V.G.1 Development and Demonstration of a New-Generation High Efficiency 10-kW Stationary Fuel Cell System

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Objectives

- To identify technology improvements, methodologies and engineered solutions to overcome challenges facing the development of fuel cells for use in combined heat and power (CHP) applications.
- To design an integrated system based on the most promising down-selected fuel cell and fuel processor building blocks.
- To build and test a prototype unit in a laboratory setting and collect 300 hours of operating data.
- Complete system optimization engineering and retrofit construction using lessons learned from prototype.
- Conduct a six-month field demonstration in an International Partnership for the Hydrogen Economy country.

Technical Barriers

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

(A) Durability

(B) Cost

(C) Performance

Technical Targets

Work under the project is aimed at developing novel fuel processing, polymer electrolyte membrane (PEM) fuel cell technologies and integration strategies in order to make progress toward achieving DOE targets for stationary PEM fuel cell power systems for year 2011. These targets and project progress are shown in Table 1.

TABLE 1. DOE Targets vs. Project Achievements

Metric	2009 Project Status	2010 Project Achievement	2011 DOE Target[1]
Electrical efficiency at rated power	System not built	32.6%	40%
CHP energy efficiency	System not built	60.8%	80%
Degradation with cycling[2]	2.5%/1,000 hours of fuel cell stack	0.85%/1,000 hours on fuel cell stack	<0.25%/ 1,000 hours[3]
	Hydrogen generator not built	TBD-testing underway	
Operating lifetime	Hydrogen generator not built	832 hours on hydrogen generator	40,000 hours
	3,500 hours on fuel cell stack	7,000 hours on fuel cell stack	
	CHP purpose-built fuel cell system not tested	1,000 hours on fuel cell system	

TBD – To be determined
[1] Complete DOE table 3.4.4 found at http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/fuel_cells.pdf.
[2] Percentage presented as per 1,000 hours given that total test data are less than lifetime target.
[3] Equivalent to <10% after 40,000 hours durability target.

Other challenges being addressed under the project are:

- Cost reduction by the simplification of balance-of-plant (BOP) components and development of an adsorption enhanced reforming fuel processor.
- Reduced startup time by improved thermal management design.

Accomplishments

- Successful commissioning of an integrated prototype in a laboratory setting.

- Automated fuel processor combustor startup and safety shutdowns implemented.
- Continuous (24 hours/day) test operation capability established.
- 53.4% gross electrical efficiency on integrated fuel cell subsystem.
- 32.6% electrical efficiency demonstrated on integrated CHP prototype system.
- 9.3 kW of waste heat recovered.
- Continuous production of ~95% purity hydrogen on separate bench-scale adsorption enhanced reforming test rig:
  - No materials degradation indicated
  - >10,000 regeneration cycles achieved
- Over 7,000 hours on separate test fuel cell stack with ~6% performance degradation:
  - ~3x improvement from previous year
- Operational hours on integrated CHP prototype system detailed in Table 2.

TABLE 2. Operational Hours on Prototype

Mode	Hours
Hot-Idle[1]	2,164
Pure Hydrogen Production	832
Power Production	396
Maximum Continuous Unattended Hydrogen Production	206

[1] Reformer combustor hot (700°C) only without synthesis gas or power production occurring.

Introduction

The development of highly efficient and cost-effective clean energy solutions is not without challenge. Hydrogen fuel cell technologies are expected to become a significant player in reducing our dependence on imported fossil fuels and curb the further accumulation of greenhouse gases and criteria pollutants. Fuel cells can be used in many applications, including but not limited to stationary primary and backup power, portable power and motive power (automobiles, motorcycles, aircraft, etc.).

This project is focused on the design, fabrication and field demonstration of a stationary CHP system that will provide multi-dwelling residential and light commercial end-users with on-site generated electrical and heating needs. The proposed technology addresses DOE targets by using PEM fuel cell stacks as they have been proven to achieve high efficiency, greater durability and lower costs than competing fuel cell technologies.

An integrated hydrogen generator employs an optimized steam methane reformer (SMR) to achieve high fuel to hydrogen output, along with the recovery and utilization of heat from waste streams to address DOE's combined efficiency (electricity plus useful heat) target of greater than 80%.

In parallel to the development of an SMR-based fuel processor, IE has collaborated with California State Polytechnic University, Pomona to research an alternate hydrogen generation method called adsorption enhanced reforming (AER). According to process simulations done at Sandia National Laboratories in 2008, AER promises up to 40% CHP system electrical efficiency when integrated into the as-designed, open-architecture (pure hydrogen interface between the fuel cell and hydrogen generator) prototype unit now operating in our laboratory.

Approach

The approach to achieving the project's 40% electrical efficiency target is incremental and based on, (1) optimization of the SMR plus fuel cell architecture and (2) the development of an 80% or greater thermally efficient AER hydrogen generator that can "plug and play" into the same SMR plus fuel cell hydrogen feed interface. The SMR plus fuel cell optimization work will rely on allowing slightly less than 100% hydrogen to enter the fuel cell (99%, balance inert) which will translate into only a small efficiency penalty to the fuel cell, but has the advantage of increased hydrogen recovery from the hydrogen generation process whereby its thermal efficiency can be boosted from 70% up to as much as 73%. Preliminary process simulations indicate that this approach can increase the overall CHP system electrical efficiency from its current status of 32.6% to approximately 36%.

An AER hydrogen generator produces a fuel cell feed stream similar to the optimized SMR plus fuel cell system approach but requires operation at 500°C versus 900°C. This means less energy is required for hydrocarbon conversion by the AER approach making the technology more thermally efficient than SMR. Predictive models have indicated that hydrogen generation efficiencies of up to 85% can be achieved with the AER technology compared to 70%-73% attainable by SMR. The multiplier between the AER hydrogen generator and the fuel cell efficiencies, less 12% for the parasitic power requirements to run the CHP system ([0.85 x 0.55] -0.12), would result in an electrical efficiency of approximately 41%. Furthermore, since with AER, hydrocarbon reforming and carbon dioxide adsorption occur simultaneously, an additional purification step is eliminated thereby reducing system complexity and costs.

Results

During Fiscal Year (FY) 2009, the integrated CHP system was designed. This last year (FY 2010) marked the construction and testing of the CHP prototype comprised of 23 modular subsystems including water delivery and recovery, fuel delivery, controller and power management, air delivery, safety, chassis, purification, reformer, fuel cell and enabling sub-subsystems. Each subsystem underwent independent bench testing and validation prior to being installed on the overall CHP system. After all subsystems were installed onto the CHP unit, the system went through a cold commissioning phase to check the functionality of electrical components, pressure test vessels and piping and validate the controller system under cold-gas flow conditions. Subsequently, the unit was hot commissioned over a one month period where combustor startup and reforming behaviors were initiated and observed. The pre-commissioning prototype is shown in Figure 1.

After commissioning, the unit was operated first during normal day shifts until the controller safety shutdown sequence and test facility alarms were automated. In March, the unit ran unattended 24 hours/day and achieved its longest continuous run of 31 days while operating in some combination of hot-idle, reforming, pure hydrogen production or electrical production mode(s). A comprehensive set of tests were conducted to evaluate system load versus hydrocarbon conversion in the reformer, fuel cell gross and net efficiency, peak system efficiency and useful heat recovery as a function of cooling water inlet temperature. Conversion ranged from 77%-89% depending on conditions. A summary of other test results are presented in Table 3.

FIGURE 1. CHP Prototype in Test Station

TABLE 3. CHP Prototype Test Results

CHP Technical Accomplishments

	Expected Initial Performance @ 10kW	Achieved@ 11kW	Expected Target With Optimization
Pure Hydrogen Produced (SLPM)		135	
Natural Gas Fed to Reformer (SLPM)		54	
Natural Gas Fed to Combustor (SLPM)		6.3	
Hydrogen fed to Combustor (Proxy for PSA off-gas) (SLPM)		5	
Fraction of Natural Gas Power Converted to Pure Hydrogen*	72%	68.2%	73.5%
Fuel cell Gross power (W)		11540	
Hydrogen Consumed by Fuel Cell (SLPM)		120	
Gross Efficiency of Fuel Cell	53%	53.4% ✓	55%
Fuel cell parasitic power (W)	720	620 ✓	600
Hydrogen production parasitic power (W)	850	610 ✓	700
Percentage of DC Power Available to Customer		89.4%	
End-to-End Electrical Efficiency (Electricity Out / LHV Fuels In)	33.2%	32.6%	36.2%
Thermal Power Recovered from Hydrogen Generator (W)**	4200	2732**	5000
Thermal Power Recovered from Fuel Cell (W)	4200	6640 ✓	5000
End-to-End Thermal Efficiency		30.1%	
Overall Combined Heat and Power Efficiency	61.1%	60.8%	>71.5%

As represented by check marks in Table 3, four initial performance milestones were achieved during functional validation testing. These data were collected from a sub-optimized prototype. The highest recorded electrical efficiency was 32.6% (natural gas compression parasitic power demand not factored in) with a combined CHP efficiency of 60.8%. Optimization steps, including but not limited to, returning pressure swing adsorption (PSA) exhaust gas to the reformer combustor, replacement of an existing flue heat exchanger with a larger one, improved insulation and operating the reformer at higher temperatures will be carried out in the coming months. Performance estimates for an optimized SMR plus fuel cell system architecture based on the aforementioned steps are shown in the far right column of Table 3. These estimates are lower than DOE targets due largely to the input energy requirement of reforming at ~900°C and associated heat losses. To address this gap, IE continues to develop strategies to advance AER and AER fuel cellFC interface technologies that could meet these targets in a real commercial system.

The prototype startup times from stone cold (20°C) to full electrical production, referred to as "cold start" ranged from 4-6 hours. The hot start time defined as the period from which the fuel processor was in "hot-idle" (combustor fired only maintaining the reactor without reforming near 700°C) to full electrical production was approximately one hour. To date, the CHP prototype has undergone 29 cold starts/stops, and nine hot starts/stops without degradation in mechanical integrity and/or catastrophic failure such as a sudden loss of pressure while operating.

Work on AER was conducted in collaboration with California State Polytechnic University, Pomona under the direction of Professor Dr. Mingheng Li. A four-tube (2" diameter by 48" long each) reactor was designed, constructed and tested from the middle of last year through March of 2010. The experimental rig produced hydrogen continuously by reforming in one tube for 30 seconds and then switching to an adjacent tube that would reform for the next 30 seconds. As there were four tubes in total, each tube, while not reforming would undergo 90 seconds of regeneration (desorption of undesired reaction products in preparation for the next 30 second reforming step). Tests were done using ethanol, liquefied petroleum gas (LPG) and methane as the feed. Regeneration was done with a simulated fuel cell cathode exhaust gas (oxygen reduced air with water vapor) to emulate process conditions that the AER fuel processor would see when fully integrated into a CHP system. The reactor beds were packed with a mixture of Ceria impregnated hydrocarbon reforming catalyst and potassium-promoted hydrotalcite carbon monoxide/dioxide adsorption pellets. Experimental conditions are shown in Table 4.

During the testing phase, more than 350 hours of hydrogen production were logged with each reactor tube having been subjected to roughly 10,000 reforming-regeneration cycles. We did not observe any decrease in hydrocarbon conversion (80-90% depending on process settings) or materials degradation as commonly found throughout the literature regarding prior art.

TABLE 4. AER Experimental Conditions

Primary Experimental Parameters	
Variable	Range of Values
Bed Temperature	475°C to 550°C
Feed Rate	0.01 to 0.03 mol/min
Steam/Carbon Ratio	2 to 4
Supplementary Experimental Parameters	
Carbon Source	Ethanol, LPG, Methane
Cycle Time	72, 96, 120, 144, and 168 seconds
Tubes in Cycle	Three tubes or four tubes
Steam Clean Time	10 and 20 seconds

The sample data represented in Figure 2 show a steady flow of product gas (~96% H_2, ~4% balance being a mixture of CO, CO_2, N_2 and CH_4). Of the ~4% balance, CO which is known to poison PEM fuel cells exists at the sub-100 parts per million (PPM) level. While this amount is too much for use in these fuel cells, a passive device can be used in conjunction with AER to convert this CO back to CH_4 prior to entering the stack; CH_4 is harmless to the stack. The CO_2 in the stream is also at the sub-100 PPM level.

In parallel to the design, construction and testing of the AER rig, process models were developed using HYSYS software. With inputs setting the operating temperature at 500°C, pressure at 60 psig and steam to carbon ratio of 2:1, the model predicted a reformer gas outlet equilibrium concentration of 2.56% CH_4, 79.2% H_2 and 18.15% H_2O. After condensing out the water downstream of the reformer, the concentration becomes

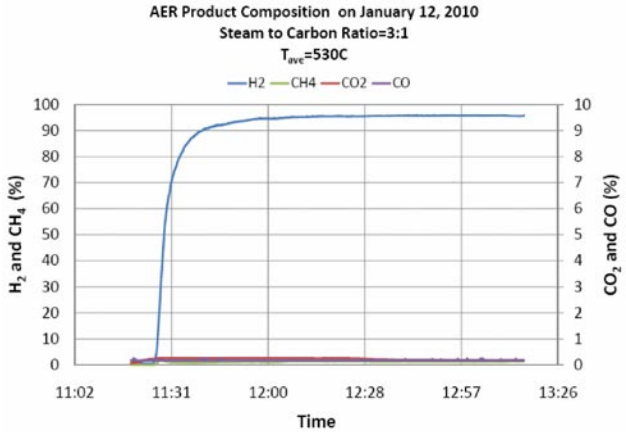

FIGURE 2. Continuous Hydrogen Production with AER

3.24% CH_4 and 96.76% H_2. These modeled predictions are consistent with the experimental data.

Conclusions and Future Directions

Progress during project year three was marked by the construction and validation testing of a CHP prototype in IE's laboratory. Over 350 hours of electrical production were logged whereby 32.6% system electrical efficiency was achieved. More than 2,100 hot hours and 29 start/stop thermal cycles were carried out.

Continuous production of near fuel cell grade hydrogen has been achieved with a bench-scale AER rig. Over 10,000 process cycles were logged without signs of materials (reforming and adsorbent pellets) degradation.

The coming year will focus on PSA retrofit engineering, system-wide optimization and field demonstration.

Major tasks/direction going forward:

- PSA retrofit engineering.
- System repackaging, pre-deployment testing and optimization.
- Six-month field demonstration in the United Kingdom (Chalvey, Slough).

FY 2010 Publications/Presentations

1. Diane Aagesen, et al; 2010 DOE Annual Merit Review and Peer Evaluation Meeting, Washington, D.C., June 10th, 2010. Presentation FC 31.

2. Duraiswamy K, et al; Development of a High-Efficiency Hydrogen Generator for Fuel Cells for Distributed Power Generation; accepted for publication in the International Journal of Hydrogen Energy, 2010.

3. Diane Aagesen, Development and Demonstration of a 10kW PEMFC Combined Heat and Power System; The Fuel Cell Seminar, Palm Springs, California, 2009.