

Award Date	Federal Agency	Agreement #	Description	Plug Power Award
8/1/2003	U.S. Dept of Energy Topic 3.2	DE-FC36-03GO-13101	Development of High Temp Membrane	\$5,835,413
9/21/2001	US Army Corps of Engineers - CERL	DACA42-01-C-0053	Fuel Cell Demonstration - Watervliet Arsenal	\$1,190,770.00
10/18/2002	US Army Corps of Engineers - CERL	DACA42-03-C-0005	Fuel Cell Demonstration - NSU/West Point	\$1,170,356.00
6/1/2009	US DOE Topic 7A	DE-0000488	Fuel Cell Backup Power	\$2,702,672

7.0 Task Schedule

The following table summarizes the status of each task of the program.

Task Number	Project Milestones	Task Completion Date				Progress Notes
		Original Planned	Revised Planned	Actual	Percent Complete	
1	Concept Development	Jan 08	Jul 08	Jun 08	100%	Complete
2	System Definition	May 08	Nov 08	Nov 08	100%	Complete
3	System Integration	Apr 09	Jun 09	Mar 10	100%	Complete
4	Prototype Field Demonstration	Dec 09	Apr 10	Mar 10	100%	Transferred to Topic 7A
5	Project Close-out	Mar 10	May 10	Mar 10	100%	Transferred to Topic 7A
6	Project Management	Ongoing	Nov 10	Aug 11	100%	Complete
7	National Grid Demonstration Project	Feb 11	Dec 11	Dec 11	100%	Ongoing, Running until end of life

Table 2: Task Summary

8.0 Program Objectives, Barriers and Targets

8.1 Objectives

The objective of this effort is to design and produce an advanced prototype PEM fuel cell system with the following features:

- 5 kW net electric output
- Flex fuel capable – LPG, NG, Ethanol
- Reduce material and production cost and increase durability
- Increase electrical efficiency over the current alpha design
- Increase total efficiency by incorporating combined heat and power (CHP) capability

To show a path to meet long term DOE objectives

- 40% system electrical efficiency
- 40,000 hour system / fuel cell stack life

- \$750/ kW integrated system cost (w/ reformer)

8.2 Technical Barriers

- System Performance
- System & fuel cell stack direct material cost
- System & fuel cell stack durability

This project addresses the following technical barriers from the 3.4.4 section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

- Durability
- Cost
- Performance

8.3 Technical Targets

Integrated Stationary PEM Fuel Cell Power Systems (5-250 kW) Operating on Reformate:

This project is conducting fundamental analysis and demonstration of fuel flexible (ethanol / LPG) CHP integrated system. Results of the current system design have shown the ability to meet the following DOE 2011 targets.

- Survivability (min and max ambient temperature) -35 to +40C
- Noise < 55 dB(A) @ 10m

Learning gained from work activities of this project will be applied toward the design and manufacture of a system that is on a path to meet the following DOE 2011 targets:

- Durability @ <10% rated power degradation: 40,000 hours
- Cost @ 2000 units /year: \$750 / kW_e
- Performance^a
  - Electrical Efficiency @ rated power: 38.5%
  - Combined Heat and Power (CHP) efficiency @ rated power: 78.5%

^a Target values adjusted to account for LPG fueled system

8.0 Summary of Activities

8.1 Task 1 - Concept Development

The Systems Engineering team for this project defined a set of requirements this design must meet to be successful. These were collected into a System Requirements Document which was released to the design engineers who used

it to define detailed specifications for each part of the system. An overview of these requirements can be found in the following Table.

	Model	GenSys Telecom Product	
		3T24 / 48	6T24 / 48
Product Requirement			
Power Rating			
Max Continuous Power (Net BOL)	watts	3,000	6,000
Min Continuous Power	watts	750	1,500
EOL Continuous Power	watts	2400	4,800
Power Output			
Nominal Voltage		27.25 / 54.5	
Max voltage		30 / 60	
Min voltage		21 / 42	
Heat Output			
Heat recovery kit		No	
Peak CHP efficiency	%	N/A	
Usage Profile			
Duty cycle		Continuous	
On/off duty cycles	#/yr	10	
Operating Conditions			
Operating Ambient Temp	°C	-5 to 50	
Operating Altitude - (min / max)	ft	-197 / 6000	
Water Independent Operation		No make-up water required	
Audible Noise - (Nominal / Max)	dBa	60 / 70	
Freeze Prevention Heater		Optional low temp kit	
Fuel			
Primary Fuel		LPG	
Secondary Fuel		Natural Gas	
Durability			
Product design life	years	10	
Stack Life (B50)	hours	>20,000	
Certifications			
ANSI FC-1		Certified	
FCC		Class B	

Table 3: System Requirements

Once the system requirements were defined, component selection and sub system modeling and testing commenced.

Initial program deliverables included the ability to run on ethanol. However, after modeling and cost analysis, it was determined that running a system on automotive grade was not technically possible with current catalysts and using laboratory grade ethanol was not economically feasible as compared to LPG and the during the remainder of the project only LPG was used as the feedstock.. See Appendix A for more details.

A gap analysis was conducted using the GenSys alpha system design as a baseline to develop the scope of work required to advance the design toward the end product goals. The complete design was reviewed on a function basis and each functional group was evaluated for its contribution to overall system reliability, cost and efficiency. Potential design improvements were listed for each module of the current design and each were evaluated individually against the other items on ability to improve reliability, reduce material cost and improve overall system efficiency. A total of 325 items were evaluated. This list was down selected until a total of 113 items which had the highest contributions for improvement were determined. These became the work tasks for the concept development part of this program. A chart showing the breakdown of these items can be found in the following figure.

Figure 1: Task Breakdown

A review of the concept design for this project was held on June 25, 2008. This was a detailed review at a module level for the overall system, power generation, fuel air delivery, electronics and controls, reactant processing, thermal management modules for the following areas.

- ❖ Design Quality
  - Characteristic Curves / Component Specs
  - Critical Parameter Definition
  - Updated FMEA

- Reliability Assessment
- Controls Strategy
- ❖ Product Cost
  - Cost Estimates - for quantities of 1, 100, 1000, 10K annual production volumes
  - Serviceable Parts Schedule and Cost
- ❖ Delivery
  - Test Plans & required hardware necessary to finish system definition & qualification
  - Work items required to finish detail design phase with time & cost estimates

A separate section was held to review the cost roll-up of the design. The results of this review were used to focus future activities for the GenSys design beyond the scope of this project.

8.2 Task 2 – System Definition

During the system definition phase the subtasks for system specifications, module flow-down requirements were completed. Module and component design quickly followed and many of the components were selected. Module and component testing helped to confirm the equipment performance as follows.

2.1 System Specifications

A System Requirements Document (SRD) was completed for this design. This document was reviewed, approved and used as a basis to define the architecture and how the modules of the system would be constructed. A process and instrumentation diagram (P&ID) was created for the system and each module. Figure 2 is an example of P&ID for the Thermal Management Module (TMM).

Figure 2:– Sample P&ID

Using the P&ID as a starting point a Process Flow Diagram (PFD) was created and a system model was produced using ASPEN process modeling software. Once the model was tuned and working correctly simulations of various output power levels, ambient conditions, and elevations were ran. Table 4 shows the characteristics that were modeled.

Table 4:ASPEN Modeling Characteristics

Characteristic	Levels
Net Output Power (kW)	1, 1.5, 2,3,4,5,6
Ambient Temperature (C)	0, 25, 50
Elevation (m)	0, 2000
Max Output Coolant Radiator Limiter	Simulate at maximum radiator capability
Max Elevation Cathode Blower Limiter	Simulate at maximum cathode blower capability

In addition the model was used to assess the effects of several component level design trade-offs such as pressure drop and auxiliary power usage. As components were tested and data became available the model was updated with actual values to improve its simulation of reality.

[illegible]

On the electrical side of the design a similar set of documentation was created. An Electrical Interconnect Diagram (EID) which determines the amount of I/O required for the system controller and an Electrical Single Line (ESL). This document was especially useful in defining how the system would be installed in the field. Figure 4 is an example of an ESL that has been extended to show both the input fuel and CHP interfaces of the design.

Figure 4: Example Single Line Drawing

2.2 Module Flow-Down Requirements

In addition to the SRD and IOC documents discussed earlier critical parameters and cost targets were specified for each component. An example table for the Gas & Air Delivery Module can be found in the following Figure.

System Specifications	Units	Design	Range	
			Min	Max
Air Flow Rate	slpm	359	53	456
Air Inlet Temperature	*C	25	0	50
Relative Humidity	% R.H.	50	0	100
Pressure Ratio		1.2	1.04	1.31
Efficiency	%	82	75	100
Tach Feedback Signal	VDC		0.5	5
Control Voltage	VDC		0.5	5
Noise	dB A	65	-	70
Voltage Range	VDC	48	46	50

Constraints

Description	Units	Design	Range	
			Min	Max
B10 Service Life	yrs	2		5
B10 Operating Life	Hours	44,000		
B10 On/Off Cycles	Cycles/yr	100	0%	5%
Service Intervals (Routine)	Hours	25,000		
Storage Temperature	*C	25	-40	85
Outside Diameter	cm	TBD		
Outside Depth	cm	TBD		
Service Handling Weight	kg	TBD		
Mounting Points and Orientation		TBD		
% to Landfill		TBD	0	TBD
Safety Compliance		UL and CE, NFPA 58		

System Parameters	Units	Design	Range	
			Min	Max
Certifications		UL and CE, NFPA 58		
Storage Temperature	*C	25	-40	85
Aux Power Consumption	Watts	500	-	750
Dimensional Envelope	in.	TBD		
Mounting		TBD		
Weight	(kg)	3	-	4
Cost	(\$)	591	532	702
On/Off Cycles	Cycles/yr	10	0%	5%
Service Intervals (Routine)	Hours	44,000	17,500	87,658
Service Life	yrs	2		5

Confidential and Proprietary Information of Plug Power

Figure 5: Sample Critical Parameter Table

Using this input a component specification was generated for each part and prototype hardware was acquired from various suppliers and internal sources.

2.3 Module Design and Component Selection

With the design complete for each component and preliminary solutions selected, 3D models were created to represent the various modules of the system. These modules were then put together to form the integrated system. A brief function description and model representation follows.

Structure Module

Protects the system component from the ambient conditions and provides support for the remaining modules. Figure 6

Figure 6: Structure Module

Reactant Processing Module

A set of catalytic reactors and heat exchangers that convert fuel into reformat the hydrogen rich feed for the fuel cell stack.

Figure 7: Reactant Processing Module

Power Generation Module

Contains the fuel cell stack and associated balance of plant which creates electricity from reformat.

Figure 8: Power Generation Module

Power Conditioning Module

This module converts the unregulated electrical energy from the stack to a usable form of AC or DC power.

Figure 9: Power Conditioning Module

Thermal Management Module

Removes process heat from the system and supplies the energy for CHP applications. This module is designed to allow the system to operate in combined heat and power mode or in power generation only mode. The

common parts of the two options are designed so that the only change necessary is replacing the CHP heat exchanger with a radiator.

Figure 10: Thermal Management Module

2.4 Module and Component Testing

Aspects of the design that required new hardware or required operating existing components outside of the existing dataset were tested in a stand alone configuration to acquire data to use in the system model or measure performance effects of new operating conditions. The following items were tested.

Reactant Processing Module @ 6 kW Net Electrical Output Operating Point
A goal of this project was to extend the capability of the existing GenSys reforming hardware to allow for operation at the 6 kW net electrical output point. This testing was conducted in Plug Power's laboratory in Apeldoorn in the Netherlands. The results of this test concluded that the current reformer design had the capability of producing the required reformat for 6 kW net electrical output while maintaining the following critical parameters.

- less than 0.3 vol.% CH₄ in reformat
- CO levels at or below the target of 10 [vppm] CO
- Stable reactor temperature profile within operating limits

Cathode Blower

A new cathode blower was required to supply reactants to the fuel cell stack with sufficient head pressure to overcome the increase in pressure drop of the new stack design. Test results are found in Figure 11.

Figure 11: Cathode Blower Performance

High Efficiency Inverter

The Inverter is a Plug Power internal design to provide for high efficiency and low voltages provided by the fuel cell. It achieved 93.5% at mid load and maintained over 90% through the whole load range. Ongoing development efforts brought the peak efficiency to 97% and at least 92% at every point. See Figure 12.

Figure 12: Inverter Efficiency Map

Stack Humidifier

A shell and tube type humidifier and a pleated-frame type humidifier were tested. The pleated-frame type humidifier would need to be resized to provide twice the residence time at the tested flow conditions. However the shell and tube type humidifier performed well and exceeded expectations on the water transport effectiveness and met constraints for pressure drop. Figure 13 provides details on the humidifier characteristics -namely effectiveness and pressure drops (summation of cold and hot sides). The HS-1 module was able to meet the requirements without any insulation on the shell side. This indicates the robustness of this type of humidifier against the noise condition of no insulation. Typically in humidifiers, the residence time and dewpoint approach temperature are inversely related - so a healthy optimization is required to achieve proper sizing - i.e. length given a required membrane exchange surface area. The dewpoint approach temperatures were collected as requirement and this would enable stack differential temperature controls which ensures water retention in the cathode return in vapor state.

Figure 13: Humidifier Effectiveness

Fuel Cell Stack

The initial stack performance specification was jointly developed through collaboration between Plug Power and Ballard. One of the key drivers for Plug Power was to evaluate a system concept where the stack was provided by a strategic supplier. Ballard was the chosen supplier because of their strong presence in the industry and recent positive history in working together. Their MK 1300 series stack was chosen because of performance, stack cost, and warranty considerations. As we began to evaluate the MK1300 series stack in the design concept we realized that the high pressure drop (> 2 psig) stack impacted a variety of balance of plant components.

The fuel and air pumps (currently need 3 - 4 pumps) were driven to higher direct material cost due to the increased performance requirements. For example, we discovered that no margin existed for the Cathode compressor at 6 KW EOL conditions. As a result we needed to source a more expensive cathode compressor or needed to remove the stack at 7700 hrs (50 C). Additionally, compressor life issues were unknown and very high aux power was observed. We also observed issues with controllability of the pumps and blowers and the water knock-out design was much more challenging due to high pressure drop across the stack. System efficiency was at least 4 points below the Plug Power Convergent Stack due to higher fuel flow requirements to maintain a minimum pressure drop for water removal from anode channel.

Ultimately, Plug Power decided to go back to the internal stack (referred to as the Convergent Stack) for a variety of reasons. The lower pressure drop meant simpler balance of plant. A single fuel air pump was used with control valves to

divert air. The resulting air delivery savings alone was approximately \$500. The water knock-out design was much less challenging and enabled more water removal without leaks. The low power system efficiency was higher at 1 KW due to a Plug Power control concept of periodic blasting. The convergent plates performed similar to previous GenSyS designs and easily incorporated. The cathode blower regained latitude for 6kW EOL and used much less auxiliary power. The Plug Power Convergent Stack active area of 262 cm² gave more possibility for stack DMC reduction without compromising on efficiency.

The decision to use the Convergent Stack was driven by a combination of an unavailable design from Ballard, drive to lower cost DMC, and higher system efficiency. After the initial prototype was constructed with a Ballard stack, the follow-on prototype used the Convergent Stack with good success and operability.

Water System

A CAD model of the water system is found in Figure 14.

Figure 14: Water System Module

8.3 Task 3 – System Integration

The system integration began with reformer control development. All new subsystem actuators for this design were verified. Each catalyst was brought up and initial design set points were checked for proper gas composition. The prototype system was brought online and generated power for the first time on March 11, 2009. The reformer automatically started and control to constant hydrogen demand for heat up. The reformer startup time for this portion is 75 minutes with opportunity for further improvement; this represents a 50% improvement in start-up time over the prior system design. Stack control integration took longer than anticipated due to the large anode pressure drop (compared to the prior design). The higher pressure drop when running the stack caused reformer steam control/pressure oscillations and limited the maximum net power to 4 KW. The following Figure shows the system under test.

Figure 15: System Integration Testing

After significant amount of system work and testing was done on the Ballard 1300 stack, a decision was made to use a Plug Power stack in Q309. The Ballard stack was designed to use reactant pressure drop to aid in internal water management. While effective at removing water, the higher pressure drop placed an increased burden on the air and fuel supply systems. Major problems were identified which warranted the change:

- Unstable reformer operation due to high fuel pressure requirements.
- Figure 16 shows the effects the stack pressure drop has on the stability of the system controls for the reformer using the Ballard stack. The higher DP leads to oscillations in steam pressure which in turn cause fluctuations in temperature and fuel/air flows. These oscillations cause unstable reformer performance and poor gas quality which contribute to lower reliability and lower efficiency. The second chart shows the contrasting stable temperatures with no steam oscillations using the Plug Power stack.

Figure 16: Comparison of Reformer Performance of Ballard and Plug Power FC stack

- Reduced Stack Efficiency.** To summarize the benchmarking study of a commercially available stack to Plug Power stack with respect to performance, efficiency and pressure drops. Internally, we tested 3 different MEA constructions and 4 different catalyst iterations using 8-cell short stacks. Based on the short stack testing, we selected the nominal Membrane Electrode Assembly design that ensured low cost due to high volume manufacturability without compromising significantly on performance and longevity. Two such stacks were tested and performance curves were taken. The following Figure 17 shows stack efficiency comparison between ideal, the Ballard 1300 stack and our designs – both high volume and low volume methodology. With Plug Power’s design, we saw ensured high efficiency at all power levels.

Figure 17: Stack efficiency comparisons for Plug designs vs. outsourced stack.

In addition, due to lower stack pressure drop in Plug design, a further reduction in parasitic power was possible which subsequently increased the overall system efficiency. Please refer to the following Figure 18 for pressure drop comparison between the Plug design and the Ballard stack for reactant flows and coolant flows.

Figure 18: Pressure Drop Comparisons between commercially available stack and Plug Power stack design

System Efficiency

Various factors (reformer efficiency, steam generator efficiency, stack efficiency, power converter efficiency, and auxiliary power draw) contributed to the overall system efficiency (defined as the net electrical output power divided by the fuel heat rate). One prototype system was converted to the Plug Power stack and compared to the Ballard system prototype. The system effects were studied through side-by-side comparison of the two systems at similar operating points.

Figure 19 shows the effect that each stack had on the overall system efficiency and compares the end result to a previous version of the GenSys system design. As these results show, the system with the Plug Power fuel cell stack installed offered higher efficiency over the entire operating range.

Figure 19: Efficiency Comparison Effects of Stack Design

In addition as part of the system development and characterization testing performed, studies were made of the relative impact of two key reformer operating parameters and fuel composition on overall system efficiency.

In the first part of the testing the following reactor set-point temperatures were evaluated:

1. ATR reactor inlet steam fraction, as indicated by the temperature of the saturated inlet fuel-air-steam mixture; and
2. ATR reactor exit temperature.

The ATR inlet water content and reactor exit temperature must be controlled within certain ranges to allow the reformation reactions to proceed with desired results (high conversion of methane through the reactor, good selectivity to hydrogen, and minimal coke formation). Within these operating ranges, it is of interest to know the relative impact of both parameters on system efficiency.

Figure 20 shows the relative change in system efficiency at 3-kW load due to changes in the steam mix temperature as a function of the ATR exit temperature set-point. The ATR temperature set-point change had a smaller effect, increasing efficiency by less than a half-point for a 50 °C decrease in temperature. The steam-mix temperature was seen to have a more significant efficiency impact.

Figure 20: Efficiency Change Vs. Steam Mix T Change and ATR-Out T at 3-kW Load

The following Figure 21 shows the same chart at 4-kW load. Similar efficiency trends are seen, although the changes are smaller.

Figure 21: Efficiency Change Vs. Steam Mix T Change and ATR-Out T at 4-kW Load

The efficiency gains due to reduced ATR temperature and reduced steam level must be traded with the increased risk of reactor coking and increased methane slip. Un-reacted methane reduces H₂ production efficiency and may cause temperature oscillations in the system tail gas oxidizer reactor. The ATR reactor operating set points were selected based on consideration of both efficiency and operating life.

Another factor tied into the reactor operating parameters was LPG fuel composition. LPG composition in the US is more uniform than in other areas of the world, with propane forming the bulk of the US fuel mixture (typically > 80% propane). In India, LPG composition varies both regionally and seasonally, with butane forming the larger fraction of the fuel. Propane fraction in Indian LPG can be as low as 5 to 20% in some regions. Increasing the ATR reactor temperature for reformation of heavier fuels is one of the strategies considered to optimize reformer operation.

While most of the Phoenix development testing was run with standard HD-5 grade LPG, comparison tests were run with a specially prepared mixture having an initial composition of 20% propane/80% butane. Within the LPG tank the propane fraction in the vapor phase exceeded the propane fraction in the liquid phase due to the differing vapor pressures of propane and butane, so the butane fraction increases as the tank is drawn down. At the time the system efficiency data was taken, the liquid composition of the special tank was estimated at 6% propane/94% butane by volume (producing a vapor propane fraction of 14%) based on temperature and pressure measurements of the tank in an equilibrium condition.

The flow rate for both regular and heavy LPG sources was measured using a Coriolis mass-flow meter. For the test the same ATR exit set-point temperature was used for both fuels. The fuel test results showed the following:

1. System operation was insensitive to fuel source. System startup with both fuels was similar, and switching between fuel sources while running showed no noticeable system performance effects.
2. The effect of fuel source on system efficiency was small. Over a load range from 1 to 5 kW, less than a half point efficiency difference was seen between runs with the different fuel sources.

8.4 Task 4 – Prototype Field Demonstration

Plug Power visited the CERL facility in Champaign Illinois on February 19, 2009 and began planning for the installation of the prototype system

Figure 22 outlines the electrical schematic planned for the installation of the prototype system. Because the hardware used for this demonstration is

prototypical and the inverter design has not been type tested, grid parallel operation at the CERL site would not be possible. For this application the fuel cell system will be installed as the prime power source for the site AC load. The inverter through the use of its internal transfer switch will allow the grid to be used as back-up if the fuel cell needs to be taken off-line for maintenance. The inverter also has the ability to be controlled locally (or remotely via the internet) by a computer. This functionality with the addition of AC load banks will allow simulated load profiles to be run if the site load will not be sufficient to conduct a valid test of the fuel cell's functionality. The site specific hardware will be provided by Plug Power, housed in a separate module to allow for ease of installation.

Figure 22: Electrical Single Line Diagram

These plans were modified slightly during a program review meeting with DOE on Nov 2, 2009. It was decided that a commercial Gensys Phoenix design would be installed instead of the prototype originally intended. The Phoenix design would represent the best of Plug Power technology. And, since a fleet of 20 Phoenix systems were being deployed under Topic 7A program, it was further decided to transfer Task 4 to Topic 7A Emergency Backup Power Systems, Market Transformation Activities. The remaining system was included in the test fleet of 20 Phoenix systems. This fleet will be installed starting in Aug 2011.

8.5 Task 5 – Project Close Out

The GenSys operation, design, and prototyping of this project have been completed. The remaining operation of the Genysy Blue CHP fuel cell will be

supported by Plug Power and for the purposes of this program will be considered closed-out. If the GenSys Blue project continues it will be supported under other funding.

8.6 Task 6 – Project Management

The project management contact within Plug Power has changed ownership at several points in this program. Plug Power appreciates the oversight and guidance of the DOE in assuring that intended project deliverables were met.

8.7 Task 7 – National Grid Demonstration Project

This task was added in Q32008. Plug Power, National Grid and the DoE filed a joint press release on November 16, 2008 announcing the demonstration of the micro-CHP system using high-temperature PEM technology. In December, the National Grid Program Manager, John Rathbun, initiated contact with local National Grid account managers to canvas the area for potential sites that could host the demonstration. The response was overwhelming, but ultimately five sites were selected and site visits were scheduled.

The site visits were conducted on December 4th and 5th. The sites visited were Hudson Valley Community College, Rensselaer Polytechnic Institute, Ballston Spa High School, Schenectady Museum, and Union College. Union College was selected as the site in Q1 2009.

Site planning and installation design for the GenSys Blue μ CHP was completed during the Q2 2009. The mechanical interface to the dormitory heating and domestic hot water systems and the electrical interface with grid protection was designed. The paper work for grid interconnect was completed and filed with National Grid. The GenSys Blue unit was delivered and the mechanical installation was started the week of June 21, 2009. The electrical installation was completed the first week of August. The GenSys Blue system was then commissioned. After wiring and mechanical connections were complete, the system was operated in manual mode to allow for controls development. Preliminary control architecture was designed that allowed the GenSys Blue to provide heat and power for the Union College dormitory residence. The system went through a final inspection by National Grid and was cleared for unattended operation, grid connection, and power generation in Aug 2009.

Figure 24: GenSys Blue at Union College

Since installation in Beuth House at Union College, the GenSys Blue high temperature PEM fuel cell system has continued to run and provide heat and electricity. The system has been continually evaluated and improvements to hardware and controls have been implemented as more is learned about the system's operation. Figure 25 illustrates one example of control improvements that were made to the system software. The reformer in the system had exhibited oscillations in the 1kW-2 kW power range. The team characterized the time constants for the reformer operation and developed adaptive controls that adjusted the control response as a function of power level. Figure 25 shows the improved control stability after the new control software was implemented.

System Controls Improvements

Reformer Performance Improvements

Figure 25: GenSys Controls Improvement

System Statistics:

Figure 25-27 illustrate the operating characteristics of the Gensys Blue system to-date. Overall, the system has accumulated 2500 hours operation and has exported greater than 3 MWh electric in addition to 40 MWh thermal to the facility. Initial electric efficiencies at the beginning of stack life were observed to be 33%-35%. As the stack degraded, efficiencies dropped of to approximately 20%. The period of non-operation that started in April 2010 was a result of a stack failure; had the stack lasted, we would have run the system until May 2010 when the students typically vacate the building. The delay in starting up in the winter heating season was due to a delay in receipt of stack materials. A new stack was installed in Feb 2011 and provided good operation during the latter half of the 2010-2011 heating season. In May 2011 the system was shut down and will be restarted in the 2011-2012 heating season. The stack will continue to run until it has reached its useful life and the disposition of the program will be decided at that point.

Union College System Epsilon +4 Runtime

Figure 26: Operating Hours

Union College System Epsilon +4 Electrical Energy Exported

Figure 27: Exported Power

Figure 28: Exported Thermal

9.0 Accomplishments

The program achieved the following results:

1. System achieved a net electrical output of 6kW or 20% more than the target of 5 kW.
2. System can use LPG or NG. Ethanol was excluded as a fuel source early in the program due to poor economic and technical feasibility.
3. Material costs were reduced by 63% compared to the Alpha design.
4. Peak Electrical efficiency was increased to 31.5%; an improvement of 16% over the Alpha design.
5. A system was demonstrated which incorporated combined heat and power and was installed at the Union College. The system continues to run and has achieved electrical efficiencies of 33% and CHP efficiency of 85%.

In terms of being on a path to meet the long term DOE objectives, this program was instrumental in advancing towards that goal.

Net electrical efficiency was improved substantially over the Alpha design to 31.5%. Further efficiency improvements are expected in areas of:

- Stack efficiency by improved MEAs
- Improved air compressor efficiency
- Optimized Power electronics efficiency
- Improved fuel conversion efficiency

The current system cost is ~\$3,100/kW at 200 units/yr. While this remains significantly above the \$750/kW DOE target, production tooling, higher production volumes and component optimization and reduction activities are expected to reduce the system cost significantly.

Durability of the system remains to be validated during the demonstration program that is part of the 7A program.

10.0 Budget

Federal Cash (To report multiple grants, also use FFR Attachment):							
a. Cash Receipts						\$4,249,982.98	
b. Cash Disbursements						\$4,249,982.98	
c. Cash on Hand (line a minus b)						\$0.00	
<i>(Use lines d-o for single grant reporting)</i>							
Federal Expenditures and Unobligated Balance:							
d. Total Federal funds authorized						\$4,249,983.00	
e. Federal share of expenditures						\$4,249,982.98	
f. Federal share of unliquidated obligations						\$0.02	
g. Total Federal share (sum of lines e and f)						\$4,249,983.00	
h. Unobligated balance of Federal funds (line d minus g)						\$0.00	
Recipient Share:							
i. Total recipient share required						\$4,249,983.00	
j. Recipient share of expenditures						\$4,249,982.98	
k. Remaining recipient share to be provided (line i minus j)						\$0.02	
Program Income:							
l. Total Federal program income earned						\$0.00	
m. Program income expended in accordance with the deduction alternative						\$0.00	
n. Program income expended in accordance with the addition alternative						\$0.00	
o. Unexpended program income (line l minus line m or line n)						\$0.00	
11. Indirect Expense	a. Type	b. Rate	c. Period From	Period To	d. Base	e. Amount Charged	f. Federal Share
	Fixed	189.8% / 40% / 5%	Jan 01, 2009	Dec 31, 2009	\$1,002,833 / \$5,261,381	\$3,042,177 / \$2,104,552 / \$53,100	\$1,521,089 / \$1,052,276 / \$26,350
					\$1,062,000		
	g. Totals:				\$ 7,926,214	\$ 5,199,829	\$ 2,599,915

11.0 Conclusions

Design and prototype construction was completed on a 6kW PEM FC system utilizing LPG or NG as a fuel source. Peak system efficiency of 31.5% was achieved at a net power output of 3 kW. Material costs were reduced by 63% compared to previous designs.

A high temperature GenSys Blue Unit was installed at Union College which was a combined heat and power system. The unit continues to operate.

Plug Power would like to thank the Department of Energy for their continued support.

Appendix A

Ethanol Cost Modeling

The potential economic benefits of using ethanol as a fuel stock for fuel cell system using an ATR reformer was further investigated. Since the right-sized heat exchanger was unavailable, ASPEN process modeling was used to project best case performance of the system operating on ethanol. These results, and those of prior lab tests, were compiled into a model for the economics of ethanol operation. Figure A1 shows the results of this model and comparison to field data taken when operating on LPG.

Figure A1 – Ethanol Cost Comparison

The comparisons were made at the 50% rated power operating point; this is roughly the point of optimum system efficiency hence the best case for economic analysis. The results show that the cost of the current laboratory grade ethanol, required to be compatible with reforming catalysts, drastically detracts from the advantages of the higher hydrogen content of ethanol compared to LPG. This high purity feedstock costs about 3.5 times that of automotive fuel grade ethanol. In the future, as alternative and hopefully catalyst friendly denaturants are used, ethanol reforming could offer a significant cost advantage over natural gas and LPG feedstock. It was decided that if attractive economics could not be shown at the 50% rated power point, no other (less efficient) partial loads need be considered. Due to the economics of the current fuel composition, and the complexity, time and cost of acquiring the necessary heat exchanger hardware, no further ethanol testing is planned for this program.