High Temperature Solid Oxide Electrolyzer System

Steve Herring
Jim O’Brien, Paul Lessing, Will Windes, Dan Wendt, Carl Stoots, Grant Hawkes, Mike Mc Kellar, Manohar Sohal
Idaho National Laboratory

Joseph J. Hartvigsen, S. Elangovan, Dennis Larsen
Ceramatec, Inc.

Mark Petri, Richard Doctor, Bilge Yildiz, Diana Matonis, Tanju Sofu, Debbie Myers
Argonne National Laboratory

Brian Bischoff
Oak Ridge National Laboratory

2005 DOE Hydrogen, Fuel Cells & Infrastructure Technologies Program Review
Overview

Budget
(total for INL plus partners below)

FY-04: $1050 k
FY-05: $1440 k

Partners

Ceramatec, Inc.
Development of planar cell technology

Argonne National Laboratory
Computation Fluid Dynamics of Cells
Overall Plant Flowsheet
Advanced Electrode and Electrolyte Materials

Oak Ridge National Laboratory
High Temperature Inorganic Membranes for Steam/Hydrogen separations
Technical Barriers

Adapted from 3.1.4.2.2 Hydrogen Generation by {Water} Electrolysis

G. Capital Cost - R&D is needed to develop lower cost materials with improved manufacturing capability to lower capital costs while improving the efficiency and durability of the system. Development of larger systems is also needed to improve economies of scale.

H. System Efficiency – Development is needed for low-cost cell stack optimization considering efficiency, electrochemical compression and durability.

I. Grid Electricity Emissions – Low-cost, carbon-free electricity sources are needed.

K. Electricity Costs – High Temperature solid oxide electrolysis can use lower cost energy in the form of steam for water splitting to decrease electricity consumption. Technically viable systems for low-cost manufacturing need to be developed for this technology.
Research Objectives

- Develop energy-efficient, high-temperature, solid-oxide electrolysis cells (SOECs) for hydrogen production from steam
- Develop and test integrated SOEC stacks operating in the electrolysis mode
- Develop optimized plant configuration for coupling to Generation IV Reactor
- Combine components in an Integrated Laboratory-scale Experiment
- Scale-up to a 200 kW Pilot Plant and a 1 MW Engineering Demonstration Facility
Approach (vs Objectives)

• Develop energy-efficient, high-temperature, solid-oxide electrolysis cells (SOECs) for hydrogen production from steam.
  – Optimize energy efficiency, cost and durability
    ▪ optimize electrolyte materials (e.g., YSZ, ScSZ, sealants)
    ▪ investigate alternate cell configurations (e.g., electrode-supported or tubular)
• Develop and test integrated SOEC stacks operating in the electrolysis mode with an aim toward scale-up to a 200 kW Pilot Plant and a 1 MW Engineering Demonstration Facility
  – Increase SOEC stack durability and sealing with regard to thermal cycles
  – Improve material durability in a hydrogen/oxygen/steam environment
  – Perform a progression of electrolysis stack testing activities at increasing scales and complexities
  – Develop computational fluid dynamics (CFD) capability for SOEC
  – Utilize advanced systems modeling codes (e.g. HYSYS, ASPEN)
  – Perform Cost and Safety Analyses
## HTE FY-05 Task Area Overview

### HTE Systems Definition

<table>
<thead>
<tr>
<th>WP#</th>
<th>Org/ PIs</th>
<th>FY 05 k$ (inc. FY04 Carryover)</th>
<th>Description/Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ID15EL11]</td>
<td>INL / O’Brien, Herring</td>
<td>400</td>
<td>Engineering analyses in support of experiments and development of larger scale HTE facilities.</td>
</tr>
<tr>
<td>[CH15EL11]</td>
<td>ANL / Petri</td>
<td>237</td>
<td>ANL work also includes SOEC materials research</td>
</tr>
</tbody>
</table>

### HTE Experiments

<table>
<thead>
<tr>
<th>WP#</th>
<th>Org/ PIs</th>
<th>FY 05 k$ (inc. FY04 Carryover)</th>
<th>Description/Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ID15EL21]</td>
<td>INL / Stoots, Herring</td>
<td>832</td>
<td>HTE Experimental activities, including scale-up.</td>
</tr>
</tbody>
</table>

### HTE Membrane Technologies

<table>
<thead>
<tr>
<th>WP#</th>
<th>Org/ PIs</th>
<th>FY 05 k$ (inc. FY04 Carryover)</th>
<th>Description/Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>[OR15EL21]</td>
<td>ORNL / Bischoff</td>
<td>60</td>
<td>Evaluate the applicability of inorganic high-temperature membranes for use in large scale HTE operations</td>
</tr>
</tbody>
</table>
## Technical Accomplishments

### HTE Accomplishments since May 2004

| FY2004 | • An assessment of the engineering materials issues and requirements for construction of an HTE system was completed to provide input to the high temperature materials testing program.  
• The high-temperature electrolysis system configuration study was completed, identifying the options and technical issues for HTE systems, including electrolyzer cell and module configurations and high-temperature steam distribution.  
• An experiment plan for the development of high-temperature electrolysis components and systems was completed to provide input to the longer term scaling of HTE systems.  
• An assessment of the high temperature reactor and HTE process interface requirements was completed  
• Completed engineering analyses for high-temperature electrolysis scaling demonstration experiments, including steam distribution systems and electrolyzer cell and module configurations.  
• Completed a series of button cell experiments to examine cell operational characteristics under a range of conditions.  
• Completed initial testing of a 10 cell stack in preparation for hydrogen production testing.  
• Complete final design for laboratory-scale HTE experiments |
| FY2005 (to date) | • Developed engineering process model for HTE system performance evaluation, including the development of CFD and electrochemical modeling for planar geometry electrolyzer cells, including mass and thermal transport.  
• Demonstrated high-temperature electrolysis stack testing at a production rate of 50 normal liters per hour of hydrogen.  
• Produced 15 button cells using plasma deposition on nickel aluminide substrate (now being tested) |
### Theoretical Efficiency of High Temperature Electrolysis

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>Electrical generation eff.</th>
<th>Hydrogen production eff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>35%</td>
<td>40%</td>
<td>45%</td>
</tr>
</tbody>
</table>

#### Energy Input to Electrolyser

- \( \Delta H_R \): Total Energy Demand
- \( \Delta G_R \): Electrical Energy Demand
- \( T \Delta S_R \): Heat Demand

<table>
<thead>
<tr>
<th>Reactor Outlet Temperature (°C)</th>
<th>Energy Demand per unit mass of steam (MJ/kg H₂O)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>0</td>
<td>35%</td>
</tr>
<tr>
<td>550</td>
<td>200</td>
<td>40%</td>
</tr>
<tr>
<td>600</td>
<td>400</td>
<td>45%</td>
</tr>
<tr>
<td>650</td>
<td>600</td>
<td>50%</td>
</tr>
<tr>
<td>700</td>
<td>800</td>
<td>55%</td>
</tr>
</tbody>
</table>

*Note: P=1 atm*
Schematic of Stack Testing Apparatus

- N₂
- H₂ + Ar + H₂
- Air + O₂
- H₂O + Ar + H₂
- 3-way valve
- Humidifier bypass
- Stack
- Furnace
- Cooling Water
- Condenser
- Power Supply
- H₂ Exhaust
- Air
- Air + O₂

Project ID: PD24
5-25-2005
Electrolysis Stack Performance Testing Hardware

10-cell electrolysis stack; has produced up to 100 SLPH H₂

Stack mounted on test fixture

View of air flow passages, inside furnace at 800°C
Hydrogen Production at 830° C

Test conditions:
N2: 2000 sccm
H2: 400 sccm
H2O inlet dewpoint: 80 C
T_furnace: 830 C

Hydrogen production rate, NL/hr:
72
60
48
36
24
12
0

Based on stack ionic current

Based on dewpoint measurements
Energy Budgets in fuel-cell and electrolysis modes

Stack ASR = 1.25, $T = 927$ $^\circ$C, $y_{H_2,i} = 0.1$, $y_{H_2,o} = 0.95$

$$V_{tn} = -\frac{\Delta h_R}{2F}$$

(1.291 V at 1200 K)
Overall hydrogen production efficiencies as a function of power-production thermal efficiency and electrolyzer per-cell operating voltage.
Stack temperatures during a DC potential sweep; comparison to FLUENT results

<table>
<thead>
<tr>
<th>sweep #</th>
<th>sccm N2</th>
<th>sccm H2</th>
<th>T_{dp,i} (C)</th>
<th>T_{f} (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>2018</td>
<td>411</td>
<td>82.9</td>
<td>800</td>
</tr>
</tbody>
</table>

Stack operating voltage (V) vs. Stack temperatures (C)
FLUENT Single-Cell SOEC Model

1x Scale in z-direction

10x Scale in z-direction

Top separator plate
Edge rails
Air flow channel
Air electrode
Electrolyte
Insulator
Steam/hydrogen electrode
Steam/hydrogen flow channel
Edge rails
Bottom separator plate
CFD Contour Plots
Electrolyte/insulator temperature contours

- 1100 0.156 A/cm²; 1.164 V
- 1105.5 0.2344 A/cm²; 1.306 V
- 1197 0.4688 A/cm²; 1.640 V

1091 near thermal minimum
near thermal neutral
above thermal neutral

Electrolyte current density contours

- 1100 -1.46e+03; -2.097
- 1105.5 -1.5e+03; -2.07e+03
- 1197 -3.0e+03; -3.892

- 1091 -1.2e+03; -1.878
- 1104.5 -1.45e+03; -2.097
- 1139 -2.13e+03; -2.734

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- 1105.5 -1.5e+03; -2.07e+03
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Electrode exchange current densities and several gap electrical contact resistances were determined empirically by comparing FLUENT predictions with stack performance data.
ANL’s oxygen and hydrogen electrode development

ANL’s non-stoichiometric LSF (LSF-ns) shows improved oxygen electrode performance over LSM.
- Further improvement in LSF-ns performance is expected by optimizing the electrode microstructure and electrode/electrolyte interface.
- Single-phase, mixed-conducting hydrogen electrodes are being studied as alternatives to Ni-YSZ (Nickel – Yttria Stabilized Zirconia).
  - Addresses oxidation-related degradation in high steam environment.

Area-specific resistance (ASR), Ω-cm²

<table>
<thead>
<tr>
<th>Oxygen Electrode Composition</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>800</td>
</tr>
<tr>
<td>La_{0.8}Sr_{0.2}MnO_{3} (LSM)</td>
<td>8.4</td>
</tr>
<tr>
<td>La_{0.8}Sr_{0.2}FeO_{3} (LSF-s)</td>
<td>2.2</td>
</tr>
<tr>
<td>LaNiO_{3} (LN)</td>
<td>1.4</td>
</tr>
<tr>
<td>La_{0.8}Sr_{0.2}CoO_{3} (LSC)</td>
<td>1.3</td>
</tr>
<tr>
<td>La_{0.7}Sr_{0.2}FeO_{3} (LSF-ns)</td>
<td>0.81</td>
</tr>
</tbody>
</table>

-s: stoichiometric
-ns: non-stoichiometric
nd: no data
## Timeline

**Project start: Jan ‘03 (DOE-EE)**  
(became part of the Nuclear Hydrogen Initiative Jan ’04)

<table>
<thead>
<tr>
<th>Year</th>
<th>Activities</th>
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| **FY2005** | • Develop engineering process model for HTE system performance evaluation, including the development of CFD and electrochemical modeling for planar geometry electrolyzer cells, including mass and thermal transport. **Done**  
• Demonstrate high-temperature electrolysis stack testing at a production rate of 50 normal liters per hour of hydrogen. **Done**  
• Demonstrate high-temperature electrolysis stack testing at a production rate of 100 normal liters per hour of hydrogen.  
• Complete conceptual design documentation for HTE pilot-scale experiments |
| **FY2006** | • Complete design of HTE integrated laboratory-scale experiments  
• Construct stack /module arrays for integrated laboratory-scale experiments |
| **FY2007** | • Begin HTE integrated lab-scale experimental operations  
• Complete HTE cell testing  
• Conduct HTE stack / module tests  
• Perform initial testing on candidate pilot scale module tests  
• Complete preliminary pilot scale experiment design |
| **FY2008** | • Pilot-scale experiment final design  
• Complete HTE integrated lab-scale experimental operations  
• Implement cell/module technology improvements |
Supplemental Slides

The following three slides are for the purposes of the reviewers only – they are not to be presented as part of your oral or poster presentation. They will be included in the hardcopies of your presentation that might be made for review purposes.
INL HTE Publications since May 2004:


Hydrogen Safety

The most significant hydrogen hazard associated with this project is:

Compressed gas handling
Hot surfaces
Hydrogen combustion or explosion hazard
Hydrogen Safety

Our approach to deal with this hazard is:

**Independent Hazards Review**
Independent, laboratory-wide review of operating procedures and safety measures

**Experiment design**
Over-pressure prevention – see experiment schematic,

**Instrumentation**
Hydrogen Detectors
On-line (firewall-protected) access to experiment parameters

**Training of Project Personnel:**
Compressed gas training (TRN1041)
R&D Laboratory awareness (TRN670)
Flammable & combustible materials (SMJS992B)
Chemical Hygiene (TRN13)