II.C.6 High Performance Flexible Reversible Solid Oxide Fuel Cell

Jie Guan
GE Global Research Center
18A Mason
Irvine, CA 92618
Phone: (949) 330-8999; Fax: (949) 330-8994
E-mail: jie.guan@ge.com

DOE Technology Development Manager:
Roxanne Garland
Phone: (202) 586-7260; Fax: (202) 586-9811
E-mail: Roxanne.Garland@ee.doe.gov

DOE Project Officer: David Peterson
Phone: (303) 275-4956; Fax: (303) 275-4788
E-mail: David.Peterson@go.doe.gov

Technical Advisor: Jamie Holladay
Phone: (202) 586-8804; Fax: (202) 586-9811
E-mail: Jamie.Holladay@pnl.gov

Contract Number: DE-FC36-04GO14351

Project Start Date: October 2004
Project End Date: November 2006

Objectives

- Demonstrate a single modular stack that can be operated under dual modes:
  - Fuel cell mode to generate electricity from a variety of fuels.
  - Electrolysis mode to produce hydrogen from steam.
- Provide materials set, electrode microstructure, and technology gap assessment for future work.

Technical Barriers

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

(G) Capital Cost
(H) System Efficiency

Technical Targets

This project has been conducting exploratory studies of hydrogen production and power generation using reversible solid oxide fuel cells (RSOFCs). The advancements from these studies will be applied toward the future design of high temperature electrolysis systems that meet the following DOE 2012 distributed hydrogen production targets:

- Hydrogen cost: \$3.7/gge
- Electrolyzer capital cost: \$0.7/gge or \$400/kW
- Electrolyzer energy efficiency: 69% based on lower heating value (LHV)

Accomplishments

- Several multi-cell stacks have been built and tested under power generation and electrolysis mode. A 10-cell stack was operated over 1,000 hours alternating between fuel cell and steam electrolysis modes. The stack was run very successfully with high performance of 480 mW/cm^2 at 0.7 V and 80% fuel utilization in fuel cell mode. In electrolysis mode 6 SLPM hydrogen from steam was demonstrated using about 1.1 kW electrical power. The hydrogen generation is equivalent to a specific capability of 2.59 Nm^3/m^2 with electrical energy demand of 3 kWh/Nm^3.
- Varied hydrogen production technologies have been reviewed with focus on steam reforming and water electrolysis. The potentials and technical challenges have been analyzed. High temperature steam electrolysis has potential for high electrolyzer efficiency, thus the potentials for reducing electrical energy demand and lowering hydrogen production cost.
- The cost estimate of a RSOFC has been conducted for fuel cell mode, dual mode and the electrolysis mode. The electrical energy cost is the major contributor to the hydrogen production cost. Besides the flexibility of running under both fuel cell mode and electrolysis mode, the RSOFC has the potential for low cost and highly efficient hydrogen production through steam electrolysis. The cost of hydrogen production at large scale has been estimated at ~\$2.7/kg H_2, comparing favorably with other electrolysis technologies.

◆ ◆ ◆ ◆ ◆

Introduction

Solid oxide fuel cells (SOFCs) are known to be reversible, i.e., they can be operated under dual modes: power generation mode and electrolysis mode. In power generation mode, the SOFC acts as a fuel cell and generates electricity by electrochemically combining fuel and oxidant. In reverse mode when power is applied to the cell, the SOFC acts as an electrolyzer and produces hydrogen through steam electrolysis.

A RSOFC is a single unit that operates efficiently in both power generation and hydrogen production modes. Since the SOFC has the capability for internal reforming of hydrocarbons, the RSOFC can be made fuel-flexible. Fuel-flexible RSOFCs eliminate the need for an external reformer, thus simplifying the system and reducing system costs. With the RSOFC, a completely renewable production of electricity and hydrogen becomes possible when power generation and water or steam electrolysis are coupled. For instance, a renewable energy supply (e.g., solar, wind) can be used by the fuel cell to produce hydrogen and oxygen from water. These chemicals can be used directly or stored for subsequent uses to produce electricity through the same fuel cell in reverse mode.

Approach

The key challenges in the development of fuel-flexible RSOFCs relate to the reversibility of the electrodes and the internal reforming capability of the anode or hydrogen electrode. The reversible electrode must provide adequate performance and durability in both power generation and electrolysis operation. Challenges on the reversible hydrogen electrode for internal reforming are risks associated with carbon deposition and thermal management. The combination of reversibility and reforming capability presents significant technical challenges in electrode development. The project concentrated on three areas: reversible electrode development, reversible cell evaluation, and stack demonstration. These efforts addressed the key technical challenges except the thermal management issues associated with internal reforming. Thermal management for operation with internal reforming was addressed separately. A cost analysis and a technology assessment were also conducted to estimate the hydrogen production cost and evaluate the status and potential of RSOFC technology.

Results

Several multi-cell stacks were assembled and tested. Performance was improved from stack to stack with oxygen electrode process control and reduction of the contact resistance between the electrodes and interconnects. All stacks were operated for over 1,000 hours and the performance of individual cells was monitored. The typical degradation rate for the stacks in terms of area specific resistance (ASR) increase was about ~0.2 ohm-cm^2/1,000 hours, which was comparable to the data observed in single cell modules.

A 10-cell stack was tested to evaluate the advancements made in this project. Figure 1 shows initial stack performance under power generation mode. The stack achieved 480 mW/cm^2 at 0.7 V and 80% fuel utilization under power generation mode. Steam electrolysis for hydrogen production was measured with 30% H_2/70% H_2O feed. The average cell voltage was 1.263 V at electrolysis current density of 0.62 A/cm^2 and steam utilization of ~54%. At this point, the stack generated ~6.13 SLPM hydrogen with ~1.11 kW DC power input (Figure 2) and the efficiency of the electrolyzer alone was estimated as 76% (LHV) including steam generation and utilization.

The stack was operated under varied modes to evaluate its long-term stability. First, the stack was tested at 0.507 A/cm^2 under electrolysis with steam utilization ~45%. The degradation rate was high initially, ~700 mohm-cm^2/1,000 hours. After ~300 hours, the stack was shifted to power generation mode with internal reforming. The stack was held for about 300 hours at 0.4 A/cm^2 and 60% fuel utilization with a fuel feed consisting of 30% H_2O, 20% CH_4 and 50% N_2. The addition of N_2 was to improve the stability of steam delivery. The ASR increase under power generation

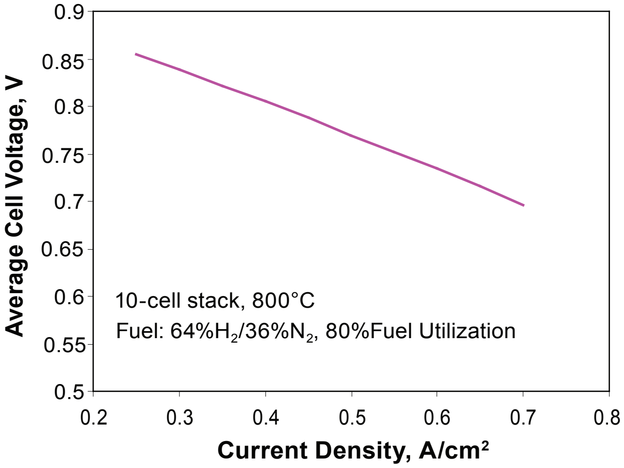

FIGURE 1. Initial Performance of Stack U089 Tested at 800°C

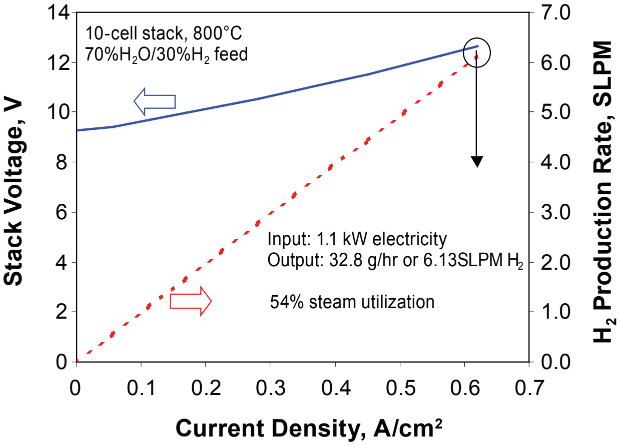

FIGURE 2. Hydrogen Production with 10-cell Stack

mode with internal reforming was in the range of 100-200 mohm-cm^2/1,000 hours, which was acceptable. The stack was then operated at 0.507 A/cm^2 for ~200 hours followed by another ~200 hours at a lower current density of 0.253 A/cm^2 in electrolysis mode. The degradation rate was in the order of 100-300 mohm-cm^2/1,000 hours, slower than that observed in the first 300 hours. In the last ~100 hours, the stack was operated under power generation mode with internal reforming and the stability trend was similar to that observed between hour 300 and 600.

A cost of hydrogen (CoH) model was developed based on the DOE's H2A model with conceptual RSOFC systems. The CoH for RSOFC systems was studied at both distributed and central station size. It was found that the optimal cell operating voltage of the solid oxide electrolyzer was around 1.2 V/cell and the extra heat needed should be provided via a non-electrical heater/furnace, such as a gas heater/furnace.

For the distributed size, the CoH was estimated at \$3.70/kg H_2 with a RSOFC system. The cost breakdown shows that the feedstock costs are mainly made up of the electricity cost while the capital cost breakdown is split relatively equally among the stack, electrolysis mode components, fuel cell mode components, and overall shared components. The sensitivity analysis (Figure 3) shows that the cost of electricity is the largest driver of cost followed by the capacity factor, internal rate of return, and stack power density.

For a central station size, the CoH was estimated at \$2.68/kg H_2. The feedstock cost breakdown is the same as the distributed case, but the capital breakdown is dominated by the stack cost. The reduction in overall CoH is attributed to the reduction of balance of plants cost. Further integration of the heat and steam production within an industrial plant would reduce the CoH by more than 10%. Again, the sensitivity analysis indicates that CoH is most sensitive to the cost of electricity (CoE).

Comparing to other electrolysis technology, the solid oxide steam electrolysis is less mature. Significant development effort is needed to fully realize its potential for high efficiency and low cost. This includes the critical element development and system demo. A simplified technology road map is presented in Figure 4. Technology feasibility of RSOFCs has been demonstrated through the project. The next critical developments are the key stack elements (cells, seals and interconnects) and a technology demo through a small system for system efficiency and dual mode operation. In parallel, seals and interconnect reliability need to be significantly advanced. With the lessons learned from the system demo and reliability improvement, stack scale-up is needed. This includes large footprint cell fabrication and large stack design. Once the stack scale-up is completed, most of the technology risks will be overcome. Additional stack risks are associated with pressurization, which might be optional depending on the system design and applications. The rest of the technology milestones are system and cost related. Key system elements such as high temperature heat exchangers and high temperature recycle blowers must be developed to determine system efficiency and reliability. The cost reduction requires a mature the manufacturing process, low cost materials, and simple balance of plant components without compromise of system performance. The last technology milestone will be a proof-of-concept demonstration for efficiency, reliability, and pressurization at system levels.

Conclusions and Future Directions

The "High Performance Flexible Reversible Solid Oxide Fuel Cell" project was very successful. This project has developed a set of materials and optimized electrode microstructures for RSOFCs and demonstrated the feasibility and operation of a RSOFC multi-cell stack. A 10-cell RSOFC stack was operated over 1,000 hours alternating between fuel cell and steam

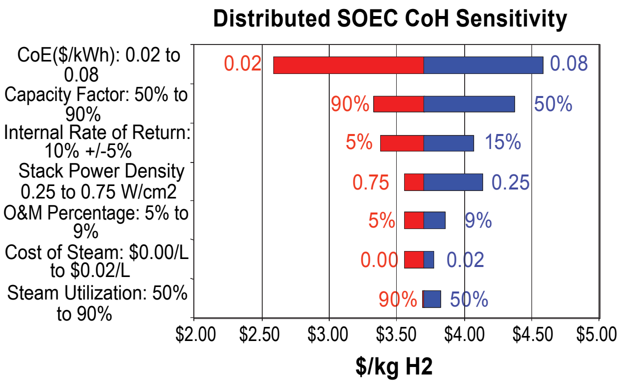

FIGURE 3. CoH Sensitivities for Distributed Size Case

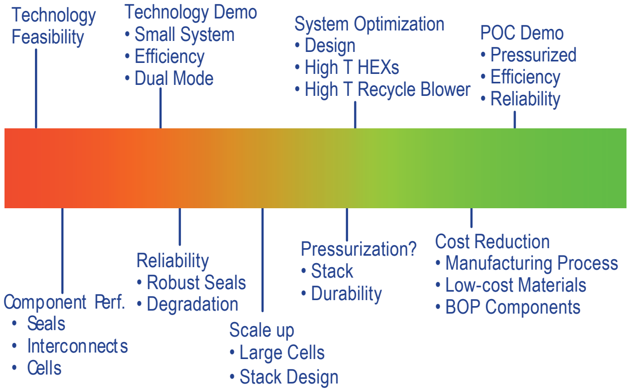

FIGURE 4. Technology Roadmap for Reversible Solid Oxide Fuel Cell Systems

electrolysis modes. The stack ran very successfully with high power density of 480 mW/cm^2 at 0.7 V and 80% fuel utilization in fuel cell mode and >6 SLPM hydrogen production in steam electrolysis mode using about 1.1 kW electrical power. The hydrogen generation is equivalent to a specific capability of 2.59 Nm^3/m^2 with electrical energy demand of 3 kWh/Nm^3. The performance stability in electrolysis mode was improved during the project with a degradation rate reduction from 8,000 to 200 mohm-cm^2/1,000 hours. Both a cost estimate and technology assessment was conducted. Besides the flexibility of running under both fuel cell and electrolysis modes, the RSOFC system has the potential for low cost and highly efficient hydrogen production through steam electrolysis. The cost for hydrogen production at large scale was estimated at ~$2.7/kg H_2, comparing favorably with other electrolysis technologies. The advancements under this project have formed a basis for future work to move the technology toward practical applications.

FY 2007 Publications/Presentations

1. Jie Guan, Nguyen Minh, Badri Ramamurthi, James Ruud, Jin-Ki Hong, Patrick Riley, and Dacong Weng, High Performance Flexible Reversible Solid Oxide Fuel Cell, Final Technical Report, February, 2007, http://www.osti.gov/bridge/servlets/purl/899650-fhtqgi.

2. Jie Guan, Badri Ramamurthi, Jim Ruud, Jinki Hong, Patrick Riley, and Nguyen Minh, High Performance Flexible Reversible Solid Oxide Fuel Cell, DOE Hydrogen Program Annual Merit Review Proceedings, May 2006, http://www.hydrogen.energy.gov/pdfs/review06/pdp_34_minh.pdf.

3. Jie Guan, Badri Ramamurthi, Jim Ruud, Jinki Hong, Patrick Riley, Dacong Weng, and Nguyen Minh, High Performance Flexible Reversible Solid Oxide Fuel Cell, DOE Hydrogen Program Annual Merit Review Proceedings, May 2007, http://www.hydrogen.energy.gov/pdfs/review07/pdp_15_guan.pdf.