High Performance Flexible Reversible Solid Oxide Fuel Cell

Jie Guan, Badri Ramamurthi, Jim Ruud, Jinki Hong, Patrick Riley, Dacong Weng, Nguyen Minh

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Overview

Timeline

- Project start date: October 2004
- Project end date: November 2006
- Percent complete: 100%

Budget

- Total project funding
  - DOE share: $1,252,683
  - Contractor share: $616,993
- Funding received in FY05: $575,198
- Funding for FY06: $677,485

Barriers

- Barriers addressed
  - K. Electricity Costs
  - G. Capital Costs
  - H. System Efficiency
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
**Approaches**

**PROGRAM ELEMENTS**

- **BASELINE MATERIALS SELECTION**
  - Conventional SOFC Based Materials
- **FUEL FLEXIBLE REVERSIBLE ELECTRODES**
  - Reversible Multifuel Anode and Reversible Electrodes
- **REVERSIBLE SINGLE CELLS**
  - Electrode Supported Cells Operating At <800 °C
- **REVERSIBLE STACKS**
  - Planar Design Metallic Interconnect

**CONCEPTS**

- **Assessment of SOFC Material Properties Relevant to Reversible Operation**
- **Electrode Configuration**
  - Microstructure
  - Composition
  - Catalytic Activity
- **Thin Electrolyte Electrode Supported Cells Made by Calendering**
- **Half Sealed Planar Design**

**APPROACHES**

**COST ESTIMATE**

- **Technology Analysis**

**Technical focuses:**
- Reversible electrode modeling
- Electrode compositions and microstructure engineering

**Key challenges:**
- Performance for cost and efficiency
- Low degradation for reliability
Cell Configuration

- SOFCs have the flexibility, running under power generation mode and hydrogen production mode.
- High temperature solid oxide steam electrolysis can lower the electricity consumption.

- **Fuel**, CH₄, H₂, etc.
- **Oxidant**, air.

**Power Generation Mode**

\[
\text{CH}_4 + 4O_2^- \rightarrow 2H_2O + CO_2 + 8e^-
\]

\[
2O_2 + 8e^- \rightarrow 4O^2-
\]

**Hydrogen Production Mode**

\[
2H_2O + 4e^- \rightarrow 2H_2 + 2O^2-
\]

\[
2O^2- \rightarrow O_2 + 4e^-\]

- **Oxygen Electrode**, Perovskite
- **Electrolyte**, YSZ
- **Hydrogen Electrode**, Ni/YSZ
Stack Configuration

Cell
- Oxygen electrode
- Electrolyte
- Hydrogen electrode

Module
- Interconnect (IC)
- Cell
- Interconnect (IC)

Multi-cell Stack
- Cell/ICs Repeat units

Imagination at work
Oxygen Electrode Performance

- Screened several lanthanum strontium manganites (LSM), lanthanum strontium ferrites (LSF), and lanthanum strontium cobalt iron oxides (LSCF) as oxygen electrodes.

- Under both modes, electrode performance increases in the order of LSCF > LSF > LSM/YSZ.
Oxygen Electrode Performance Stability

- Excess performance degradation was observed with LSM/YSZ as the oxygen electrode in electrolysis mode (SOEC) mainly due to electrode delamination.

- LSCF and LSF showed better performance stability in electrolysis mode than LSM/YSZ electrode.
Oxygen Electrode Analysis

interface delamination

Cr transport and accumulation in LSCF electrode

Sr migration and depletion?
Performance Stability Improvement

- No significant difference in degradation rate between cells held under a constant load in fuel cell mode compared with cells that were held at OCV.

- The dominant degradation mechanisms were likely to be thermally activated.

- Coated interconnect significantly improved the performance stability.
Oxygen Electrode Reversibility

Non-symmetrical vacancy model

- Vacancy diffusion and activation at the oxygen electrode/electrolyte interface are different for fuel cell mode and electrolysis mode.

- Higher current densities can lead to depletion of vacancies at the interface in electrolysis mode.

Symmetrical vacancy model

- Experimental data matched well with non-symmetrical vacancy model.
Hydrogen Electrode Performance

**Fuel cell mode**

- $V_{cell} = 0.7 \, \text{V}
- 800 \, \text{C} \, 50/50 \, H_2/H_2O
- Hydrogen electrode overpotential (V)

**Electrolysis mode**

- $V_{cell} = 1.3 \, \text{V}
- 800 \, \text{C} \, 50/50 \, H_2/H_2O
- Hydrogen electrode overpotential (V)

- Higher polarization losses predicted under electrolysis mode mainly due to difference of diffusion
- Thinner electrode and smaller particles preferred

**Conditions:**
- $T = 800 \, \text{C}$
- Fuel = 50/50 $H_2/H_2O$
- Active layer thickness = 16 $\mu m$
- Active layer particle size = 0.8 $\mu m$

Region I – $H_2/H_2O$ diffusion and reaction limited
Region II – Reaction limited
Region III – Ion conduction and reaction limited
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- At 800°C, internal reforming kinetic was fast.
- CH₄ conversion measured (gas chromatography) > 98%, agrees well with thermodynamic prediction.
- Thermodynamic calculations defined carbon deposition boundary.

X is the distance from the fuel inlet along the channel and L is the total channel length.
Performance with Internal Reforming

- Performance (I-V curve) with internal reforming similar to that with 64% H₂/36%N₂ fuel
- Improved cells efficiency and potential system simplification with internal reforming
Module Performance Improvement

- LSCF performed better than LSM/YSZ electrode
- Substantial degradation rate reduction achieved with LSCF oxygen electrode in electrolysis mode
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Multi-cell Stack Performance

- Built and tested several multi-cell stacks under power generation and electrolysis mode for more than 1000 hrs
- Performance improved with process control and contact resistance reduction

![Graph showing average cell voltage vs. current density for different stacks.](image)

Fuel: 64%H₂/36%N₂, 80% Fuel Utilization 800°C

- U089 (10-Cell Stack)
- U059 (3-Cell Stack)
- U047 (3-Cell Stack)

Built and tested several multi-cell stacks under power generation and electrolysis mode for more than 1000 hrs

Performance improved with process control and contact resistance reduction
Stack Performance Demonstration

- 10-cell stack generated >6 SLPM H₂ with ~1.1 kW electrical input
- Excellent area specific H₂ production capability (>4.5cc/min/cm² at cell voltage less than 1.3V)
- >1000 hour dual mode operation

10-cell stack, 800C
70%H₂O/30%H₂ feed

Input: 1.1 kW electricity
Output: 32.6g/hr or 6.13SLPM H₂
54% steam utilization

Electrolysis
507 mA/cm²
Internal Reforming
400 mA/cm²
Electrolysis
507 mA/cm²
253 mA/cm²
Internal Reforming
350 mA/cm²
Cost of Hydrogen Estimate

- **$3.7/kgH₂** for distributed size (1500 kg H₂/day)
- **$2.7/kgH₂** for central station size (150,000 kgH₂/day) due to capital and O&M cost reduction
- Integration of heat and steam production within an industrial plant can reduce CoH
- **CoH** is most sensitive to the cost of electricity (CoE)
Electrolysis CoH Comparison

- **Alkaline**
  - Low stack cost
  - High feedstock cost

- **PEM**
  - Large stack cost
  - Effect of high pressure not considered

- **SOEC**
  - Lowest feedstock cost
  - Low CoH due to reduced feedstock cost
SOEC Technology Assessment

Thermodynamic efficiency

Steam Electrolysis at 800°C

Water Electrolysis at 80°C

\[ \eta_{ther} = \frac{\Delta H_{H2(IBF)}}{E_{electrolyzer}} + \frac{Q}{\eta_{electrical}} + \frac{S_{steam}}{\eta_{steam}} \]

Efficiency of Electrical Power Generation

Advantages:
- High thermodynamic efficiency
- Fast electrode kinetics at high temperature
- Low electrical energy demand

Challenges:
- Stack materials for performance and stability
- Reliable seals for efficient hydrogen collection
- Electrolyzer design and components fabrication for cost reduction
- System design for heat integration
- Enabling technologies such as high temperature recycle blower and high temperature heat exchanger

Electrical demand and specific H₂ generation capability

Total Cell Resistance=0.3ohm-cm²
Nersnt Potential = 0.875V @ 0 current density

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Preliminary RSOFC Technology Roadmap

Technology Feasibility
- Component Perf. • Seals • Interconnects • Cells
- Reliability • Robust Seals • Degradation
- Technology Demo • Small System • Efficiency • Dual Mode
- System Optimization • Design • High T HEXs • High T Recycle Blower
- Scale up • Large Cells • Stack Design
- Pressurization? • Stack • Durability
- Cost Reduction • Manufacturing Process • Low-cost Materials • BOP Components

POC Demo • Pressurized • Efficiency • Reliability
Summary

• Electrode development
  – Performance: LSCF>LSF>LSM
  – “Irreversibility” of oxygen electrode observed, associated with differences in vacancy diffusion and activation at electrode/electrolyte interface
  – Internal reforming with Ni-YSZ modeled and demonstrated

• Module and stack development
  – Module and stack performance improved by electrode engineering
  – Performance stability improved with coated interconnects
  – Demonstration stack operated over 1000 hours under dual mode
  – High power density of 480 mW/cm² at 0.7V and 80% fuel utilization in fuel cell mode and >6 SLPM hydrogen production in steam electrolysis mode using about 1.1 kW electrical power demonstrated

• Technology assessment and cost estimate
  – Flexibility for dual mode operation
  – Potentials for low cost and high efficient hydrogen production through steam electrolysis
  – Cost of hydrogen production at large scale estimated at ~$2.7/kg H₂, comparing favorably with other electrolysis technologies
  – Key challenges identified and preliminary technology roadmap generated
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