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Solid Oxide Based Electrolysis and Stack Technology with Ultra-High Electrolysis Current Density (>3A/cm^2) and Efficiency

Eric Tang, Tony Wood, Casey Brown, Micah Casteel,
Michael Pastula, Mark Richards, and Randy Petri (PI)
Randy Petri (Presenter)
Versa Power Systems
2016 DOE Hydrogen and Fuel Cell Program Review
June 8, 2016
Washington, DC

Project ID: PD124

Overview

- Timeline and Budget
  - Start: July 2015
  - End: June 2017
  - Total project funding: $1,254,553
    - DOE share: $992,442
    - VPS share: $248,111
  - Total DOE funds spent
    - $431,759
      - As of Feb 29, 2016

- Barriers
  - This project aims to address major barriers with an innovative high current density and high efficiency solid oxide electrolysis technology.
    - F. Capital Cost
    - G. System Efficiency and Electricity Cost
    - J. Renewable Electricity Generation Integration

- Partners
  - NREL
  - DARPA/Boeing
  - DOE/SECA

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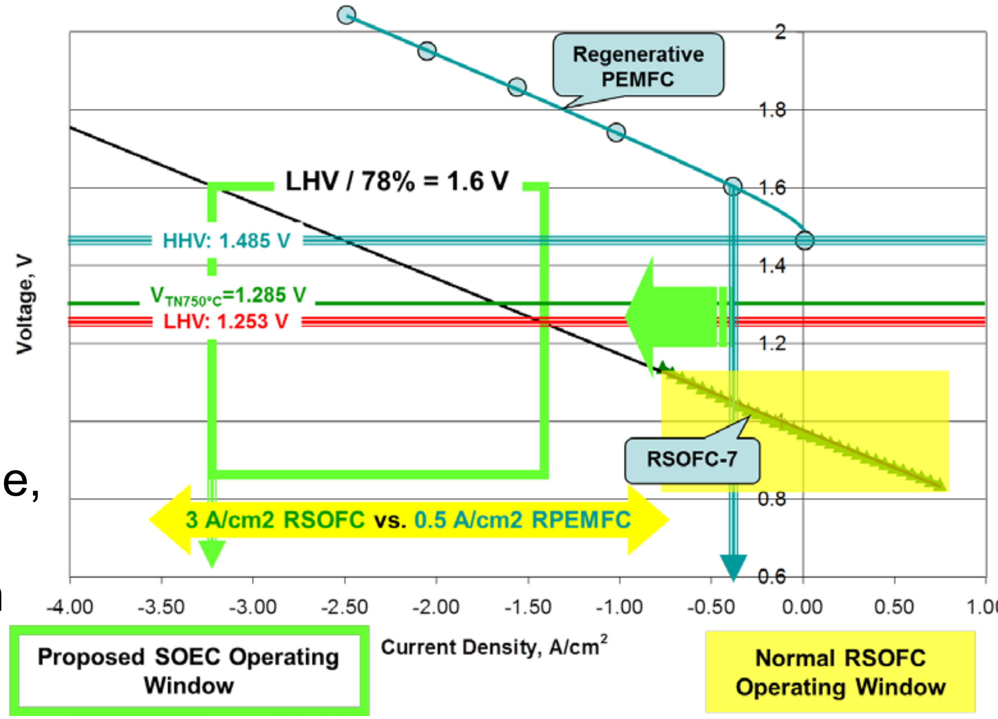
Project Background

Relevance

- 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, the RSOFC-7 cell, operating in regenerative mode, may deliver more than 3 A/cm^2 if the linear performance projection holds.

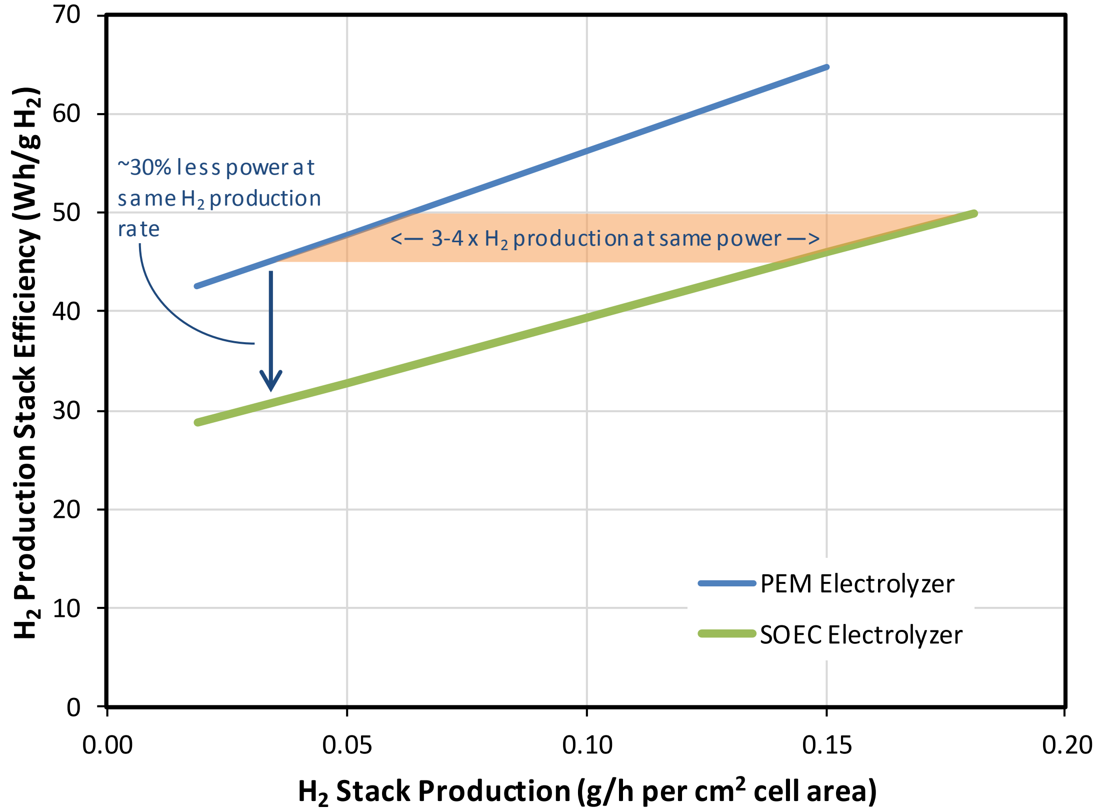


- In comparison, a PEM-based regenerative cell will have a much lower current density of less than 0.5 A/cm^2 at this voltage.
- Capital cost reduction can be strongly driven by improvements in stack current density in most systems. Improvements in stack current density result in a reduction of cell active area and a corresponding decrease in material cost.

Project Background

Relevance

- The lower cell voltage of VPS SOEC cells results in about 30% lower power consumption at any given hydrogen production rate and 4x hydrogen production at any given power consumption rate.



- An SOEC system with a higher maximum operating current limit will better match the charging rates for solar and wind based renewable energy sources. This leads to better integration to meet the energy conversion and storage needs from a wider variety of renewable energy sources.

Project Objectives

Relevance

- Research and development of SOEC technology capable of operating at ultra-high current density (> 3 A/cm^2) with an operating voltage upper limit of 1.6 V. Anticipated results include:
  - Single cell
    - Develop a solid oxide electrolysis cell platform capable of operating with current density up to 4 A/cm^2 at an upper voltage limit of 1.6 V
    - Demonstrate stable solid oxide electrolysis cell operation with high current density of more than 3 A/cm^2 for 1000 hours
  - Stack
    - Design a solid oxide electrolysis stack platform capable of operating with the high current density (>3 A/cm^2) cell technology at an upper voltage limit of 1.6 V
    - Demonstrate stable solid oxide electrolysis stack operation with high current density of more than 2 A/cm^2 for 1000 hours
  - System
    - Complete a solid oxide electrolyzer process and system design that accommodates the ultra-high operating current density platform
- All objectives intended to contribute to meeting DOE 2020 targets for advanced water electrolysis technologies

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Development Path

Approach

Building on VPS's strong solid oxide cell and stack development in the previous EERE sponsored project (Advanced Materials for RSOFC Dual Operation with Low Degradation), and leveraging cell and stack advancements from the other VPS projects (DOE SECA and DARPA projects) over the last 15 years, the project objectives will be met by executing the following scope:

- **Materials:** Addressing high current density electrolysis cell performance limitations by conducting materials development and cell design of experiments and integrating them with cell production technology development.
- **Stack Design:** Developing SOEC stack engineering modeling and process fabrication designs to address high current density operating requirements and identify key operating parameters for the design of an integrated, SOEC-based energy conversion and storage system for renewable energy sources.
- **Validation Testing:** Down-selecting and demonstrating high current density SOEC operation via single cells and stacks tests.
- **System Analysis:** Investigating high current density solid oxide electrolyzer system and its integration with renewable energy sources to meet DOE 2020 Advance Electrolysis Technologies target.

Milestone Status Overview

Milestone	Milestone Description	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Milestone Metric
M1.1	Baseline the performance and degradation rate of the SOEC cell technology	100%								**Demonstrate in single cell test a current density of more than 3 A/cm². Send baseline cell performance and degradation results to DOE.**
M1.2	Develop ultrahigh performance SOEC cell technology	100%								**Demonstrate SOEC cell technology with up to 4 A/cm² at 1.6 V in single cell test. Present test results to DOE.**
M1.3	Compete the final SOEC cell design		75%							Demonstrate with 1000 hour stable electrolysis operation (<4% per 1000 hours) at 3 A/cm² in single cell test. Send final cell design and test results to DOE.
M2.1.1	Complete preliminary stack process design and modeling	100%								**Deliver preliminary stack design and modeling results to DOE.**
M2.2.1	Demonstrate stack capable of operating at ultrahigh current		100%							Complete a short SOEC stack operating with ultra-high current density of more than 3A/cm² at less than 1.6 V. Send stack test results to DOE. (Go/No-Go)
M2.2.2	Complete full size SOEC stack design freeze									Complete detailed full size stack design with all drawings completed and approved; Demonstrate stable short stack operation at 2 A/cm². Present full size SOEC stack design and short stack testing results to DOE.
M2.2.3	Complete ultrahigh performance stack development and testing									Demonstrate an SOEC stack with 250 g/hr hydrogen production as well as stable operation at a current density of more than 2 A/cm². Send the results to DOE.
M3.1	Complete preliminary ultra-high current density SOEC system conceptual design		100%							**Send the preliminary ultrahigh current density SOEC system conceptual design to DOE.**
M3.2	Complete in-depth SOEC hot module configuration design									Present in-depth SOEC hot module configuration design to DOE
M3.3	Complete a comprehensive techno-economic study of an ultra-high current density SOEC system integrated with renewable energy sources									Present comprehensive techno-economic study of an ultra-high current density SOEC system integrated with renewable energy sources

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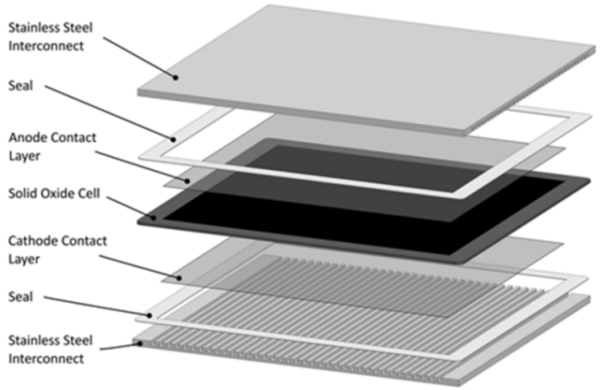
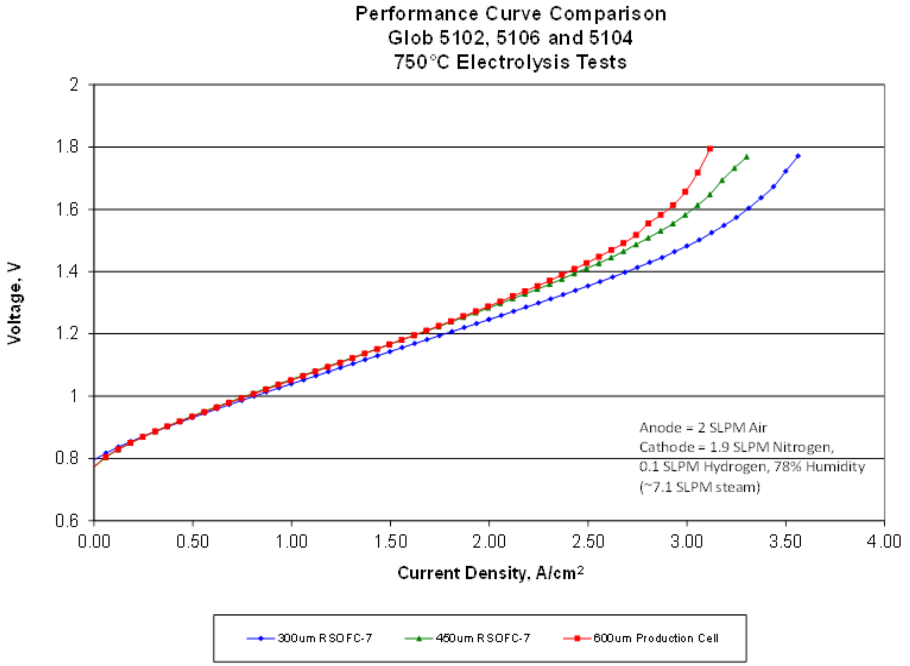
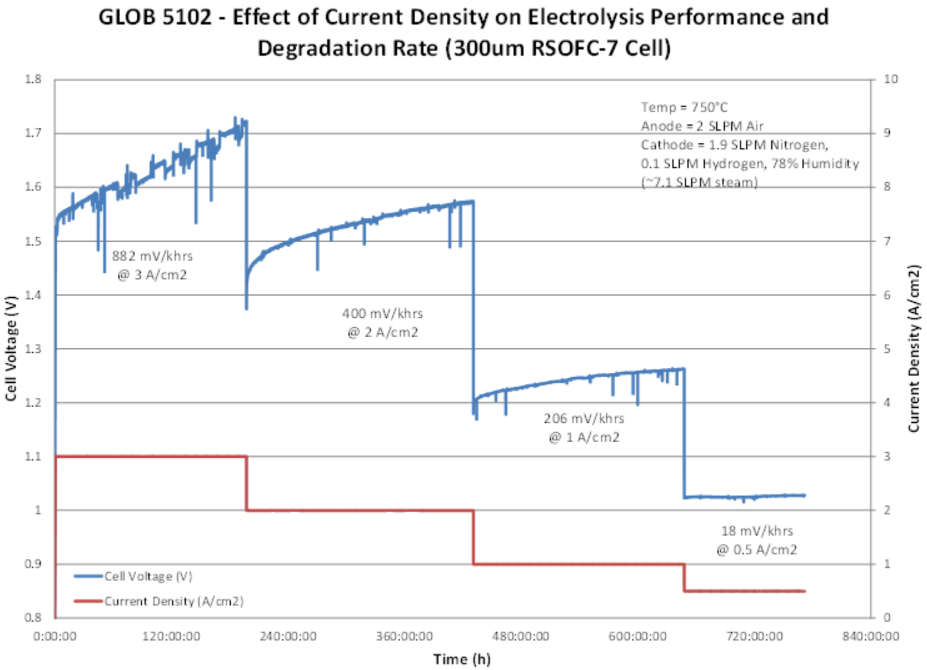
Technical Accomplishments and Progress

Milestone 1.1 (baseline 3 A/cm^2 single cell): Complete

- Three different types of cells have been characterized up to 4 A/cm^2 in electrolysis mode as well as early stage (≤200 hours) degradation rates at 3 A/cm^2.
  - **This performance meets Milestone 1.1**
- All cells have been tested 200 hours each, at current densities of 3, 2, 1, and 0.5 A/cm^2 to compare degradation rates over a range of test conditions; followed by EIS and repeat power curves to investigate degradation mechanisms.



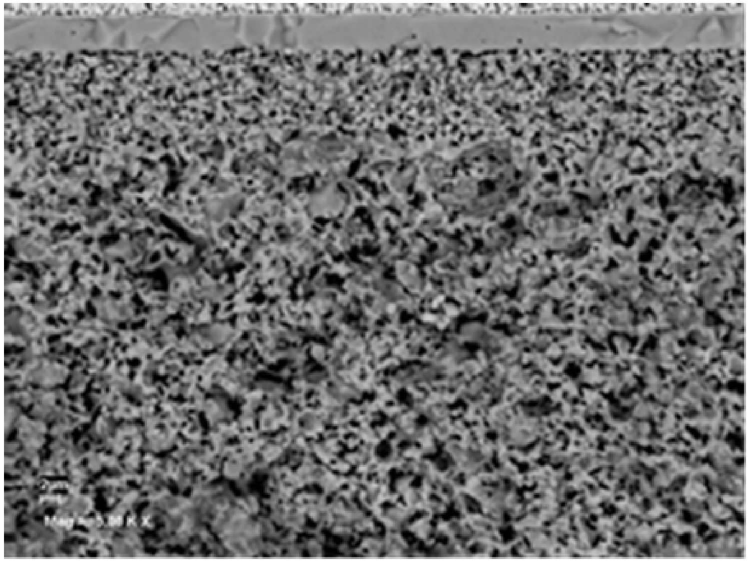


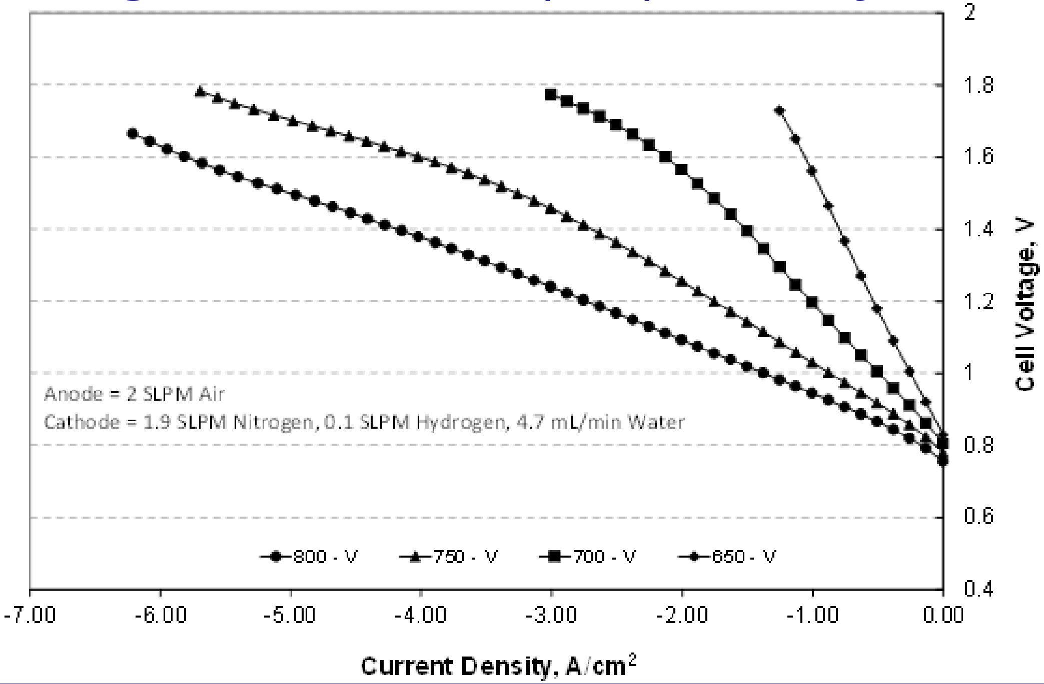


Technical Accomplishments and Progress

Milestone 1.2 (develop 4 A/cm² single cell): Complete

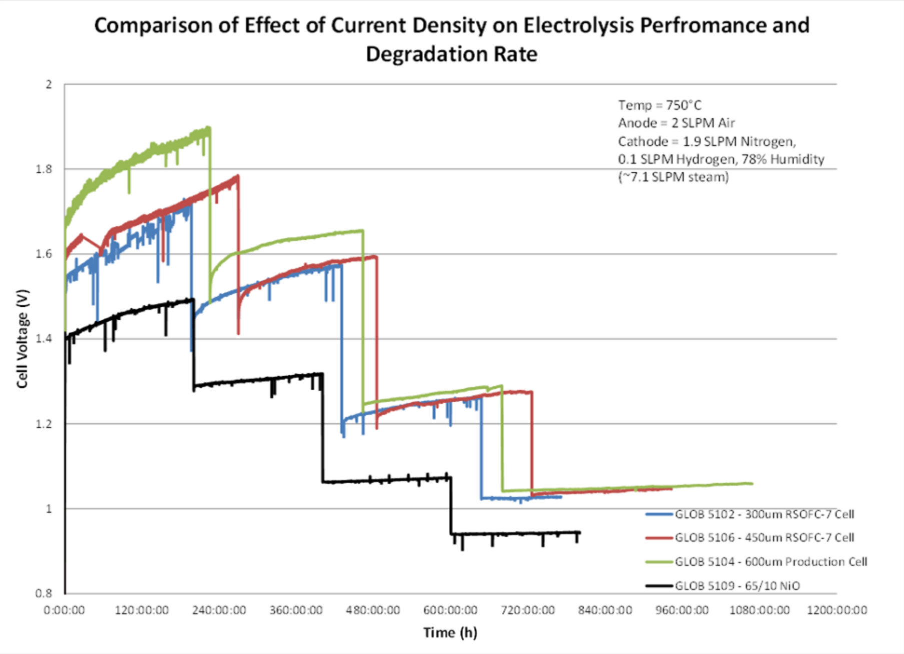
- Increasing fuel electrode porosity by modifying microstructure and increasing nickel oxide content of the as-prepared substrate have proved successful in recent SOFC development.
- The increased nickel oxide content cells can be fired to the same density as regular cells, but after reduction to nickel metal will be more porous due to the volume change as greater amount of nickel oxide is reduced to nickel metal.
- **A 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.**

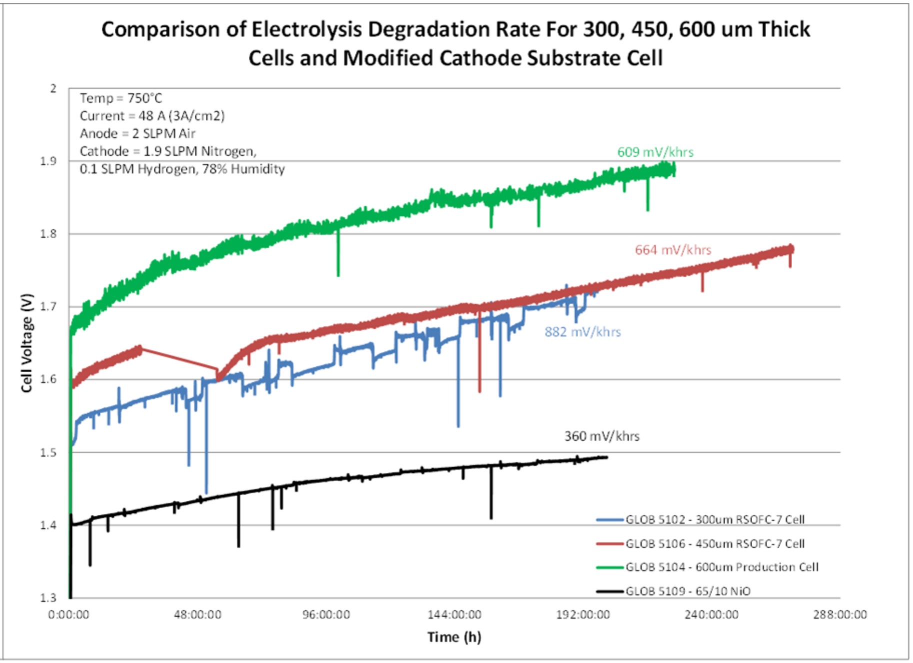




Milestone 1.3 (SOEC Cell Design): In Progress

- Use tools developed to resolve SOFC degradation to identify the key degradation mechanisms at these extreme test conditions.
- Evaluate effects of cell thickness, density, and nickel content on degradation rate at high current densities.
- **The degradation rate of HiPoD cell at 3 A/cm^2 is ~50% that of other cells and this indicates the cathode substrate (SOEC fuel electrode) is a key contributor to degradation rate, as anticipated.**

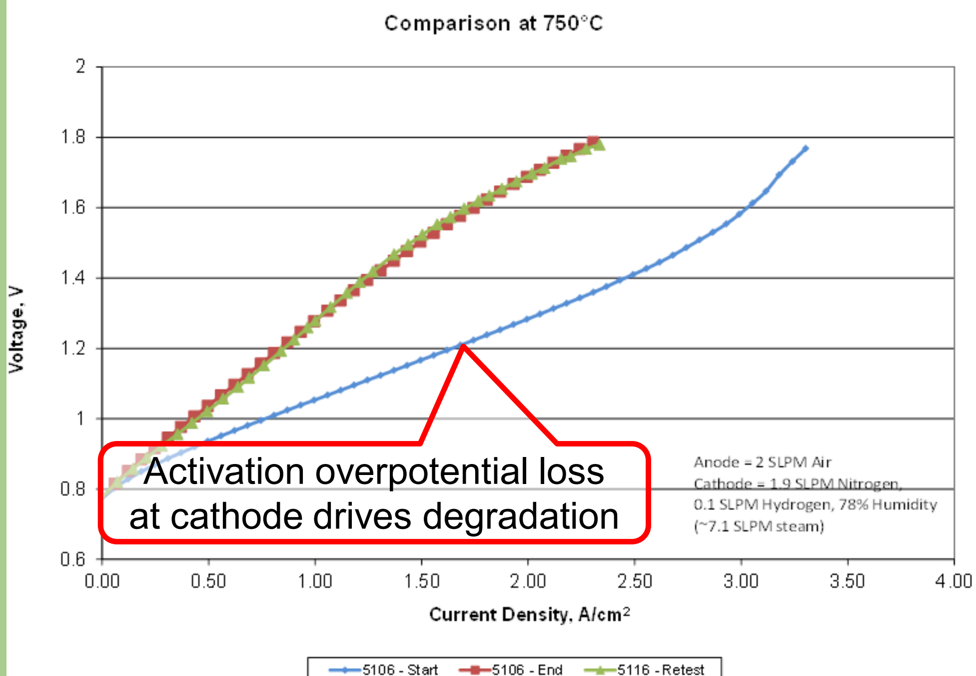


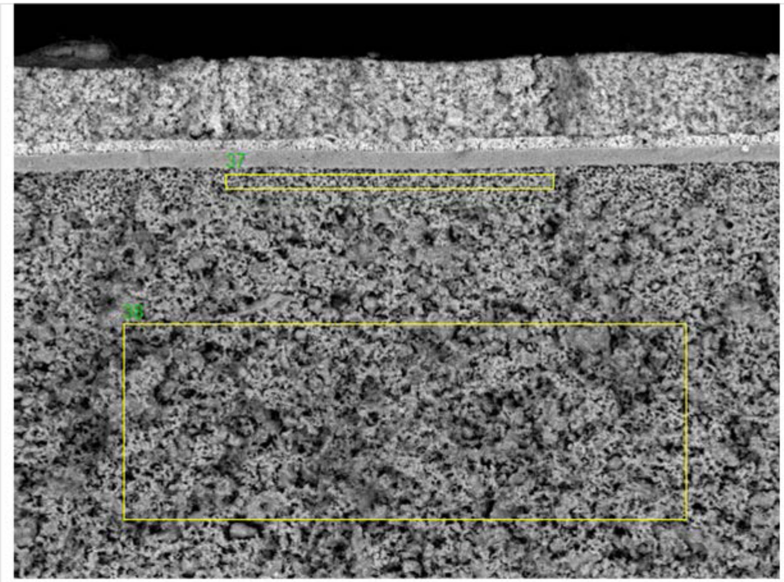


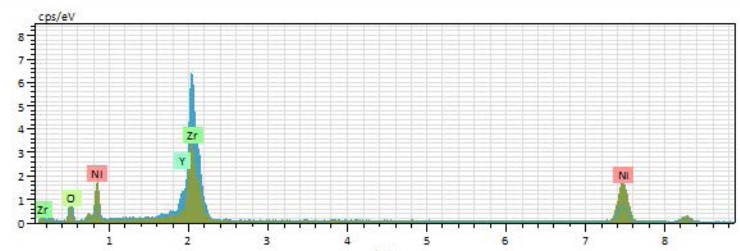
Technical Accomplishments and Progress

Milestone 1.3 (SOEC Cell Design): In Progress

- Degradation mechanism study
  - Compare electrolysis performance at start and end of test as well as retesting after reprinting anode and anode contact layers.
  - Post test analysis of cell after high current density electrolysis operation at 3 A/cm^2.







Atomic percent (%)

Spectrum	O	Ni	Y	Zr
37	55.63	13.52	4.48	26.36
38	36.11	41.43	1.87	20.59
Mean value:	45.87	27.48	3.18	23.48
Sigma:	13.80	19.73	1.85	4.08
Sigma mean:	9.76	13.95	1.31	2.88

Post test analysis revealed Ni loss at cathode functional layer

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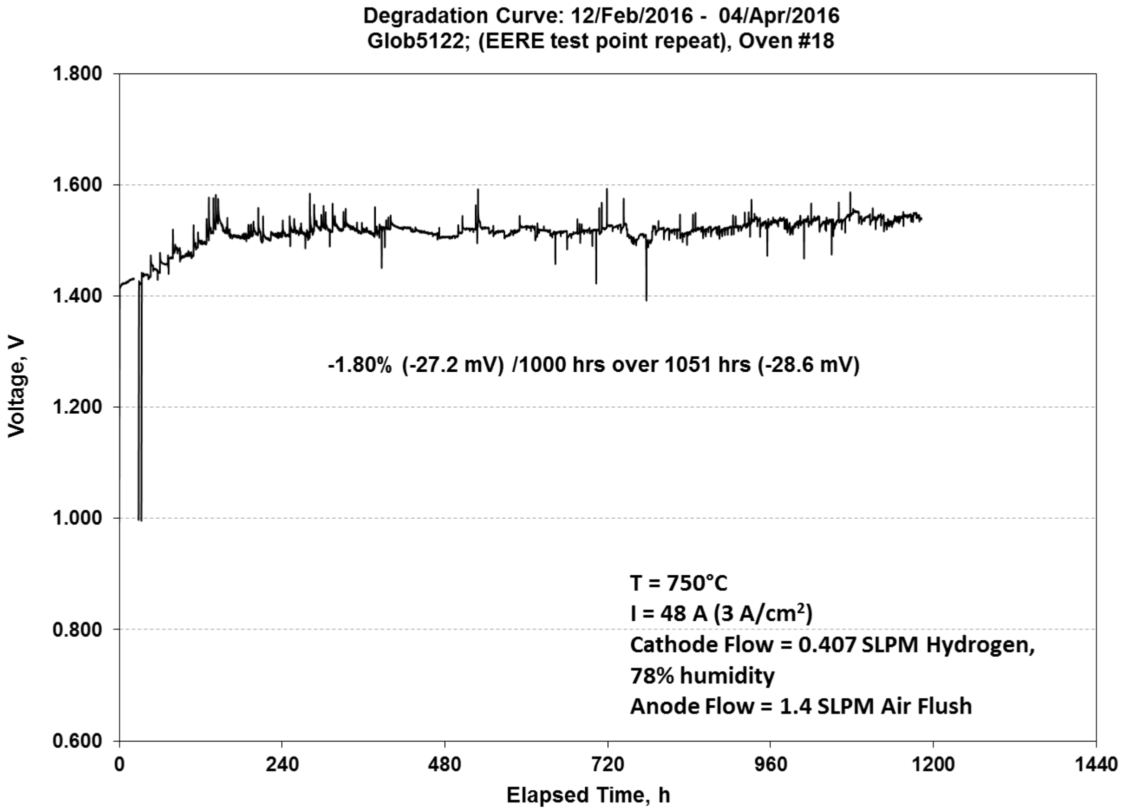
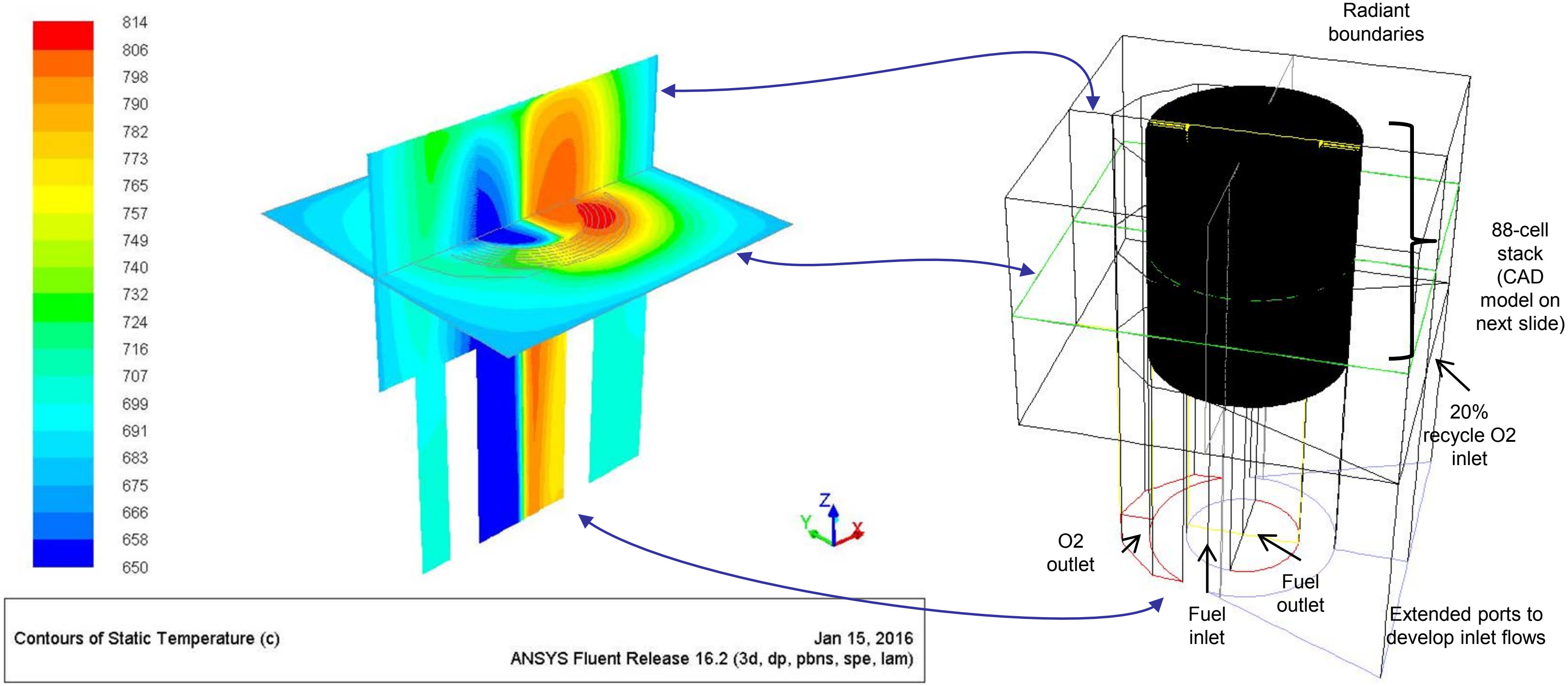
Technical Accomplishments and Progress

Milestone 1.3 (Run 3 A/cm^2 for 1000 hrs, <4% loss): In Progress

- A number of HiPoD cells were tested at high steady-state electrolysis current density of 3 A/cm^2 to:
  - Evaluate effects of cell thickness, density, and nickel content on degradation rate at high current densities
  - Explore various operating conditions, such as temperature, steam utilization, and steam concentration
- One of the most recent tests at 3 A/cm^2 demonstrated 1.8% per 1000 hour degradation rate
- **So far- this result exceeds the Milestone 1.3 target of ≤ 4% per 1000 hour**



Milestone 2.1.1 (Preliminary Stack Design/Modeling): Complete



- General layout and design of unit cell and stack complete
- Unit cell and stack CFD models built and exercised at select operating points
- **General operability envelope confirmed (peak temperatures 800 to 815°C)**

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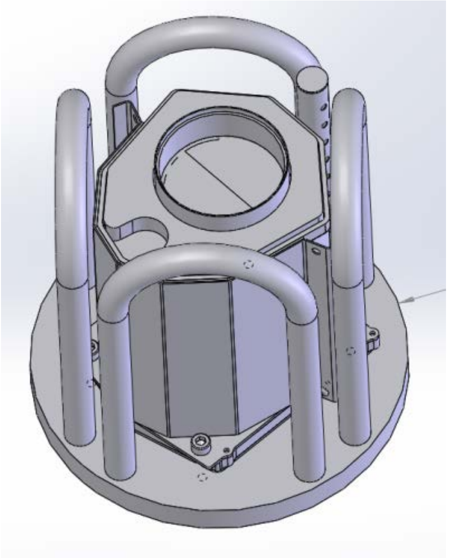
Technical Accomplishments and Progress

Milestone 2.1.1 (Preliminary Stack Design/Modeling): Complete

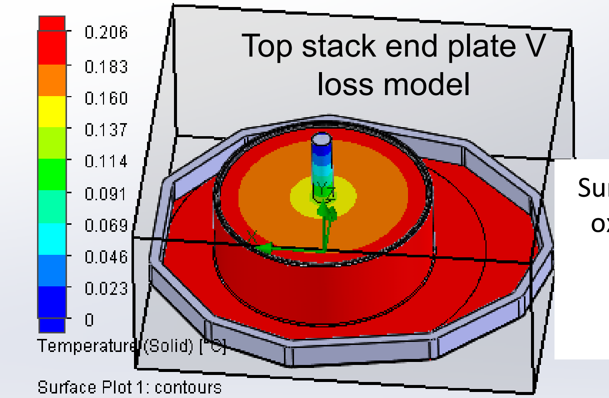
- Heat rejection is primarily to the fuel electrode (H_2O/H_2) stream (convective, sensible) and heat rejection to the environment through radiation amounts to 15% of overall net heat. This is due to the relatively large heat loads in proportion to stack area and volume. Careful design and placement of heat sinks (e.g., gas preheat bodies) should enable an increase in the radiant heat rejection.
- The bulk of input energy goes to creation of hydrogen and oxygen from water. However, thermal management is important at ultra-high current density.



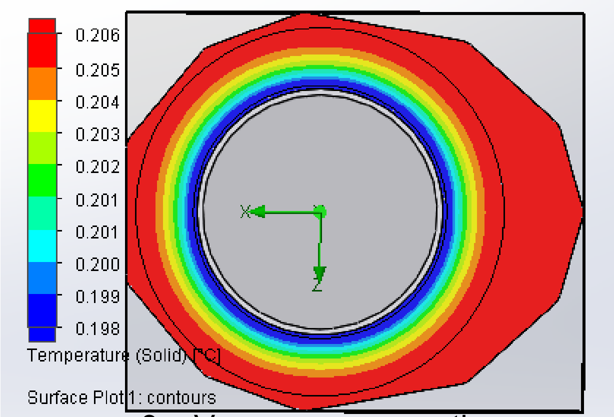
Path	Heat Flux (W)
Heat to fuel	9.48
Heat to oxidant	0.04
Heat to environment (radiation)	1.70
Total	**11.22**

Milestone 2.2.1 (Go/No-Go, 3 A/cm² Short Stack Test): Complete

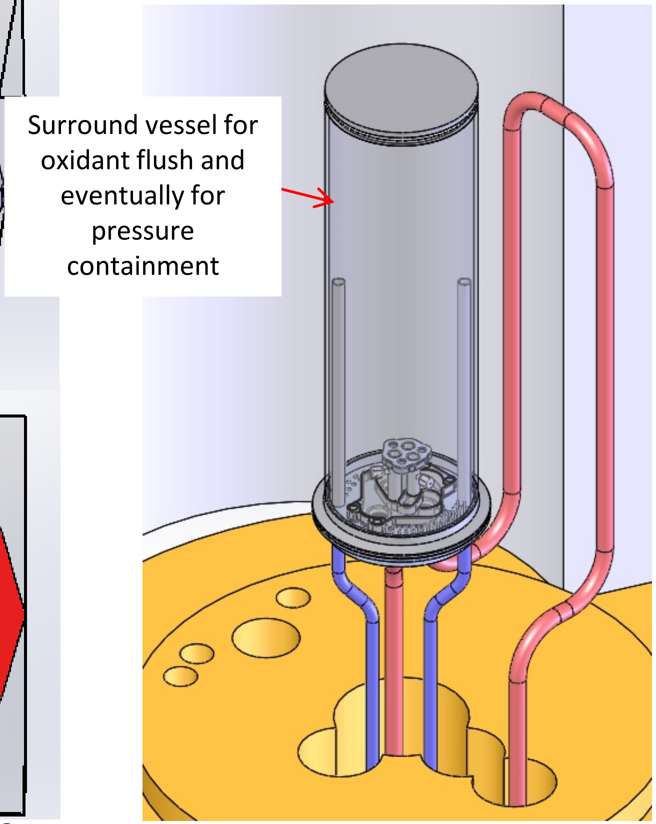
- General layout, detailed design complete (e.g., detailed interconnect design)
- Test stand modifications to support testing complete
- Test stand commissioning and technology stack testing, complete
- Current collection design (using electrical-thermal analog model) complete

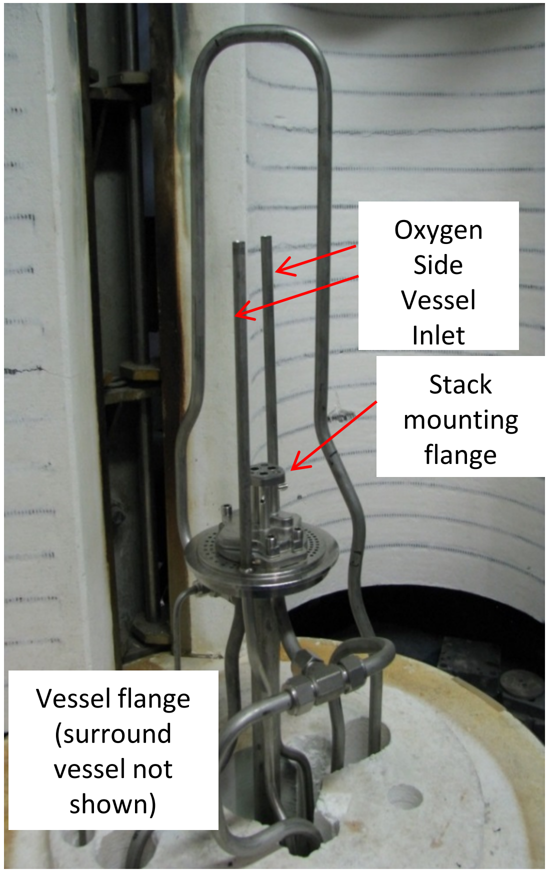


206 mV loss at 85 A



8 mV range across active area





Milestone 2.2.1 (Go/No-Go, 3 A/cm² Short Stack Test): Complete

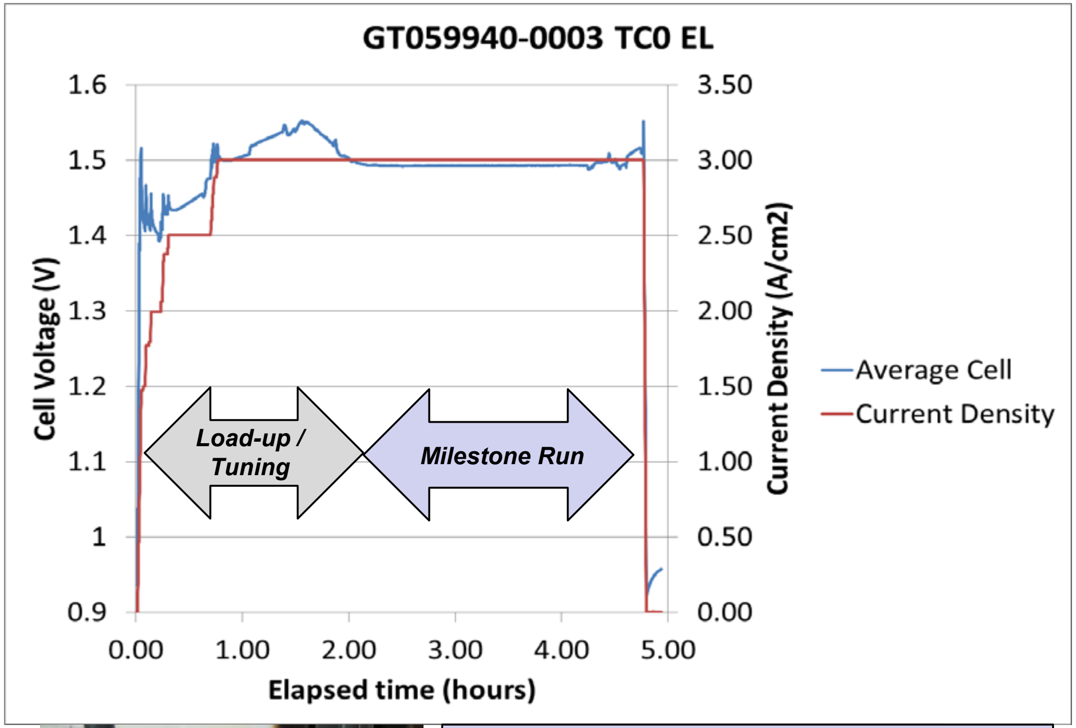
- Updated test stand to accommodate high current electrolysis
  - Replaced steam/hydrogen supply tubing to prevent steam dropout
  - Added nitrogen flush for product oxygen dilution
  - Upgraded current collection to handle higher currents
- Ran SOFC technology stack to high currents
  - Three stacks run: 2 x 20-cell, 1 x 12-cell
  - SOFC cell materials (not optimized for high current)
- Technology Stack Results
  - 2.0 A/cm² at 1.60 V/cell (avg)
  - 2.4 A/cm² at 1.67 V/cell (avg)
  - Stack is thermally stable at test conditions
  - 1.8 kWe power input
  - Effective ASR: ~0.3 Ω-cm²
  - Comparable effective ASR to single cell
  - Current collection losses match model projections

20-cell technology stack in test stand

Milestone 2.2.1 (Go/No-Go, 3 A/cm² Short Stack Test): Complete (2 months early)

Technical Accomplishments and Progress

- Objective
  - Demonstrate a short SOEC stack operating with ultra-high current density of more than 3 A/cm² at less than 1.6 V (78% LHV stack electrical efficiency for hydrogen production)
- Go/no-go test stack
  - Built with HiPoD cells
  - 20-cell stack
  - Cell active area: 22.3 cm²
  - Start of test: April 24, 2016
- Metrics achieved
  - –3.004 A/cm² (–67 A stack electrolysis current)
  - 1.493 V per cell (29.856 V stack performance)
  - ~83.9% efficiency LHV H_2



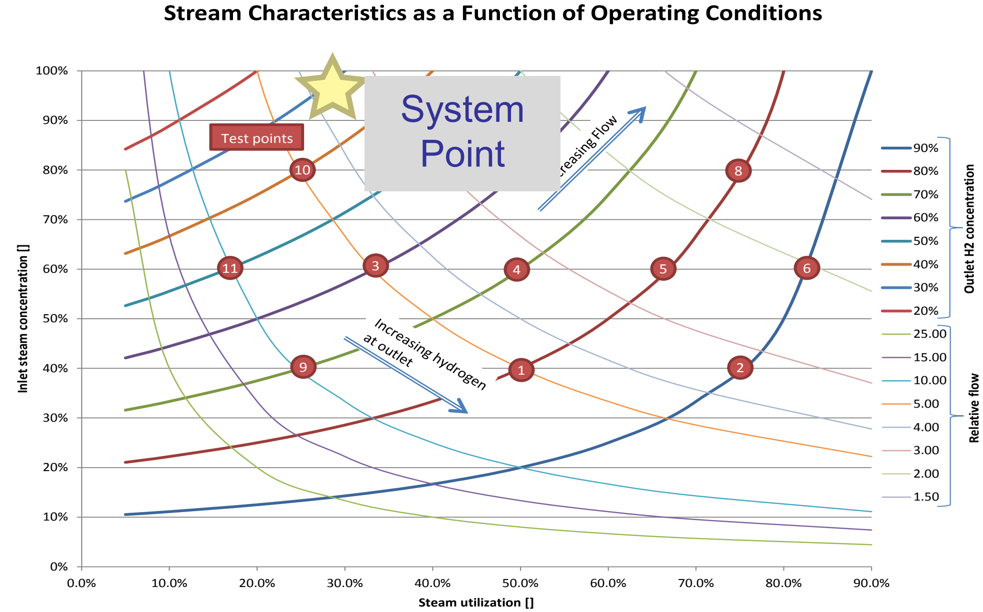
BASIS: at hour 3.5 (Apr 25, 2016; 14:42)

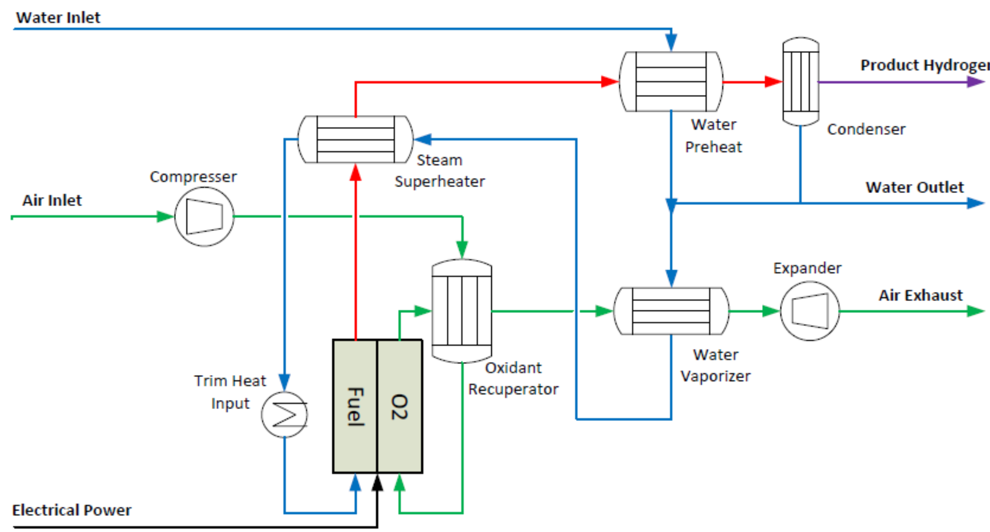
- Fuel inlet composition: 78 % H_2O, 22 % H_2 (20.110 SLPM H_2O (calc), 5.672 SLPM H_2)
- Steam utilization: 50.0%
- Air purge: air, 29.998 SLPM
- Furnace temperature: 585.0°C
- In-stack temperatures: 782.1 – 819.5°C

Technical Accomplishments and Progress

Milestone 3.1 (Preliminary System Design): Complete

- Aspen Hysys – stack conditions model
  - 0-D stack/system model built
  - Stack model facilitates exploration of heat and energy implications of different operating points on stack health
  - Enables a quick evaluation of different operating points for feasibility
  - When coupled with detailed cell/stack model, provides the basis for hot module design
- Chemstations CHEMCAD – 1500 kg/day hydrogen production system model
  - Preliminary system model built: ~85% electrical efficiency ; 39 kWh/kg H_2
  - Operating point selected to balance cell performance and system cost
    - Pressure - 8 bar
    - >95% steam inlet (<30% steam utilization)
    - Air flush
  - Parametric investigation/optimization ongoing





Proposed Future Work

- Further develop HiPod cell to meet and surpass the degradation target. Focus on reducing degradation rate to enable faster integration into systems. The degradation rate has been reduced a factor of 40 so far; between now and the end of the project targeting additional improvements driven by fundamental single cell diagnostics.
- Complete in-depth SOEC hot module configuration design
- Complete a comprehensive techno-economic study of an ultra-high current density SOEC system integrated with renewable energy sources
- Complete full size SOEC stack design freeze to meet Year 2 performance and degradation targets
- Integrate the project's technology development into completing the final Milestone:
  - Demonstrate a full size SOEC stack with 250grams per hour hydrogen production
  - Demonstrate a short SOEC stack with 1000 hours of stable operation at 2 A/cm^2
- Go Forward: address limitations of SOA electrolysis systems along two specific tracks- integration of cell/stack technology and development of system architecture.

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Summary

Relevance	Improving electrolysis efficiency, and thereby operating and capital costs, is a key aspect for enabling the competitiveness of both distributed and central hydrogen production. This project addresses efficiency and cost barriers with an innovative ultra-high current solid oxide electrolyzer.
Approach	This effort will address high current density electrolysis limitations by conducting materials development and cell design, stack modeling and design, cell and stack validation testing, and system design and analysis. Milestones include cell current densities of 3 to 4 A/cm^2, stack current densities of 2 to 3 A/cm^2, stack efficiency of 78% (LHV), endurance and degradation metrics, and a techno-economic study of the integration of an ultra-high current density SOEC system with renewable energy sources.
Technical Progress	• Completed Milestone 1.1 - Baselined three cell types performance and degradation results up to 3 A/cm^2 • Completed Milestone 1.2 - Developed new HiPod cell with ultra-high current water electrolysis capability in single cell test. The performance result met Milestone 1.2 target • Completed Milestone 2.1- Developed preliminary modeling of a SOEC stack operating at ultra-high current density • Completed Milestone 2.2.1- Demonstrated a short SOEC stack operating with ultra-high current density of more than 3A/cm^2 at less than 1.6 V. • Completed Milestone 3.1 - Developed the preliminary ultra-high current density SOEC system conceptual design • Other milestone progressed well according to the project plan
Collaboration	NREL, Boeing/DARPA, and DOE SECA

Technical Back-Up Slides

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How Objectives Address Barriers

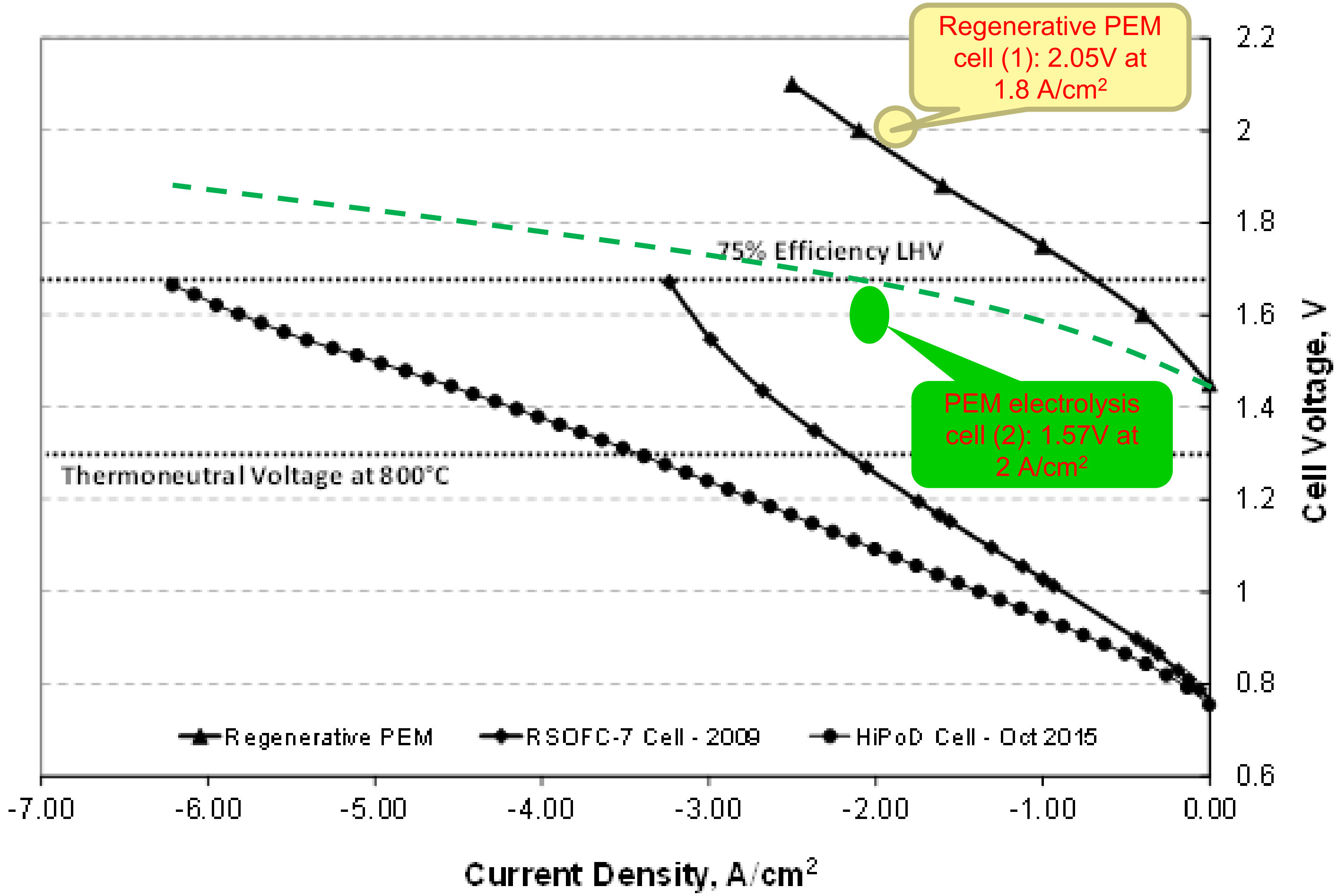
Relevance

Barrier	Project Objectives
To meet or exceed DOE 2020 water electrolysis stack efficiency target of 78% (LHV)	SOEC technology capable of reaching 78% (LHV) efficiency via an ultra-high electrolysis current of more than 3 A/cm^2 at an upper limit voltage of ~1.6 V.
System efficiency	SOEC system design that delivers the same H_2 production rate with 30% less power consumption than PEM technology.
Capital cost	SOEC system design that generates more than four times the H_2 per unit active area compared to a regenerative PEM electrolyzer at the same efficiency.
Renewable electricity generation integration (for central power)	SOEC system design with higher operating current to better match the charging rates for solar and wind based renewable energy sources. This leads to better integration to meet the energy conversion and storage needs from a wider variety of renewable energy sources.

Technical Accomplishments and Progress

Electrolysis Comparison

- V-J Curves Comparison of PEM (3 Refs), RSOFC-7 Cell and HiPoD Cell Electrolysis Operation



(1) http://www.hydrogen.energy.gov/pdfs/review15/pd098_ayers_2015_o.pdf

(2) http://www.hydrogen.energy.gov/pdfs/review15/pd103_xu_2015_o.pdf

Eric Tang, Tony Wood, Sofiane Benhaddad, Casey Brown, Hongpeng He, Jeff Nelson, Oliver Grande,. Advanced Materials for RSOFC Dual Operation with Low Degradation. s.l. : US DoE, 2012

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Collaborations

Collaborations

- NREL
  - Under EERE sponsorship, NREL re-visited energy storage system and techno-economics using RSOFC (Analysis of Solid Oxide Energy Storage, Feb 7, 2012) identifying early adopter applications and the need for more detailed alignment of duty cycles across the broad spectrum of commercial and industrial energy storage needs
- DARPA/Boeing
  - RSOFC stack integration into full reversible system
  - Stack design and development for reduced cost and weight
- SECA
  - The FuelCell Energy/VPS team has successfully passed through all gates to date in the past 10 years
  - VPS has advanced and scaled-up SOFC cell and stack technology culminating in 400 kW stack module and 400 kW System deliverables in this program