High Performance Flexible Reversible Solid Oxide Fuel Cell

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DE-FC36-04GO14351 Project ID:PDP15

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

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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

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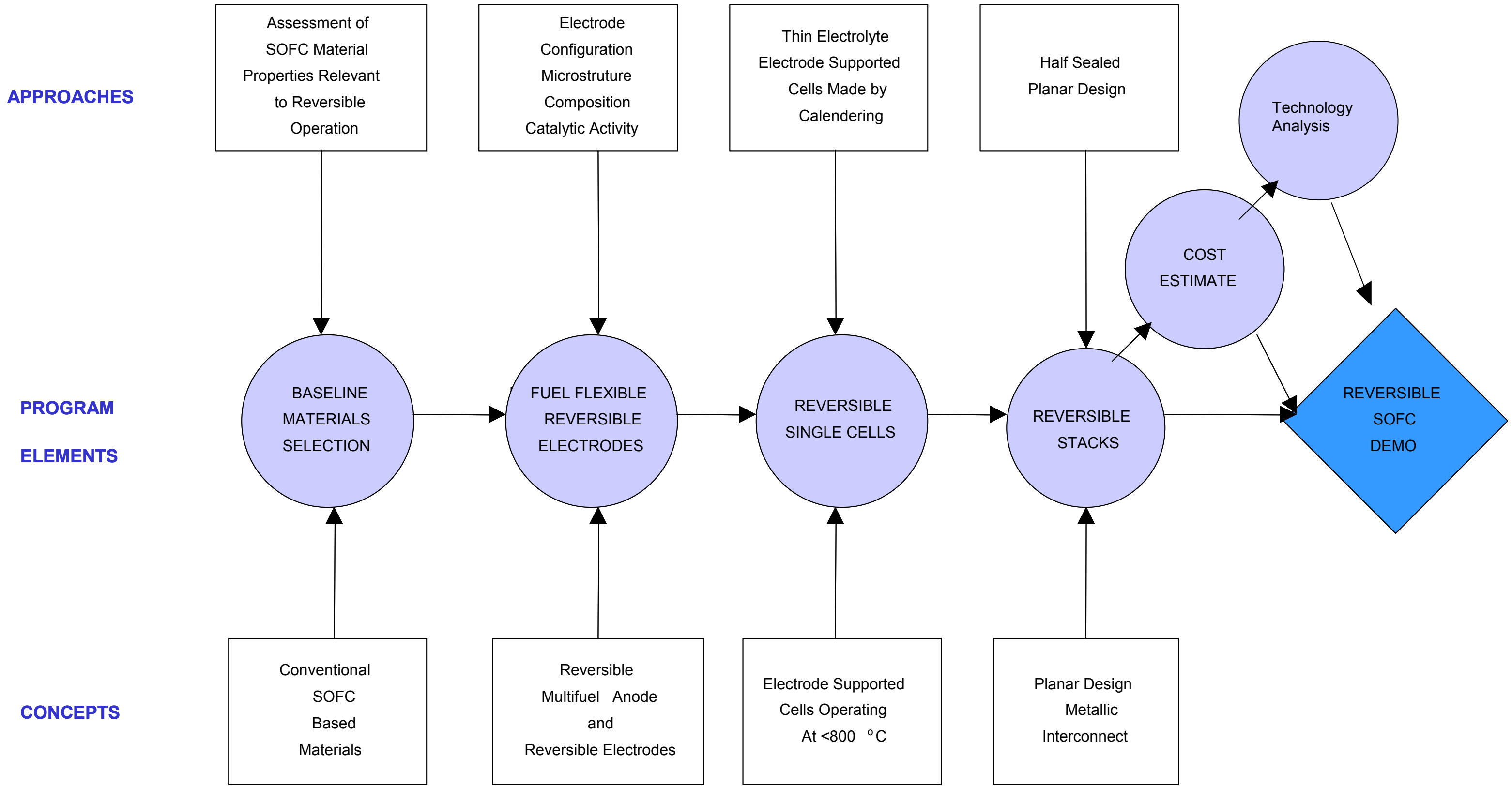
Approaches



Technical focuses:

– Reversible electrode modeling
– Electrode compositions and microstructure engineering

Key challenges:

– Performance for cost and efficiency
– Low degradation for reliability

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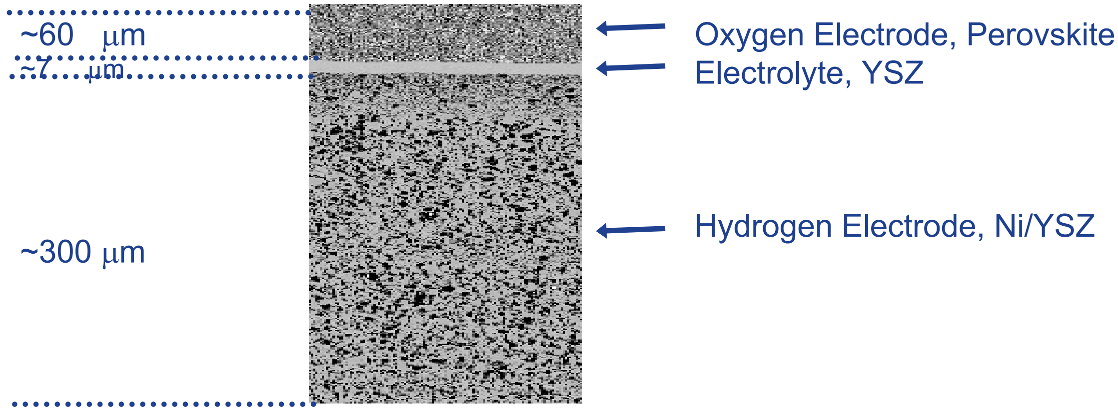
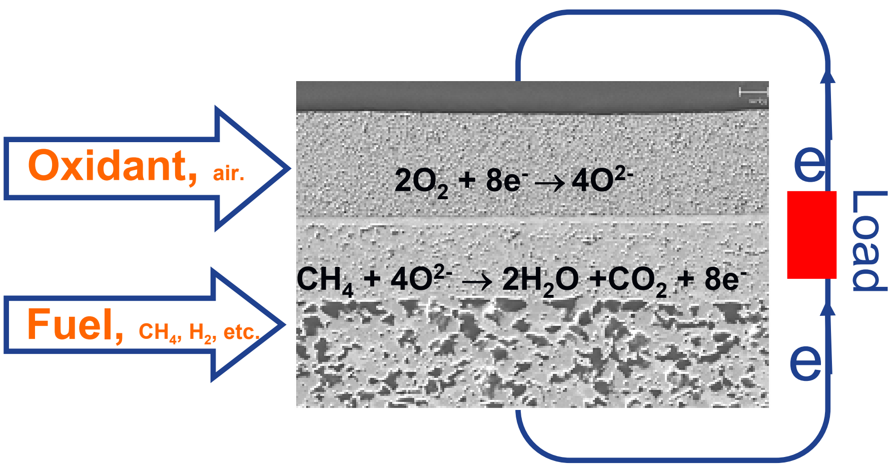
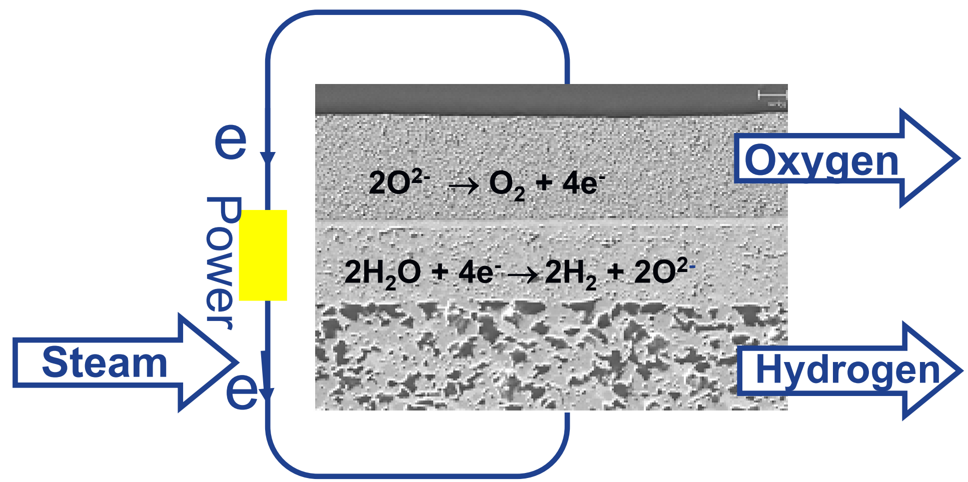
Cell Configuration



Power Generation Mode



Hydrogen Production Mode



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

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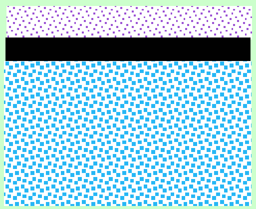
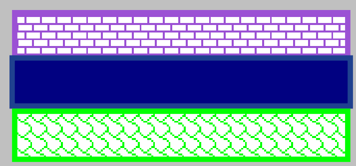
Stack Configuration

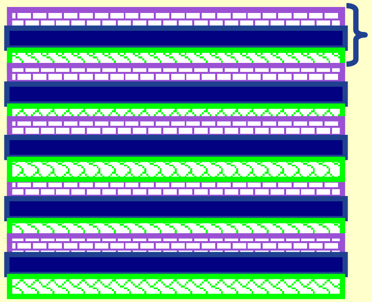
Cell



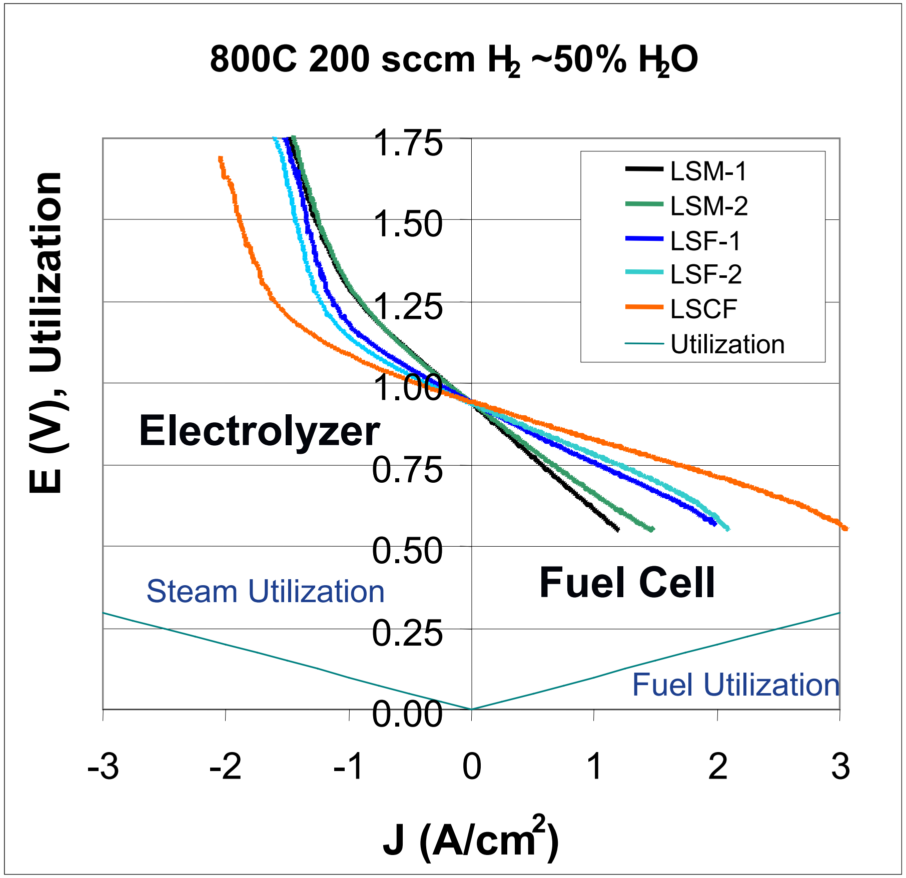
Module



Multi-cell Stack



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**

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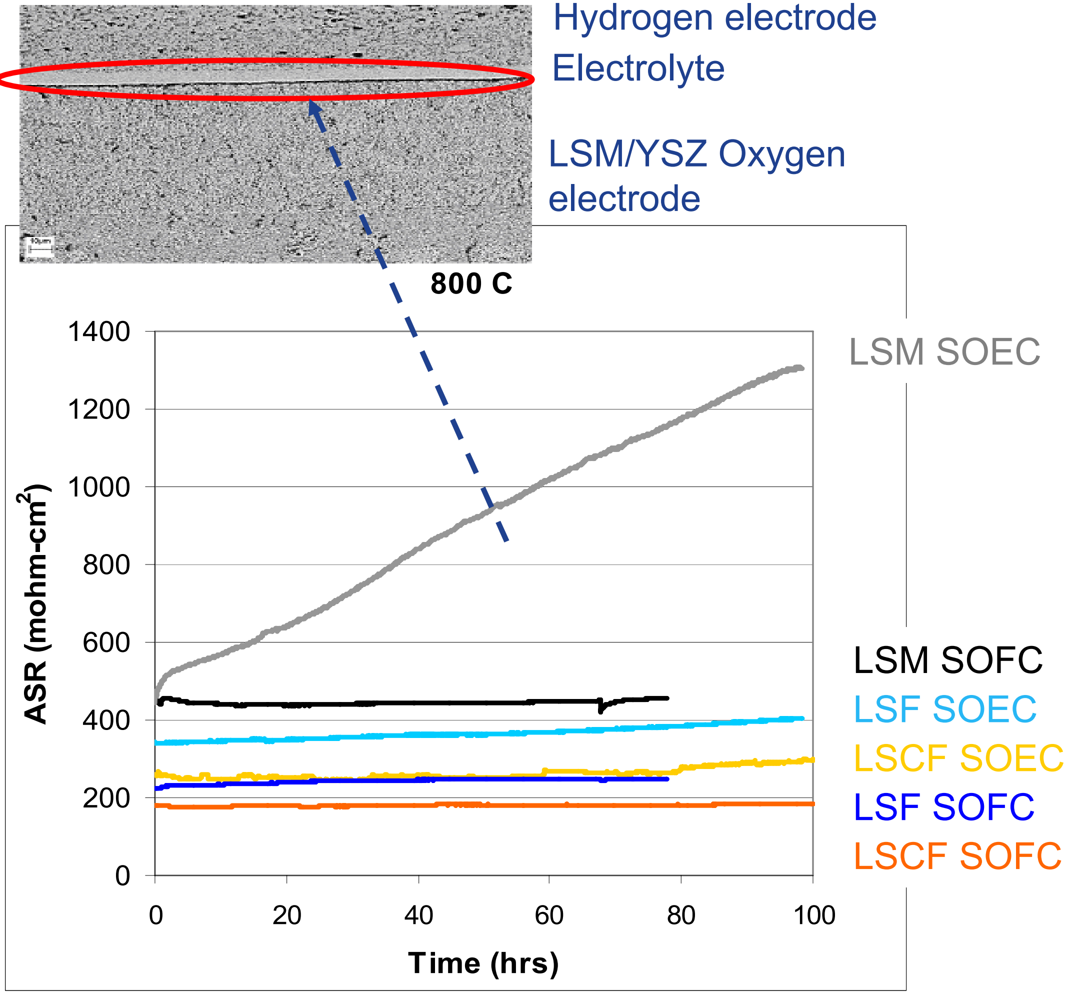
Oxygen Electrode Performance Stability



- **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**

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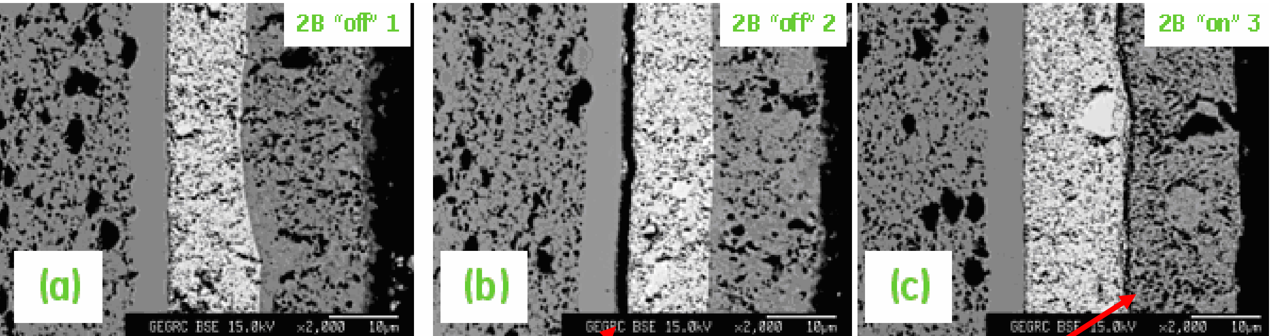
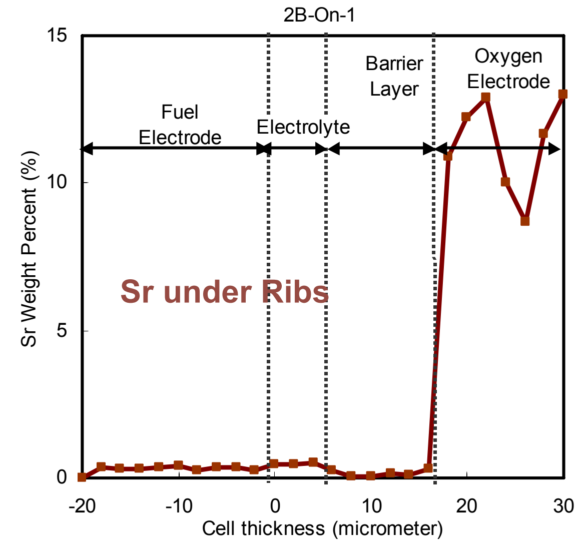
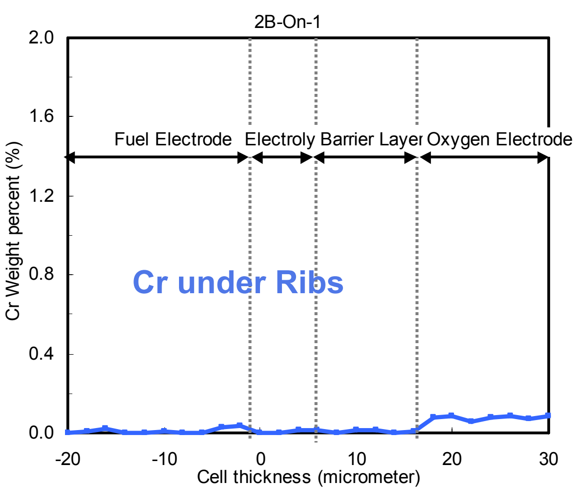
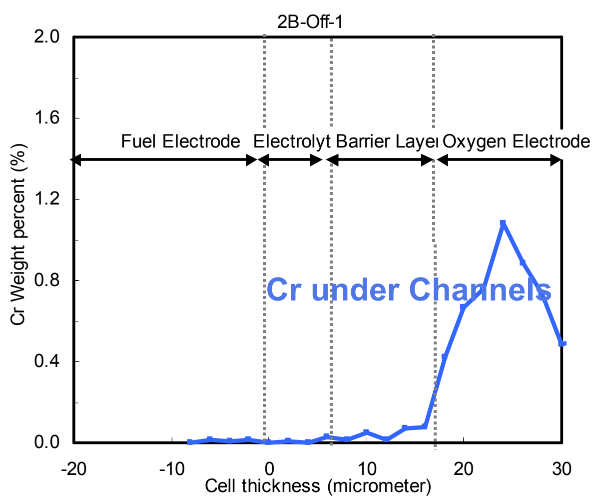
Oxygen Electrode Analysis

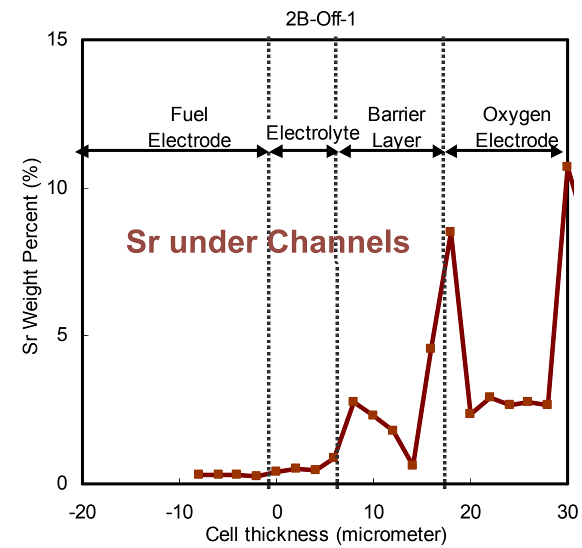




Interface delamination







Cr transport and accumulation in LSCF electrode

Sr migration and depletion?

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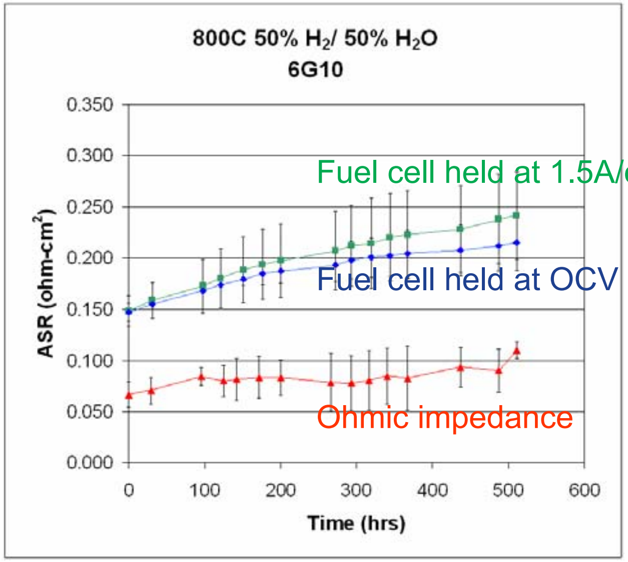
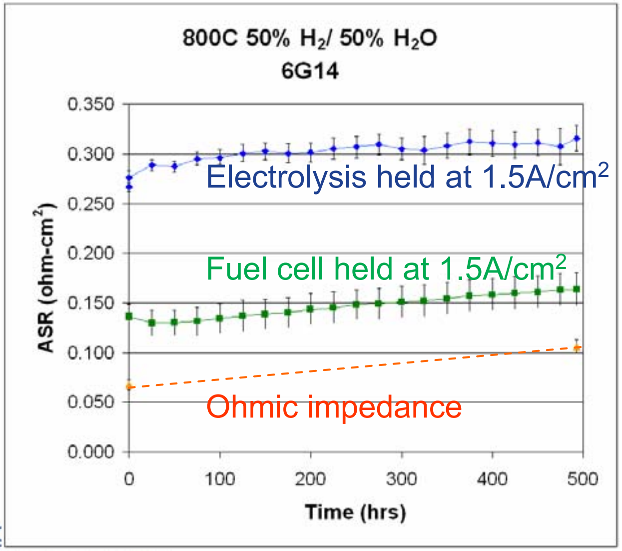
Performance Stability Improvement

Bare Stainless Steel Interconnect with LSCF Electrode



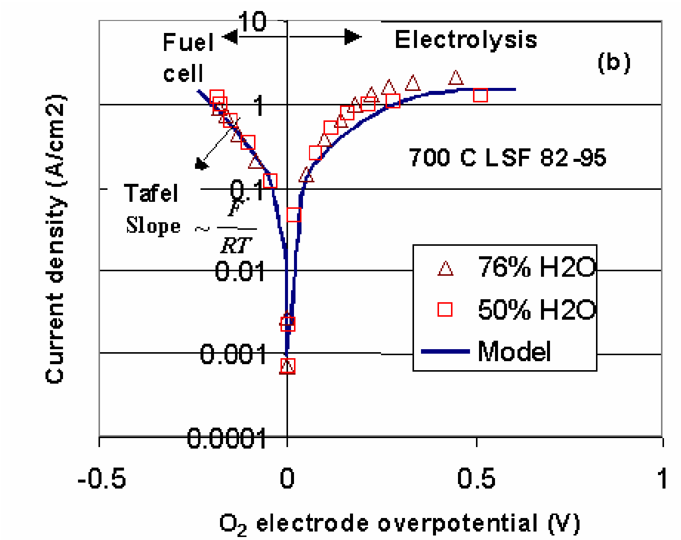
Coated Interconnect with LSCF Electrode



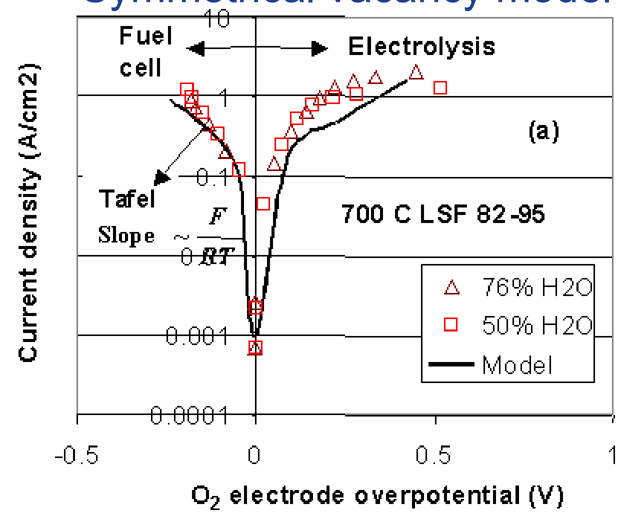
- **No significant difference in degradation rate between cells held under a constant load in fuel cell mode compared with cells that were held at OCV**
- **The dominant degradation mechanisms were likely to be thermally activated**
- **Coated interconnect significantly improved the performance stability**

Oxygen Electrode Reversibility

Non-symmetrical vacancy model



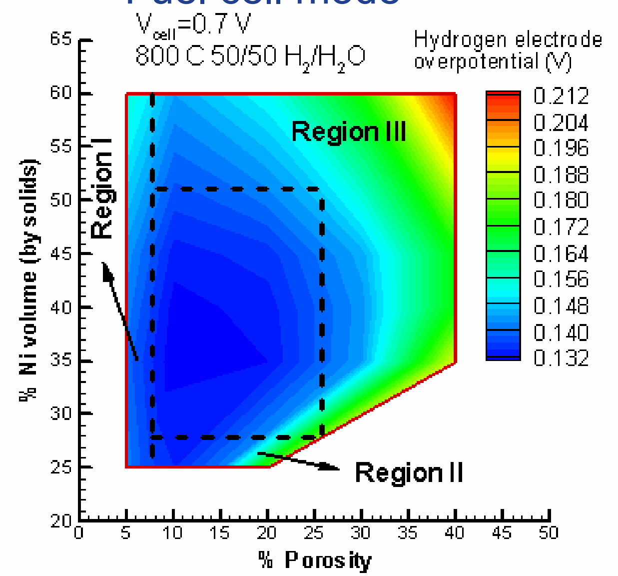
Symmetrical vacancy model



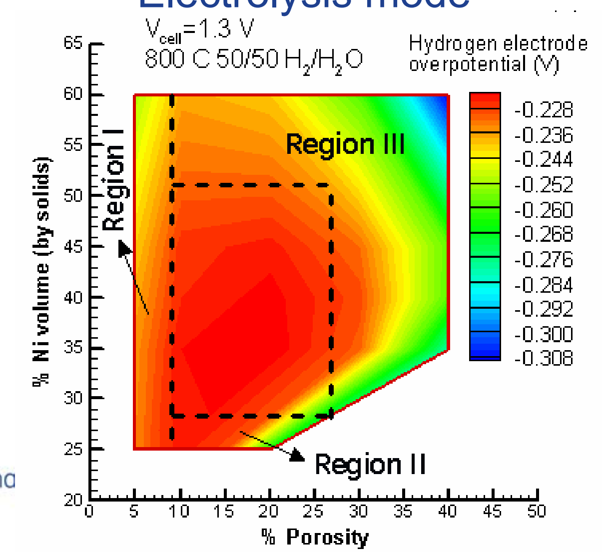
- **Vacancy diffusion and activation at the oxygen electrode/electrolyte interface are different for fuel cell mode and electrolysis mode**
- **Higher current densities can lead to depletion of vacancies at the interface in electrolysis mode**
- **Experimental data matched well with non-symmetrical vacancy model**

Hydrogen Electrode Performance

Fuel cell mode



Electrolysis mode



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

Conditions:
T = 800 C
Fuel = 50/50 H_2/H_2O
Active layer thickness= 16 μm
Active layer particle size=0.8 μm

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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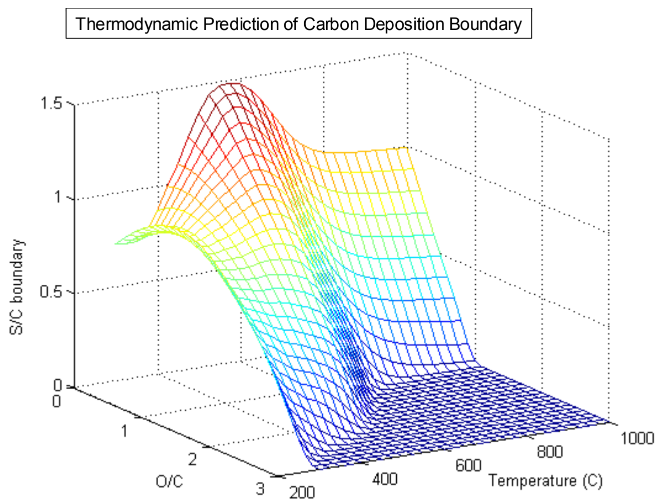
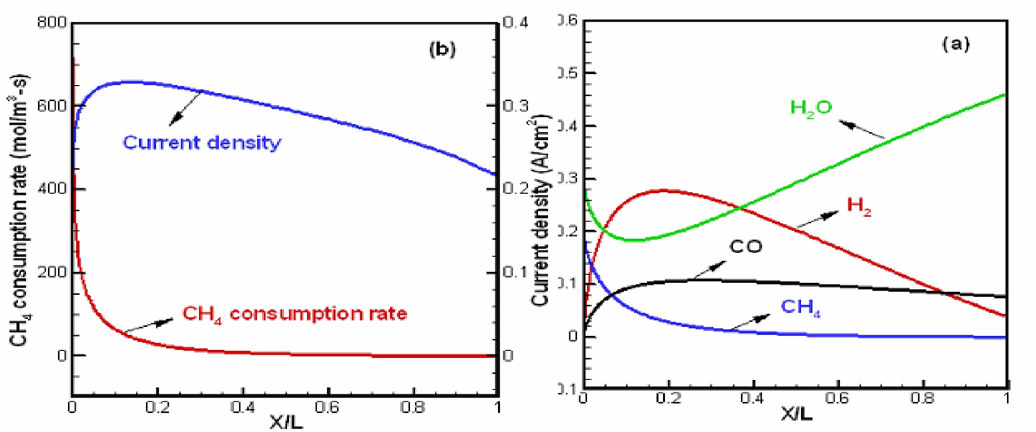
Hydrogen Electrode Internal Reforming





X is the distance from the fuel inlet along the channel and L is the total channel length

- **At 800°C, internal reforming kinetic was fast**
- **CH_4 conversion measured (gas chromatography) > 98%, agrees well with thermodynamic prediction**
- **Thermodynamic calculations defined carbon deposition boundary**

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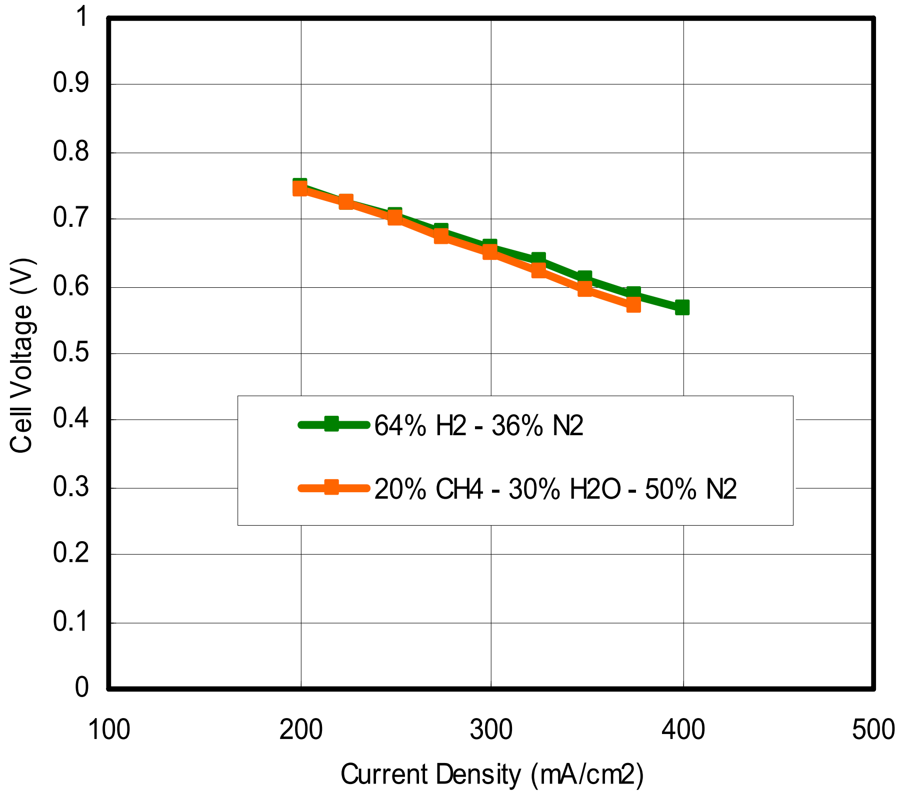
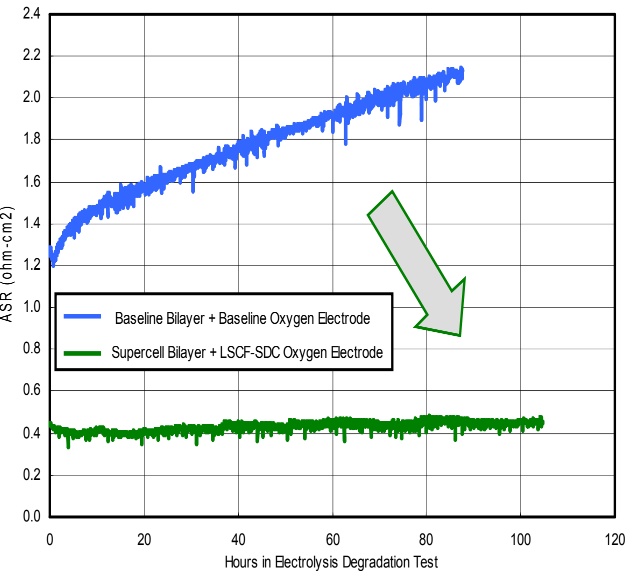
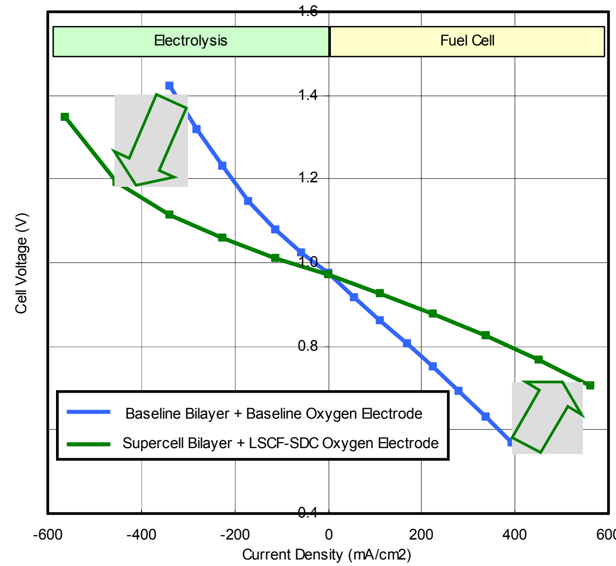
Performance with Internal Reforming

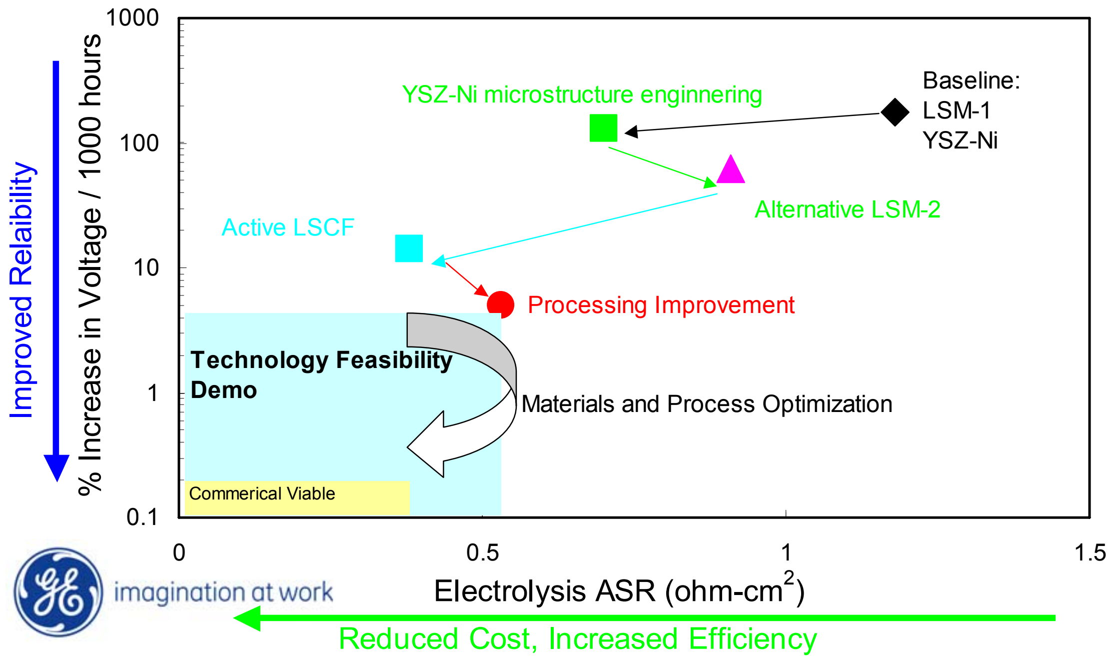


- **Performance (I-V curve) with internal reforming similar to that with 64% H_2/36%N_2 fuel**
- **Improved cells efficiency and potential system simplification with internal reforming**

Module Performance Improvement







- **LSCF performed better than LSM/YSZ electrode**
- **Substantial degradation rate reduction achieved with LSCF oxygen electrode in electrolysis mode**
- **Improved performance with electrode material selection and process engineering**

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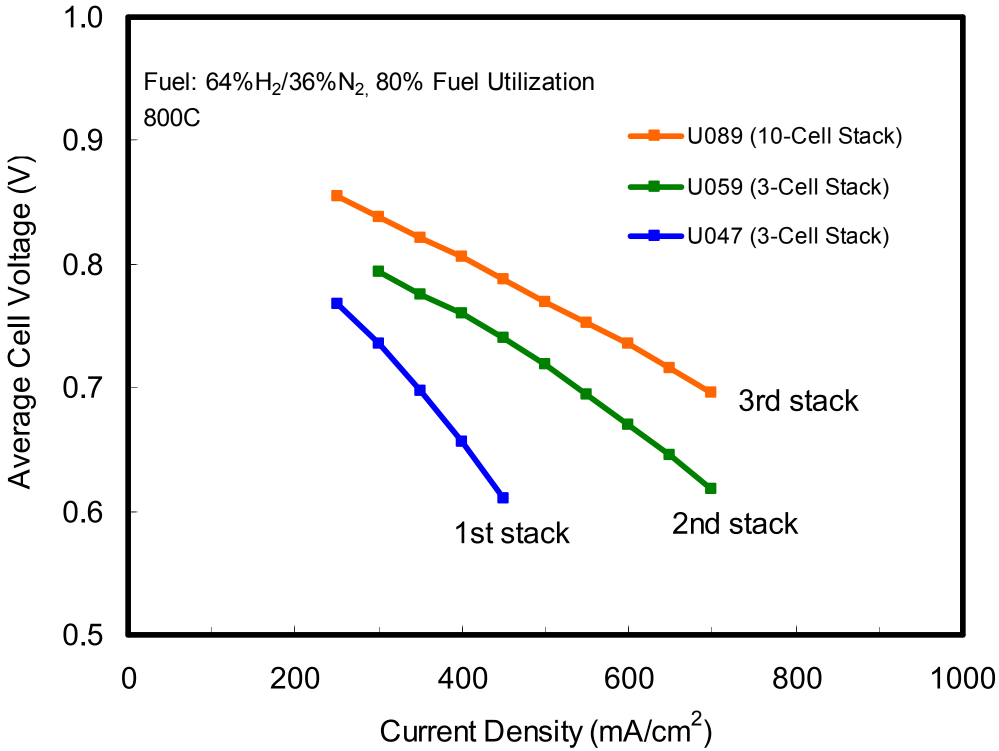
Multi-cell Stack Performance



- **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**

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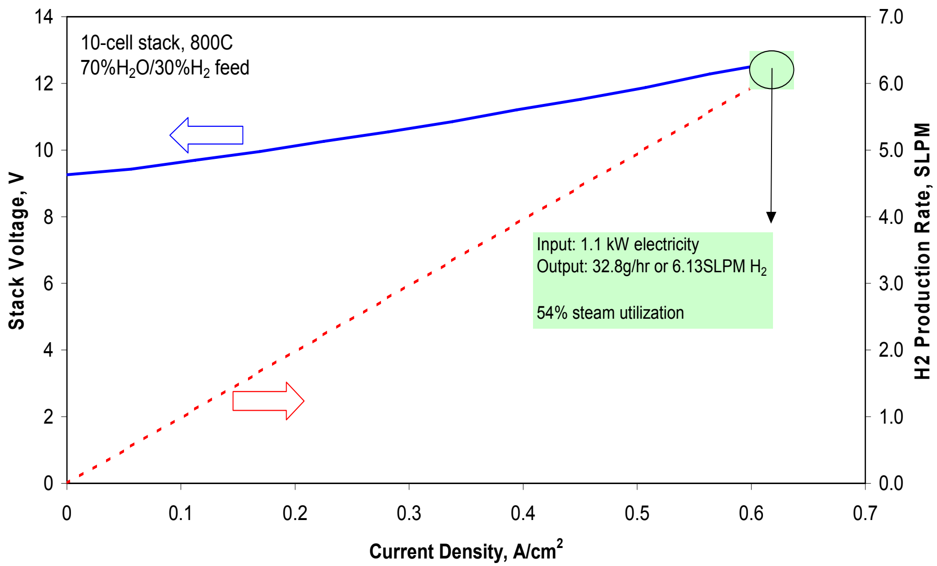
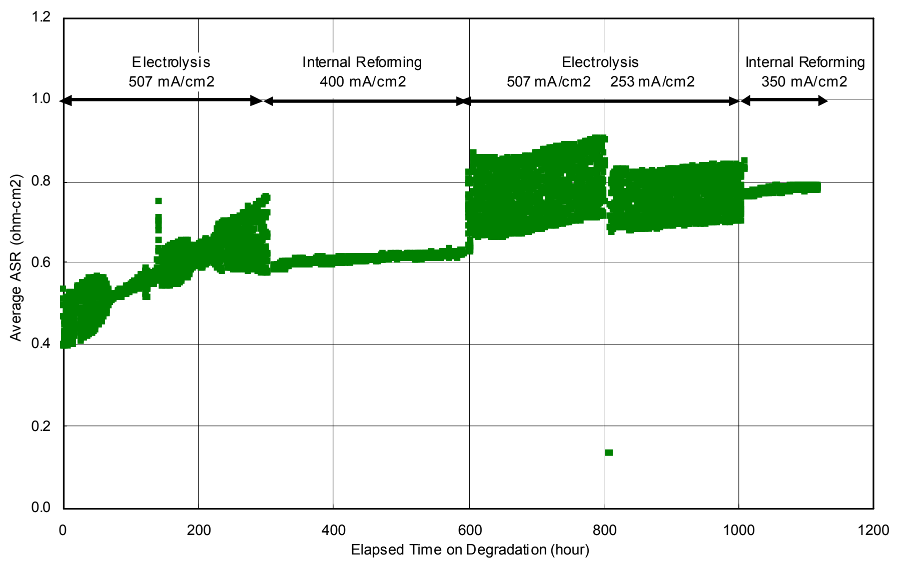
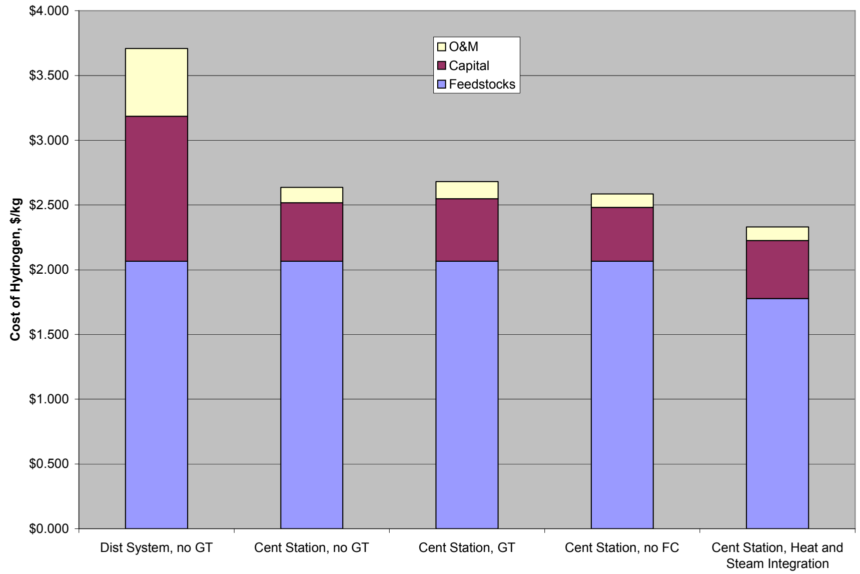
Stack Performance Demonstration

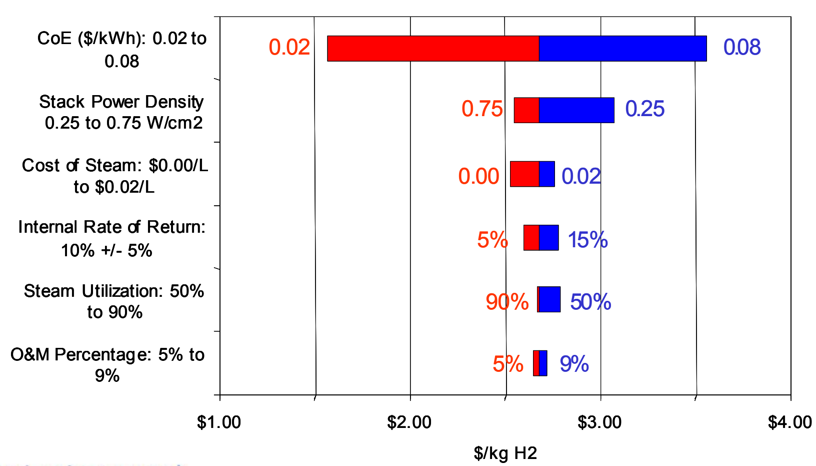




- **10-cell stack generated >6 SLPM H_2 with ~1.1 kW electrical input**
- **Excellent area specific H_2 production capability (>4.5cc/min/cm^2 at cell voltage less than 1.3V)**
- **>1000 hour dual mode operation**

Cost of Hydrogen Estimate





- $3.7/kgH_2$ for distributed size (1500 kg H_2 /day)
- $2.7/kgH_2$ for central station size (150,000 kgH_2/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)

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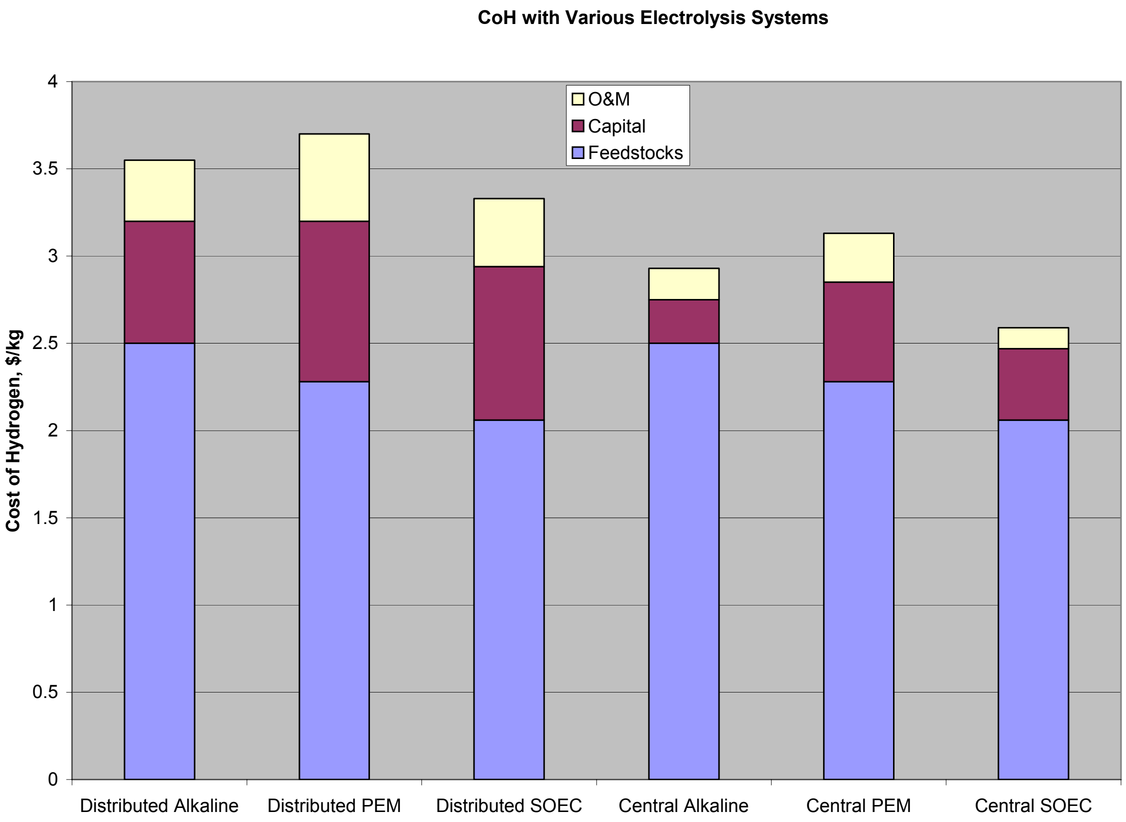
Electrolysis CoH Comparison



- **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**

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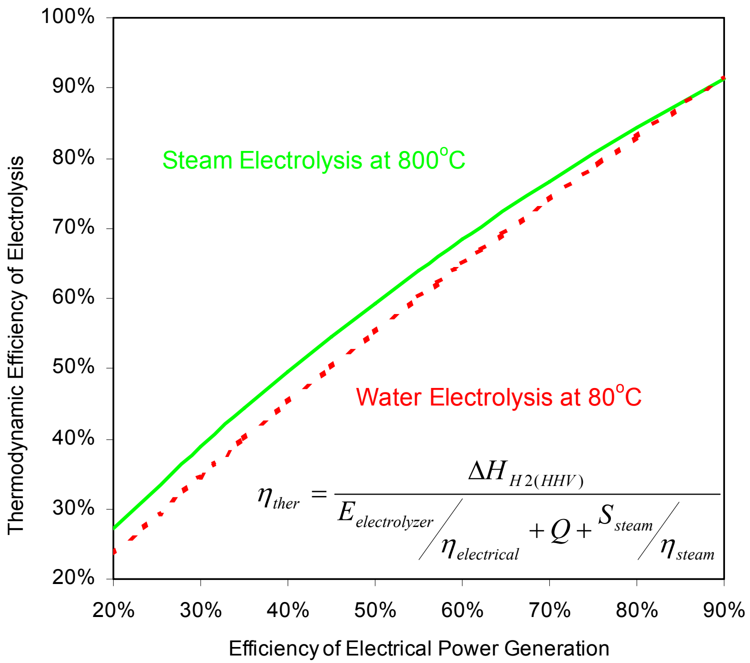
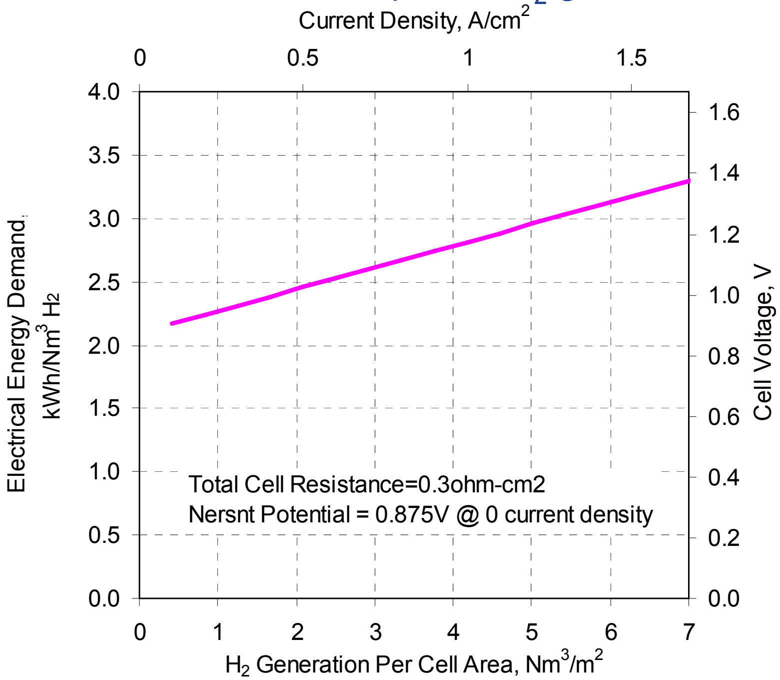
SOEC Technology Assessment

Thermodynamic efficiency



Electrical demand and specific H_2 generation capability



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

Preliminary RSOFC Technology Roadmap

Technology Feasibility

Technology Demo
- Small System
- Efficiency
- Dual Mode

System Optimization
- Design
- High T HEXs
- High T Recycle Blower

POC Demo
- Pressurized
- Efficiency
- Reliability

Component Perf.
- Seals
- Interconnects
- Cells

Reliability
- Robust Seals
- Degradation

Scale up
- Large Cells
- Stack Design

Pressurization?
- Stack
- Durability

Cost Reduction
- Manufacturing Process
- Low-cost Materials
- BOP Components

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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/cm^2 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 H_2, comparing favorably with other electrolysis technologies
  - Key challenges identified and preliminary technology roadmap generated

Acknowledgement

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