Modular SOEC System for Efficient H₂ Production at High Current Density

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2018 DOE Hydrogen and Fuel Cells Program Review

Project ID# TV041

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Overview

Timeline
• Project Start Date: 10/01/2016
• Project End Date: 09/30/2019

Barrier
• Key barriers addressed in the project are:
  – F. Capital Cost
  – G. System Efficiency and Electricity Cost
  – J. Renewable Electricity Generation Integration

Budget
• Total Project Budget: $3,750,000
• Total Recipient Share: $750,000
• Total Federal Share: $3,000,000
• Total DOE Funds Spent*: $912,770
  * Estimated as of 3/31/18

Partner
• Versa Power Systems (VPS)
• DOE/FE, National Energy Technology Laboratory (NETL)
**Objective:**

- Demonstrate the potential of Solid Oxide Electrolysis Cell (SOEC) systems to produce hydrogen at a cost of <$2 /kg H₂ exclusive of delivery, compression, storage, and dispensing

**Project Goals:**

- Improve SOEC performance to achieve >95% stack electrical efficiency based on LHV of H₂ (>90% system electrical efficiency) resulting in significant reduction in cost of electricity usage for electrolysis
- Enhance SOEC stack endurance by reducing SOEC degradation rate:
  - Single cell degradation rate of ≤1%/1000 hours
  - Stack degradation rate of ≤2%/1000 hours
- Develop SOEC system design configuration to achieve >75% overall (thermal + electric) efficiency
- Impart subsystem robustness for operation on load profiles compatible with intermittent renewable energy sources
Cell Technology Improvement

- Top-down approach to explore the effects of system and stack operating conditions on performance and durability
- Perform single cell tests to establish desirable stack and system operating conditions and reduce performance degradation rate
  - Operating voltage/current density
  - Hydrogen/steam recycling
  - Operating pressure
  - Operating temperature
  - Steam utilization
- Conduct post-test microstructural analysis to understand and improve cell and interconnect materials stability
• Develop components for scale up of the existing baseline SOEC stack design using Compact SOFC Architecture (CSA) stack platform to meet the project goals for performance and endurance
  – Full size CSA stack (350 cells) has a capacity of 25 kg H$_2$/day at a current density of 1 A/cm$^2$
• Design, build and test subscale technology stacks in 2 to 5 kg H$_2$/day size range to verify functionalities of stack components
• Demonstrate 4kg H$_2$/day production in a stack with electric efficiency better than 95% and degradation of less than 2%/khr1000 hr

Baseline 20 cell stack: Demonstrated stable electrolysis operation at 2 A/cm$^2$
Breadboard System Demonstration

- Develop basis of design and operation for a breadboard demonstration prototype:
  - >4 kg H₂/day capacity
  - Operating current density 1 to 2 A/cm²
  - Thermal integration to quantify system heat input needs by either heat recovery from effluent streams or using a steam generator

- Develop design of the breadboard system:
  - Process design (e.g. P&IDs, equipment specs, HAZOP safety analysis, and controls)
  - Mechanical design (e.g. thermally self-sustained stack module, equipment integration, and solid modelling)
  - Electrical design (e.g. power supply, instrumentation, and control hardware)

- Demonstrate targeted metrics:
  - >1000 hours steady state operation
  - >75% overall (electrical + thermal) system efficiency
  - >90% system electrical efficiency
  - Ability to operate intermittently
Leverage FCE’s SOFC baseline cell and stack technology as well as system design and scale-up in development of electrolysis systems.

Develop basis of design for a commercial forecourt 1500 kg H₂/day commercial system

- Utilize CSA stack design architecture

Develop flow sheet alternatives to optimize system performance and cost.

Perform simulation studies using Heat and Mass Balance models.

Develop Balance-of-Plant (BoP) Equipment specifications and cost.

Investigate economic impact of

- Electricity Cost
- Capital Cost
- System resiliency and dynamic response

Employ H2A analysis model.
<table>
<thead>
<tr>
<th>Task / Subtask Title</th>
<th>Milestone Description</th>
<th>Completion Date</th>
<th>Status (Percent Completed)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Endurance Improvement</strong></td>
<td>Complete 1000 hr test of single cell with voltage degradation rate of ≤2%/1000 hrs</td>
<td>12/31/2017</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Complete 1000 hr characterization test of SOEC single cell with voltage degradation rate &lt; 1%/1000 hours</td>
<td>12/31/2018</td>
<td></td>
</tr>
<tr>
<td><strong>Technology Stack Tests</strong></td>
<td><em>Stack testing (≥1000 hours) with electrical efficiency ≥95% (LHV based) at ≥1 A/cm² &amp; degradation rate ≤4%/1000 hrs</em></td>
<td>3/31/2018</td>
<td>100%</td>
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<tr>
<td></td>
<td><strong>Go-No-Go Decision: Success criteria for continuation to BP2</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Complete post-test analysis of the metric stack to be utilized in further reduction of the stack degradation rate</td>
<td>6/30/2018</td>
<td></td>
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<tr>
<td></td>
<td>Complete demonstration testing of a SOEC stack capable of &gt; 4 kg H₂/day for ≥1000 hours and a performance degradation rate of &lt;2%/1000 hours</td>
<td>3/31/2019</td>
<td></td>
</tr>
<tr>
<td><strong>System Configuration and Parametric Analysis</strong></td>
<td>Develop electrolysis performance characteristic maps of system operating parameters to be used for optimization</td>
<td>3/31/2017</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Develop system configuration and operational parameters for achieving &gt;75% overall system efficiency</td>
<td>9/30/2017</td>
<td>100%</td>
</tr>
<tr>
<td><strong>Detailed System Design</strong></td>
<td>Complete detailed system design for &gt;4kg H₂/day demonstration</td>
<td>9/30/2018</td>
<td>10%</td>
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<tr>
<td></td>
<td>Complete conceptual process design for forecourt-scale HTWS plant with a system electrical efficiency &gt;90% (based on LHV of H₂), an overall system efficiency (electrical + thermal) &gt;75 % and ability to operate intermittently</td>
<td>6/30/2019</td>
<td></td>
</tr>
<tr>
<td><strong>Demonstration System Testing</strong></td>
<td>Create conceptual design of a &gt; 4 kg H₂ / day SOEC demonstration system with estimated overall efficiency &gt;75%</td>
<td>3/31/2018</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td><strong>Go-No-Go Decision: Success criteria for continuation to BP2</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Complete procurement and assembly of &gt;4 kg H₂/day SOEC system</td>
<td>3/31/2019</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Complete demonstration of the &gt;4 kg H₂/day SOEC system with &gt;1000 hr of steady state operation and with operation on load profiles relevant to intermittent renewable energy sources</td>
<td>9/30/2019</td>
<td></td>
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</tbody>
</table>
Test of HiPoD (High Power Density) cell (5 cm x 5 cm x 0.03 cm) at 1 A/cm²

- Demonstrated voltage degradation rate of 20 mV/1000h or 1.6 %/1000h over the last 1.4 years after initial stabilization including hard shutdowns.

- Technical Accomplishments and Progress:
  - Multiple shutdowns / uncontrolled thermal cycles due to power failure.
  - Degradation Rate = 28 mV/khrs over 12,515 hours.
  - Degradation Rate = 20 mV/khrs over last 11,682 hours.

- Operating Conditions:
  - T = 750°C
  - I = 16 A (1 A/cm²)
  - Cathode Flow = 0.136 SLPM H₂, 78% humidity
  - Anode Flow – 0.467 SLPM Air Flush
Effect of Operating Conditions on Cell Degradation Test at 1 A/cm²

Test of HiPoD (High Power Density) cell (5 cm x 5 cm x 0.03 cm) at 1 A/cm²

- Operating conditions (e.g. current density, steam concentration and utilization) have significant effects on the SOEC degradation rate
- Two key mechanisms of degradation are apparent from autopsies of long-term tests:
  - Depletion of nickel in the cathode, at or near electrolyte interface
  - Formation of reaction layer in anode side
- Tests to date aimed at evaluating the relative importance of these mechanisms
- Continue efforts to increase the stability of the SOEC and reduce the degradation rate to below 1%/1000 hours
  - Modification of the cathode by addition of alternative materials to study the effects on degradation rate

Alternative test conditions may reduce degradation rate
Milestone 1.4.1: Parametric stack testing

Milestone targets

- >500 hours parametric testing
- System relevant conditions
- At least 5 operating points

Results

- >1700 hours parametric testing
- System relevant conditions
- 8 operating points

Test point 7: Degradation of 7 mV/khr = 0.6%/khr,
Stack voltage of 1.303 V, Efficiency of 96.1% LHV
- Newly developed CSA stacks include very thin (300 micron thick) HiPoD cells with active area of 81 cm²

<table>
<thead>
<tr>
<th>Property</th>
<th>Scale</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Short</td>
<td>Mid</td>
</tr>
<tr>
<td>Cell count</td>
<td>45</td>
<td>150</td>
</tr>
<tr>
<td>Electrolysis voltage, V</td>
<td>58</td>
<td>193</td>
</tr>
<tr>
<td>Electrolysis Stack Power, kW</td>
<td>4.7</td>
<td>15.6</td>
</tr>
<tr>
<td>Hydrogen Production, g/hr</td>
<td>137</td>
<td>457</td>
</tr>
<tr>
<td>Height, mm (in)</td>
<td>91</td>
<td>211</td>
</tr>
</tbody>
</table>

Illustration of CSA stack sizes

Current Stack Technology Status

Planned Future Stack Scale-up
Deployment & Test of CSA Platform

- Initial stacks based on the newly developed design (CSA design) have been built and tested in both fuel cell and electrolysis modes
  - Stack -0003 demonstrated 10 kWe input and 245 g/h hydrogen production at -1.8 A/cm² (with 82% LHV efficiency) (DE-EE0006961)
  - **Stack -0006 exceeded 1000 hours at 4.7 kWe input and 136 g/hr hydrogen production at -1 A/cm² (with 97% LHV efficiency) and is still running (this project)**
Go/No-Go #1 Stack Testing

Test conditions:
- 81 A (-1 A/cm²)
- 78% H₂O, 22% H₂ inlet composition
- 33.6% steam utilization
- 750 °C nominal stack temperature

Go/No-Go Requirements and Milestone 1.4.2:
- SOEC stack demonstration
  - > 1000 hours
  - ≥ 1 A/cm² electrolysis
  - > 95% LHV efficiency
  - Go/No-Go with degradation < 4% /khr
  - Exceeded 1000 hours and continuing
  - 1 A/cm²
  - 97% LHV efficiency
  - No degradation over test period
Automated work cell commissioned and performs:
• Stack builds
• Cell and interconnect QC

Demonstrated production rate of up to 4 stacks per 8-hour work shift
**Project Goals**

<table>
<thead>
<tr>
<th>Stack efficiency (LHV)</th>
<th>95%</th>
<th>97%</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Electrical Efficiency (LHV)</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>Total Efficiency</td>
<td>75%</td>
<td>79%</td>
</tr>
</tbody>
</table>

**System Design**

- 60% Steam Inlet Conc.
- 67% Steam Utilization
- 40% Oxygen Outlet Conc.
- 5 Bara pressure
- 1.285 V/cell
Demonstration System Features:
- > 4 kg/day H₂ production
- Up to 5 bara pressure
- Inlet air flush around stack
- Thermal-neutral stack operation
- Thermally self-sustaining system
1) - This is good initial work and data collection of actual hydrogen production. 
   • Thank you for positive feedback.

2) - It is not obvious what roles the partners are playing in the project.
   - The partner roles are poorly defined.
   • The key partner in the project, Versa Power Systems (VPS), is a wholly owned subsidiary of FuelCell Energy and is operating under the parent’s name.

3) - There is little mention of state-of-the-art or competing technologies that would ascertain the relevance and comparative advantage of the current work.
   • Comparison of SOEC performance versus publically available data for PEM (Proton Exchange Membrane) are presented in the back-up slides.

4) - Optimistic assumptions are a weakness. The team needs to address the source and availability of “waste heat” for vaporization of water.
   • Waste heat needed for vaporization is included in the overall thermal efficiency estimate for the SOEC plant. The waste heat source for water vaporization (<200°C) could be from industries such as refineries, steel manufacturing, power plants, etc.

5) - More details are needed on cost analysis and how the technology will be brought to the market. The technology validation and technology transfer plans are poorly defined.
   - It is not clear that this project really is a technology validation. It seems to be more of a technology development project.
   - The project would be strengthened by independent evaluation of the TEA results. Many questions from reviewers on the technical validity of the results in the areas of energy integration and overall process efficiency could be addressed by the addition of a partner to complete/validate this independently.
   • In line with the project schedule, detailed thermo-economic analysis will be performed in the future under the Budget Period 2 of the project.
   • We agree that this is a Hydrogen Production R&D and not a Validation Project.
• **Versa Power Systems (VPS), Operating as FuelCell Energy**
  - VPS is a key sub-recipient providing the following expertise in the project:
    - SOFC materials & components R&D
    - Stack design
    - Cell/stack pilot manufacturing and QC
    - Cell/stack testing

Cell Pilot Manufacturing Processes at VPS: (Tape Casting, Screen Printing, and Co-sintering)

• **DOE/NETL**
  - NETL is not directly involved in the project, however, indirectly contributes to the development of the SOEC through development of SOFC technologies by providing support for development of materials, cell and stack designs and manufacturing processes that are used in the SOEC:
    - Increased SOFC endurance
    - Stack/system scale-up and cost reduction
    - Power system integration and demonstration
Remaining Challenges and Barriers

- **Cell and Stack**
  - Reduce cell performance degradation to <1%/1000 hours
  - Scale up stack architecture and manufacturing process to meet the degradation target of <2%/1000 hours
  - Operate under pressure of up to 5 bara to increase the efficiency of the overall system

- **Forecourt System**
  - Develop cost-optimized system to meet $2/kg H₂ target while meeting the overall system efficiency goal of 75% (LHV of H₂)
  - Integrate system with renewable and intermittent power sources

- **Demonstration**
  - Design, fabricate and test >4 kg H₂/day demonstration prototype system operating at up to 5 bara

CFD simulations including cell electrochemical performance model is utilized to support CSA stack development
Future Work

• Cell and Stack
  – Continue studies to determine the operating conditions that lower cell degradation rates to less than 1%/1000 hours
  – Post-test microstructural analysis of cells to identify degradation mechanisms and path for cell material and fabrication process improvements
  – Cell and stack fabrication for testing and demonstration of milestone targets

• Forecourt System Techno-economic Analysis
  – Perform system design and performance optimization based on the lessons learned from stack tests
  – Develop process and control strategies to accommodate intermittent renewable electric power for hydrogen production
  – Develop conceptual layout of forecourt system
  – Perform H2A analysis

• Demonstration Prototype
  – Design, fabricate and test a breadboard system capable of >4 kg H₂/day production that will demonstrate the targeted system efficiencies

Any proposed future work is subject to change based on funding levels
Technology Transfer Activities

Reversible SOFC (RSOFC) System for Energy Storage

- In addition to the opportunities for low-cost H₂ production, SOEC technology is an enabler for development of Regenerative SOFC (RSOFC) for electric energy storage

- Advantage over conventional storage:
  - Long duration energy storage achieved by only adding hydrogen storage capacity, without adding stacks
  - Dual functionality for storing energy and production of hydrogen using renewables

- Advantage over other Hydrogen based storage:
  - Efficiency advantage due to higher efficiency of SOFC in fuel cell and electrolysis modes of operation

Dual Function RSOFC: H₂ Export and Grid-Tie Storage

Conceptual Layout of 1 MW / 6 MWh Energy Storage Plant
• Met Q1 through Q6 Milestones as well as Go-no-Go Decision Point targets as planned:
  – Long term cell performance degradation rate of ≤1%/1000 was demonstrated at 1 A/cm²
  – Cell operating parameter investigation was completed to determine SOEC stack operating windows used in the design of systems
    • >500 test conditions evaluated
  – Testing of a 20 HiPoD cell stack across a matrix of 7 operating points was completed after >1,700 hours (in excess of the required 5 operating points and 500 test hours), identifying the areas of improvements for stack design and system operating conditions
  – Baseline system flowsheet design and computer simulation models were completed:
    • Initial tradeoff study of SOEC system configurations and operational parameters were completed showing >75% overall system efficiency is achievable
  – Verified performance of a 45-cell CSA stack with virtually no degradation in ≥1000 hours of tests under simulated system conditions with electrical efficiency >95% (based on LHV of hydrogen) at ≥1 A/cm²
  – Completed the conceptual design of a >4 kg H₂/day packaged prototype unit to demonstrate the system efficiency metrics and to verify the operability of SOEC using intermittent renewables
TECHNICAL BACK-UP SLIDES
<table>
<thead>
<tr>
<th>Component</th>
<th>Materials</th>
<th>Thickness</th>
<th>Porosity</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anode</td>
<td>Ni/YSZ</td>
<td>0.3 mm</td>
<td>~ 40%</td>
<td>Tape casting</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>YSZ</td>
<td>5 - 10 µm</td>
<td>&lt; 5%</td>
<td>Screen printing</td>
</tr>
<tr>
<td>Cathode</td>
<td>Conducting ceramic</td>
<td>10 - 50 µm</td>
<td>~ 30%</td>
<td>Screen printing</td>
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</table>
HiPoD Electrolysis Performance

- Lowering fuel electrode porosity by modifying microstructure and increasing nickel oxide content of the as-prepared substrate have proved successful in recent SOFC development.
- The increased nickel oxide content cell can be fired to the same density as regular cell, but after reduction to nickel metal, it will be more porous due to the volume change as greater amount of nickel oxide is reduced to nickel metal.
- SOEC (HiPoD) cell with this modified fuel electrode delivered a performance of over 6 A/cm² in a single cell test at 78% (LHV) efficiency.
Baseline HiPoD Cell Performance Characteristics in Fuel Cell Mode
SOEC Compared to PEM

- To reach the DOE 2020 water electrolysis efficiency (LHV) target of 78%, an upper limit for the electrolysis operating voltage is 1.6 V (see Figure). This voltage will deliver a 78% LHV efficiency in hydrogen production. At this upper limit voltage, FCE’s RSOF7 cell, operating in regenerative mode, has shown the potential for achieving a current density greater than 3 A/cm².

- In comparison, a PEM-based regenerative cell will have a much lower current density of less than 0.5 A/cm² at 1.6 V.

- Capital cost reduction can be strongly driven by improvements in stack current density in most systems. Improvements in stack current density result in a reduction of cell active area and a corresponding decrease in material cost.
Accelerated Cycling (6,080 Cycles)

4 hour cycles (180)
- SOFC: 1.6 hours
- SOEC: 1.6 hours
- Transition: 0.8 hours

20 min cycles (5900)
- SOFC: 8 min
- SOEC: 8 min
- Transition: 4 min

0.03 mV/cycle degradation

Equivalent daily cycles
- 1 year
- 5 years
- 10 years
- 15 years

Cell material set: RSOFC-7

1 Cell Stack - 81 cm² Active Area
Furnace Temperature: 800°C
Fuel: H₂ + 50% H₂O, Uf/UH₂O = 30%
Oxidant: Air, Ua = 30%
Current: ± 24.3 A (0.3 A/cm²)