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)
FuelCell Energy Inc.

2017 DOE Hydrogen and Fuel Cell Program Review
June 7, 2016
Washington, DC

Project ID: PD124

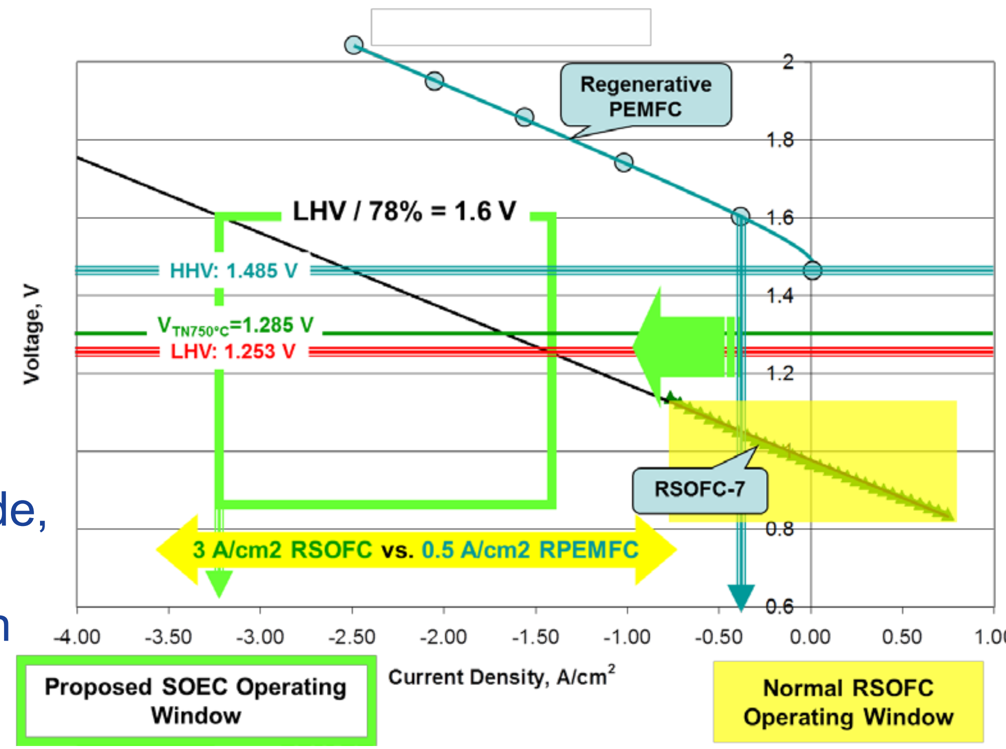
Overview

- Timeline and Budget
  - Start: July 2015
  - End: December 2017
  - Total project funding: $1,254,552
    - DOE share: $992,441
    - VPS share: $248,111
  - Total DOE funds spent
    - $786,457
      - As of Jan 31, 2017

- 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

Project Background

- 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.

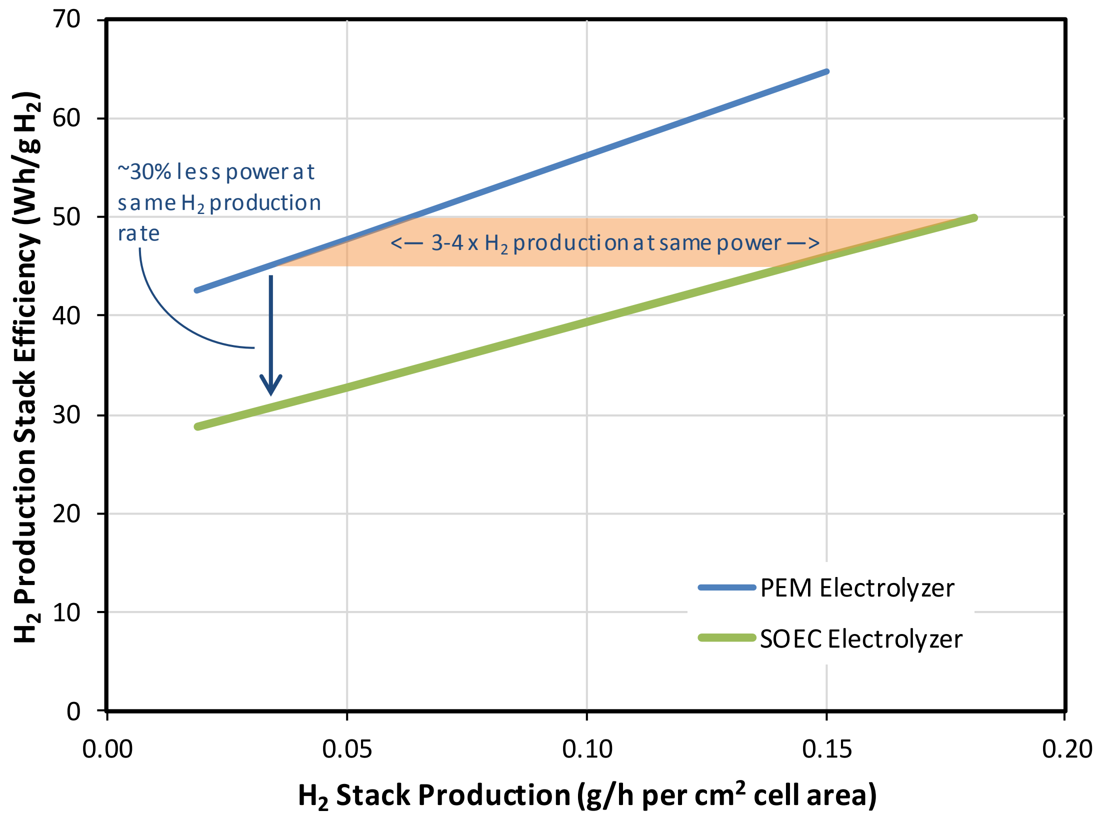


- In comparison, a PEM-based regenerative cell will have a much lower current density of less than 0.5 A/cm^2 at this voltage.
- Capital cost reduction can be strongly driven by improvements in stack current density in most systems. Improvements in stack current density result in a reduction of cell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

Relevance

Project Background

- 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

- 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 preliminary 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

Relevance

Development Path

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.

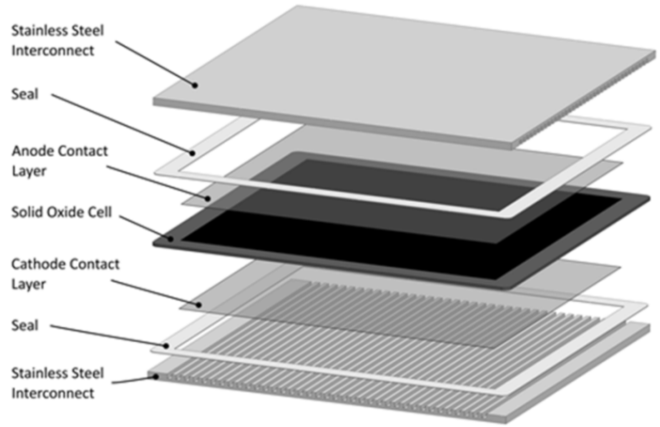
fuelcellenergy

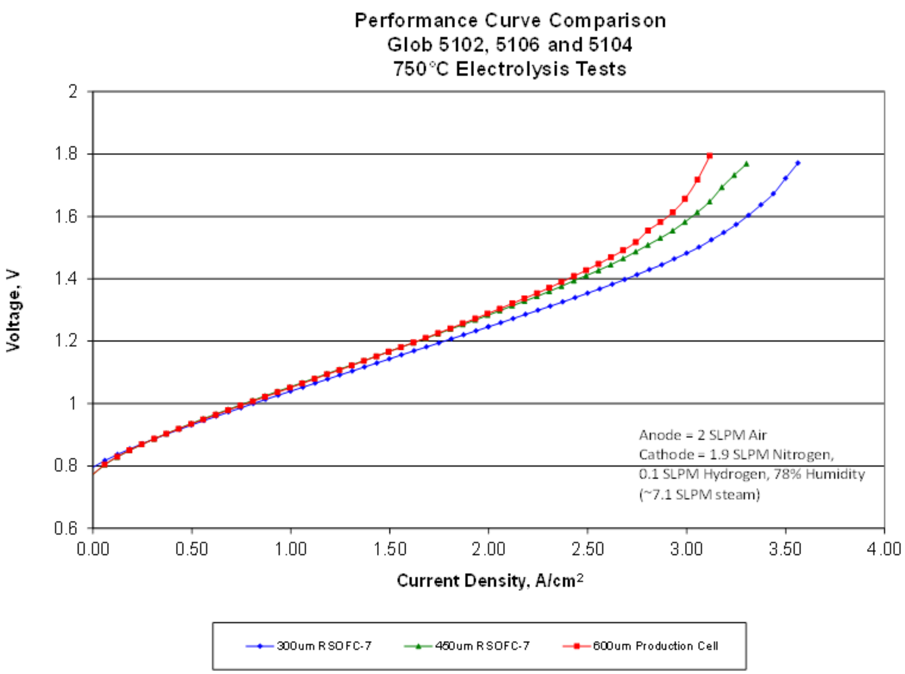
Milestone Status Overview

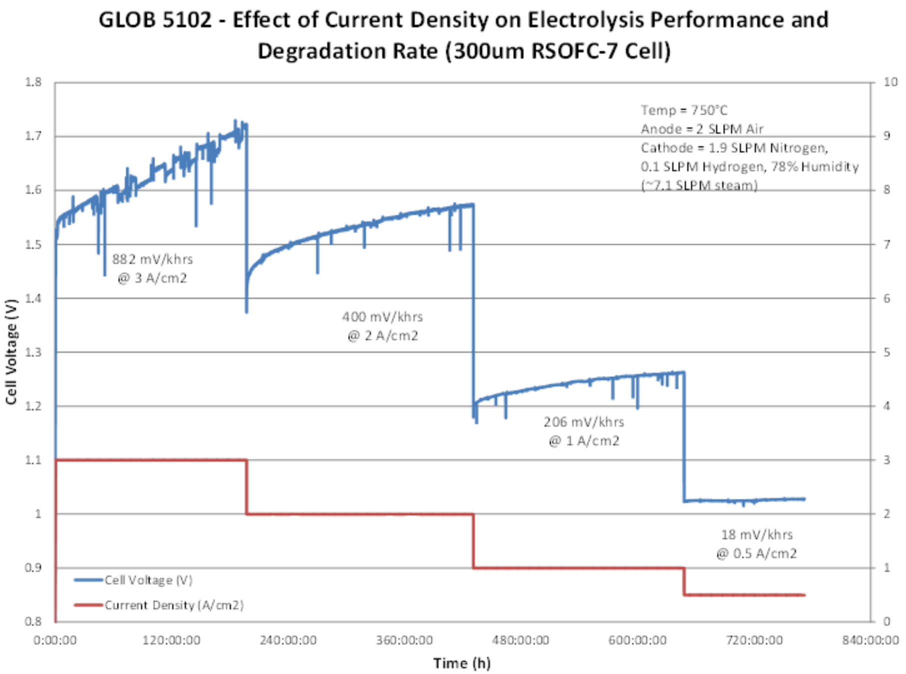
Milestone	Milestone Description	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Milestone Metric
M1.1	Baseline the performance and degradation rate of the SOEC cell technology	100%										**Demonstrate in single cell test a current density of more than 3 A/cm^2. Send baseline cell performance and degradation results to DOE.**
M1.2	Develop ultrahigh performance SOEC cell technology		100%									**Demonstrate SOEC cell technology with up to 4 A/cm^2 at 1.6 V in single cell test. Present test results to DOE.**
M1.3	Compete the final SOEC cell design			100%								Demonstrate with 1000 hour stable electrolysis operation (<4% per 1000 hours) at 3 A/cm^2 in single cell test. Send 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/cm^2 at less than 1.6 V. Send test results to DOE. (Go/No-Go)
M2.2.2	Complete full size SOEC stack design freeze						100%					Complete detailed full size stack design with all drawings completed and approved; Demonstrate stable short stack operation at 2 A/cm^2.
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/cm^2.
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					100%						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

Milestone 1.1–Baseline 3 A/cm² Single Cell: Complete

- Three different types of cells have been characterized up to 4 A/cm² in electrolysis mode as well as early stage (≤200 hours) degradation rates at 3 A/cm².
  - **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/cm² to compare degradation rates over a range of test conditions; followed by EIS and repeat power curves to investigate degradation mechanisms.



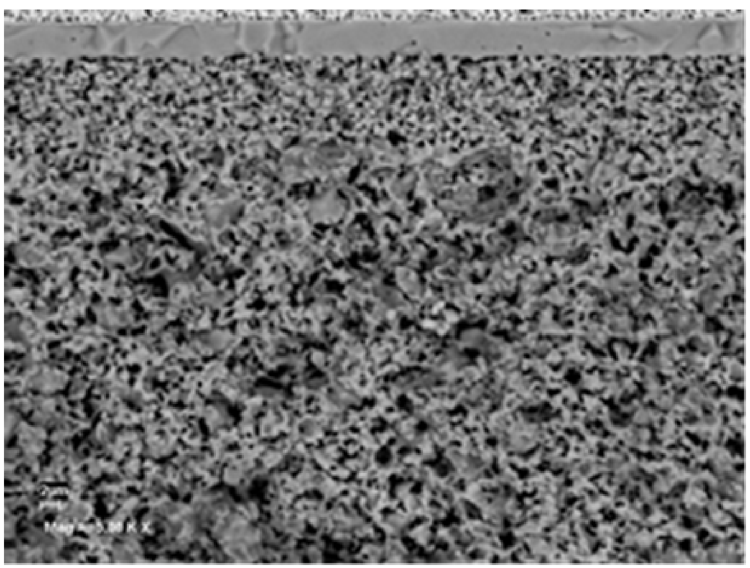


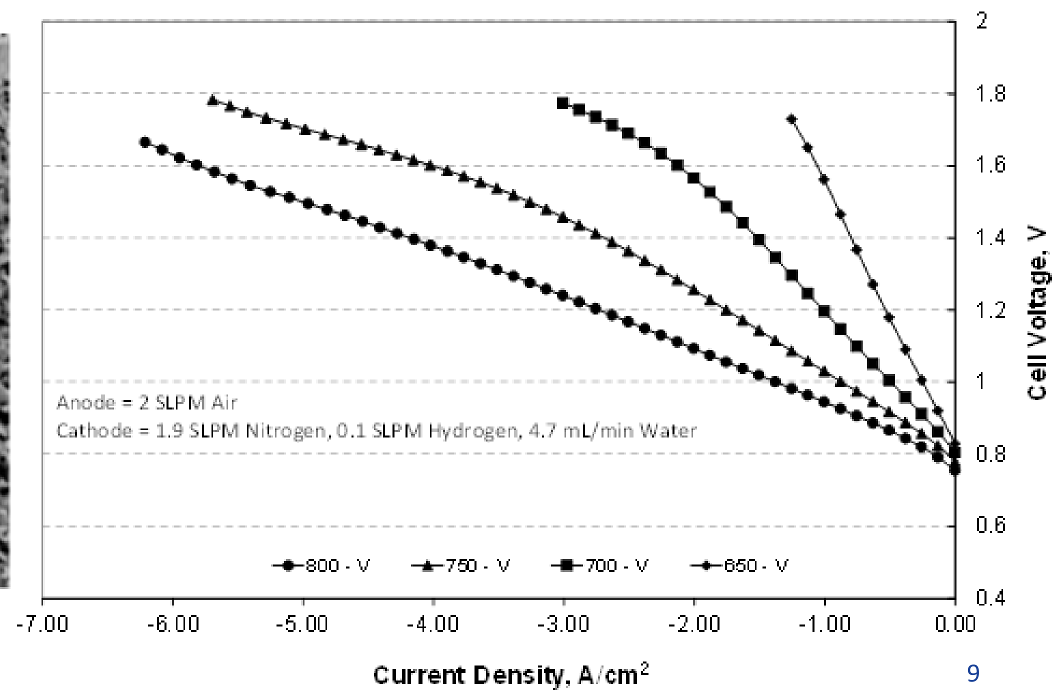


fuelcellenergy

Milestone 1.2–Develop 4 A/cm² Single Cell: Complete

- 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 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.**



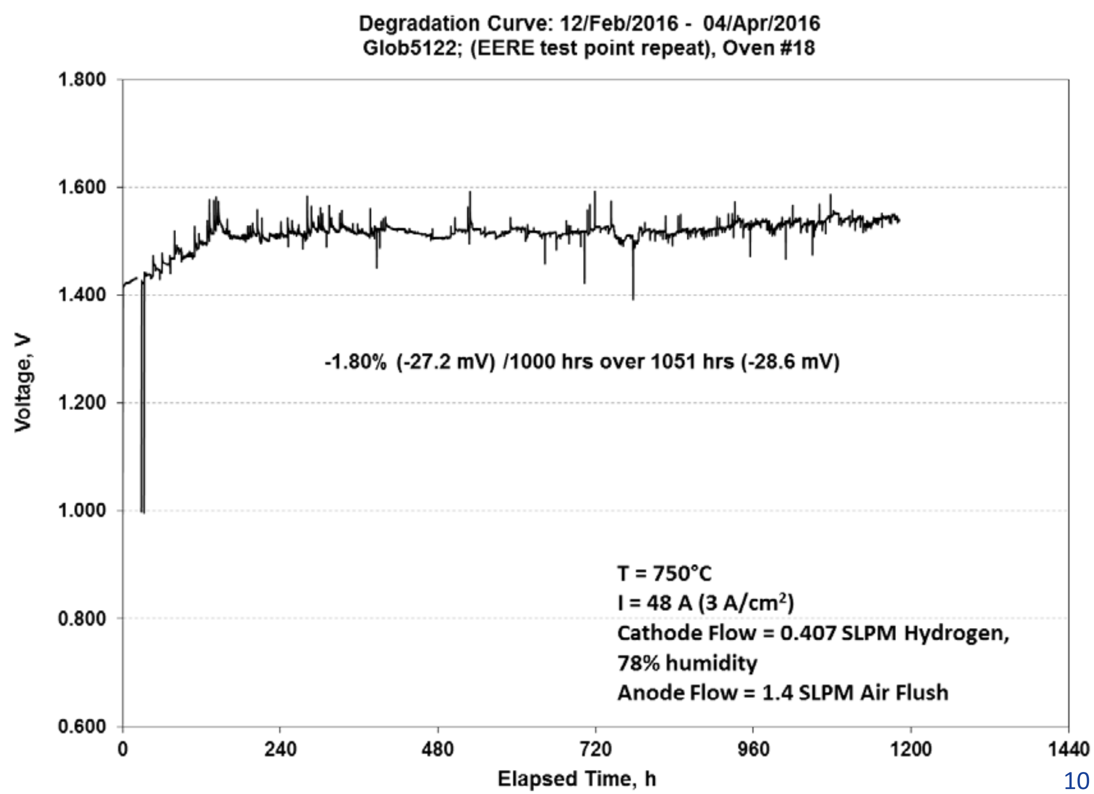


Milestone 1.3–Run 3 A/cm^2 for 1000 hrs, <4% loss: Complete

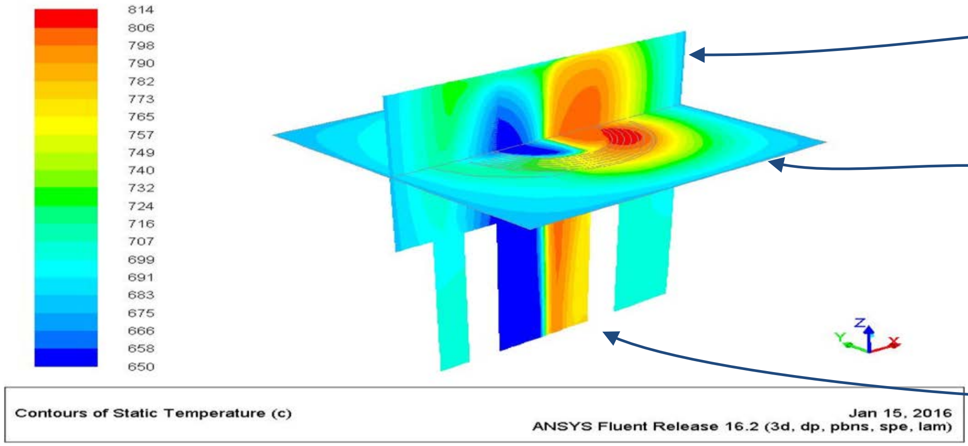
Technical Accomplishments and Progress

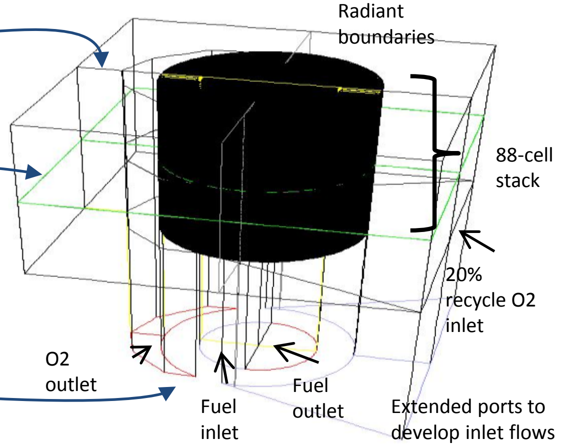
- A number of HiPoD cells were tested at high steady-state electrolysis current density of 3 A/cm^2 to:
  - Evaluate effects of cell thickness, density, and nickel content on degradation rate at high current densities
  - Explore various operating conditions, such as temperature, steam utilization, and steam concentration

- Conducted single cell long term steady-state electrolysis tests at 3 A/cm^2
- Demonstrated 1.8% per 1000 hour degradation rate
- **Exceeded the Milestone 1.3 target of ≤ 4% per 1000 hour**



Milestone 2.1.1–Preliminary Stack Design/Modeling: Complete

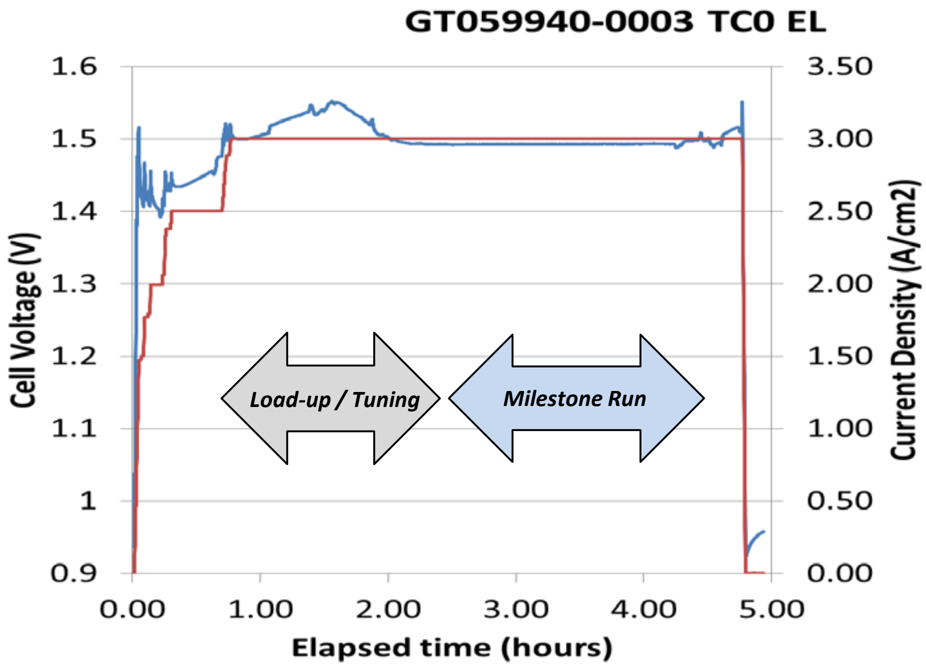




- General layout and design of unit cell and stack complete
- Unit cell and stack CFD models built and exercised at select operating points
- **General operability envelope confirmed (peak temperatures 800 to 815°C)**
- **Heat rejection is primarily to the fuel electrode (H_2O/H_2) stream (convective, 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.**

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

- 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)

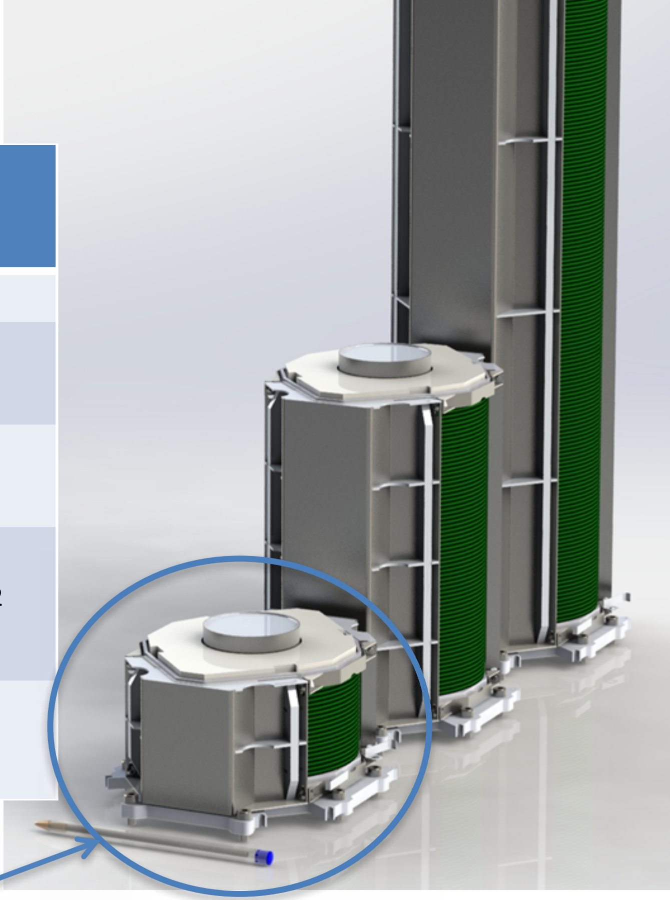
- Fuel inlet composition: 78 % H_2O, 22 % H_2 (20.110 SLPM H_2O (calc), 5.672 SLPM H_2)
- Steam utilization: 50.0%
- Air purge: air, 29.998 SLPM
- Furnace temperature: 585.0°C
- In-stack temperatures: 782.1 – 819.5°C

Milestone 2.2.2–Complete Full Size SOEC Stack Design Freeze: Complete

- Preparing for production of revised stack design, Compact SOFC Architecture (CSA) stack

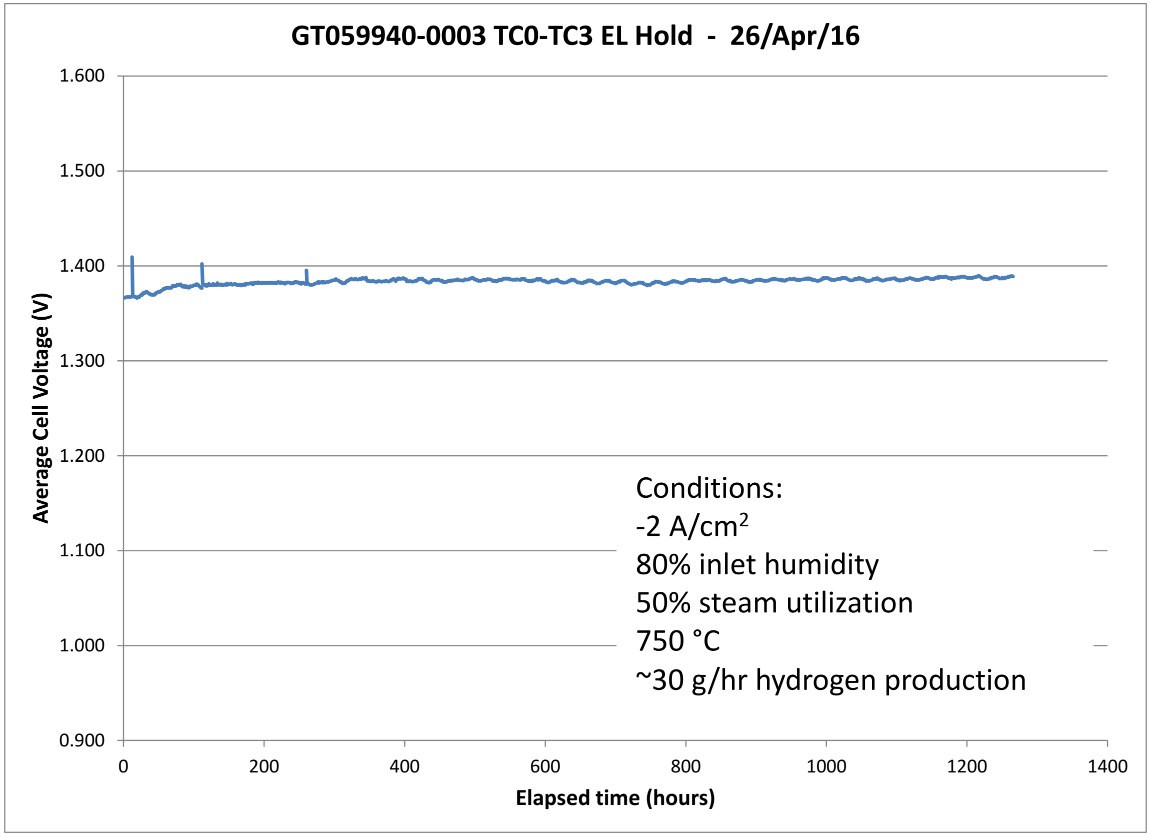
Property	Scale			Comments
	Short	Mid	Full	
Cell count	**45**	150	350	
Electrolysis voltage, V	**58**	193	450	At 1.285 V/cell
Electrolysis Power, kW	**7**	23	55	At -2A/cm^2
Hydrogen Production, kg/day	**5**	16	38	24 hrs at -1.5 A/cm^2
Height, mm (in)	**91 (3.6)**	211 (8.3)	440 (17.3)	

Illustration of CSA stack sizes



Project deliverable

Milestone 2.2.3–Stack Development and Testing: In Progress



Stack volume: 250 mL
Less than 2" tall

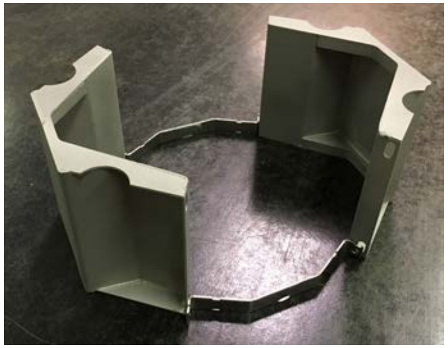
- Stable operation at -2 A/cm^2 demonstrated for over 1000 hours
- Average cell voltage <1.390 V over test period
- Sub 5 mV/khr degradation (after initial stabilization)
- Testing executed after 3 A/cm^2 milestone run (same stack)

Milestone 2.2.3–Stack Development and Testing: In Progress

Technical Accomplishments and Progress

- Updated stack design (CSA) to be deployed later in 2017 for 250 g/hr milestone test.
- The stack development effort is funded primarily under US DOE award DE-FE0026093 *Innovative SOFC Technologies:*
  - The main objective of the research and development is to reduce the SOFC stack cost to the extent which undercuts DOE's cost targets by 50%. The pathways in reaching the project's objective consist of novel materials development, transformational manufacturing processes, high performance cell components, and innovative robust and reliable stack designs leveraging advancements that have occurred in the DOE SOFC Program. To verify the advances in developing the proposed innovations, the project will culminate in a 5 kW-scale stack test for at least 1000 hours using full-size cells, operating on natural gas at self-sustained Normal Operating Conditions (NOC) that would be envisioned in a commercial system.
- Current efforts are focused on part procurement and production line retooling for the CSA stack. Some examples of incoming parts and the retooling effort are shown below.

Stack manifolds



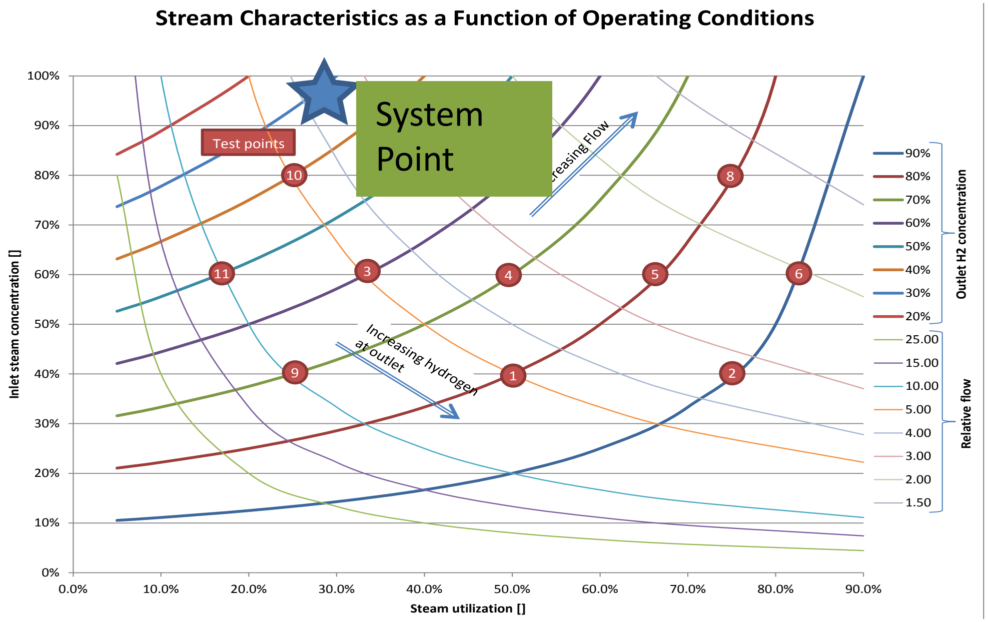
Build table parts

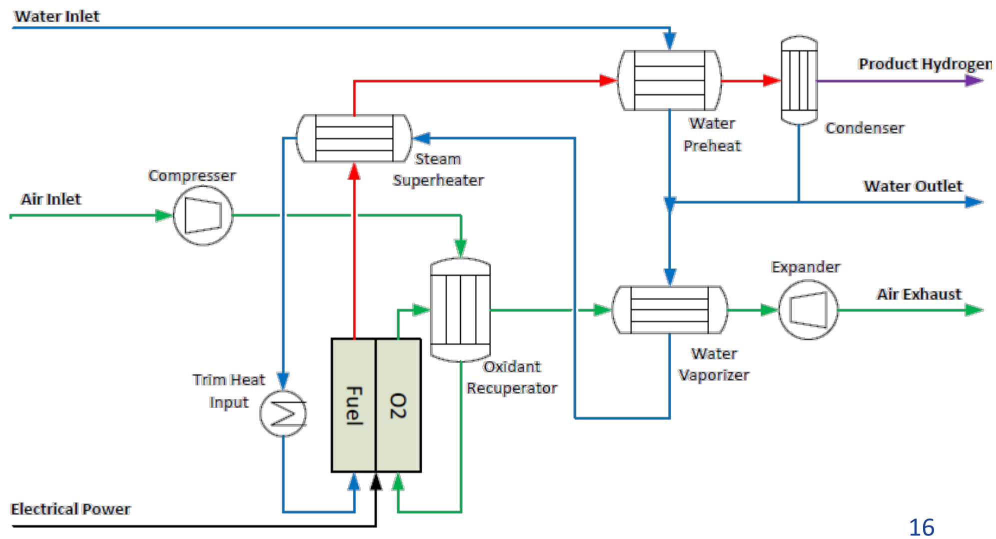
Firing jig

Robot end effector

Milestone 3.1–Preliminary System Design: Complete

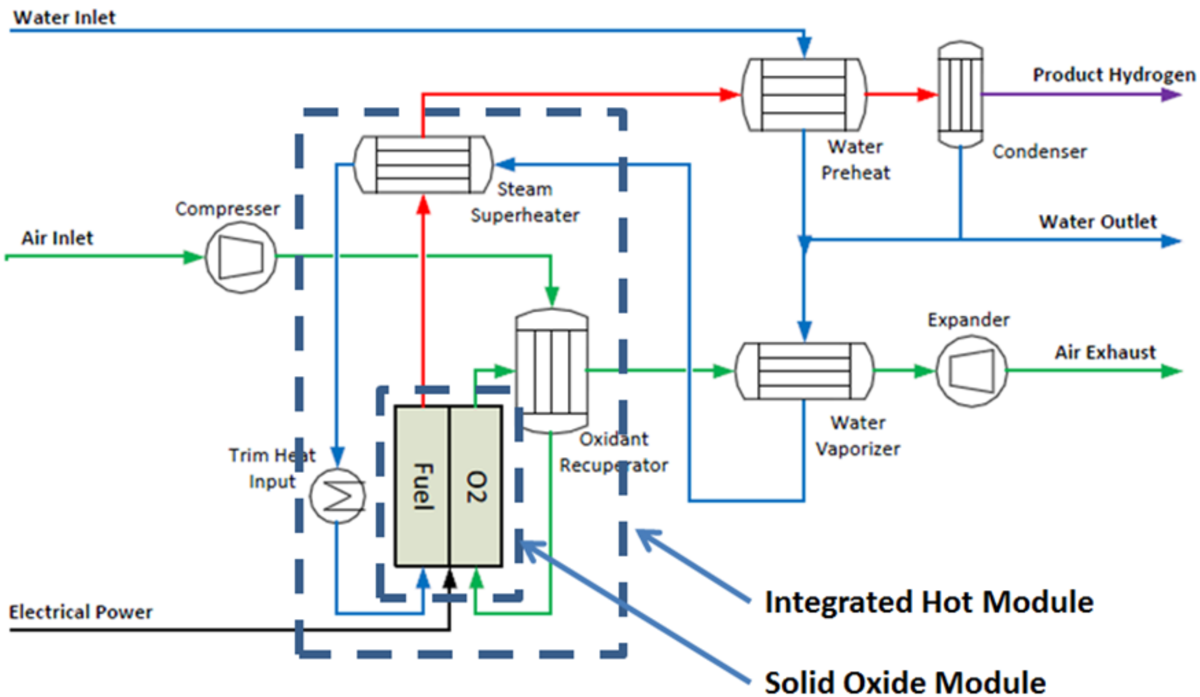
- Aspen Hysys – stack conditions model
  - 0-D stack/system model built
  - Stack model facilitates exploration of heat and energy implications of different operating points on stack health
  - Enables a quick evaluation of different operating points for feasibility
  - When coupled with detailed cell/stack 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

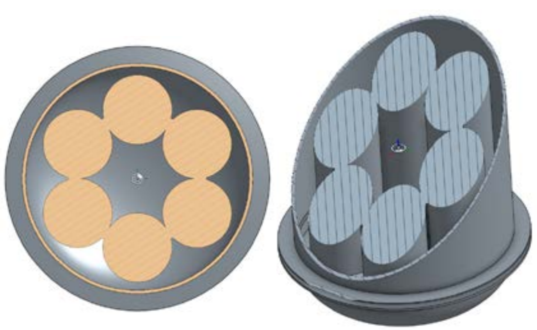




Milestone 3.2–Detailed SOEC Hot Module Design: Complete

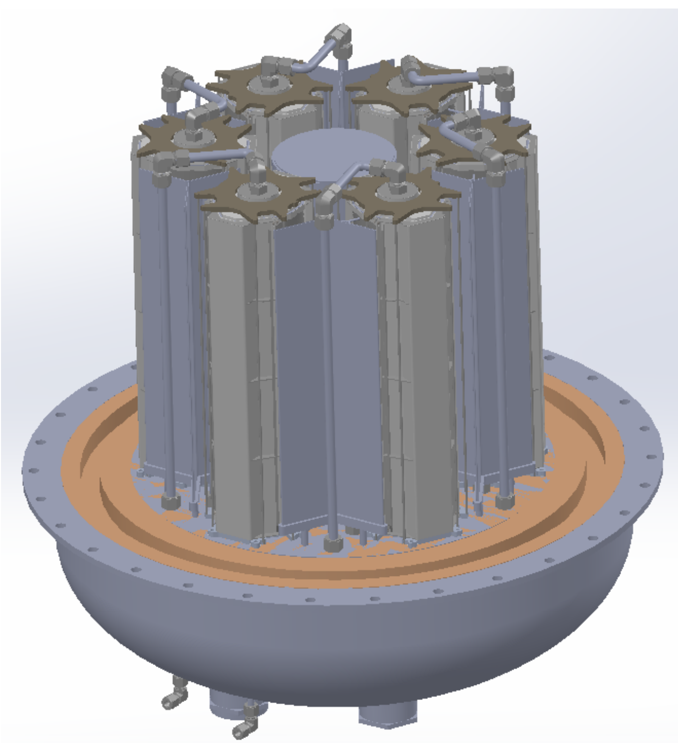
- Integrated Hot Module Approach
  - Module weight as cost corollary
  - Tight thermal integration of BoP Components
  - Reduces overall system size
  - Increases hot module size and complexity
- Integrated components
  - Heat exchangers
  - Water Vaporizer
  - Trim/Guard Heaters
- High Power Density
  - Air HX 35-50 kW
  - Steam HX 30-40 kW
  - Vaporizer 30-45 kW
  - Trim Heater 5-70 kW
- Schematic Representation

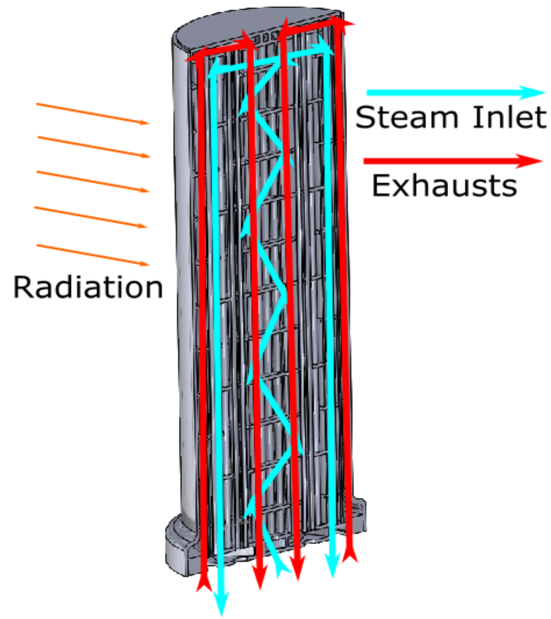




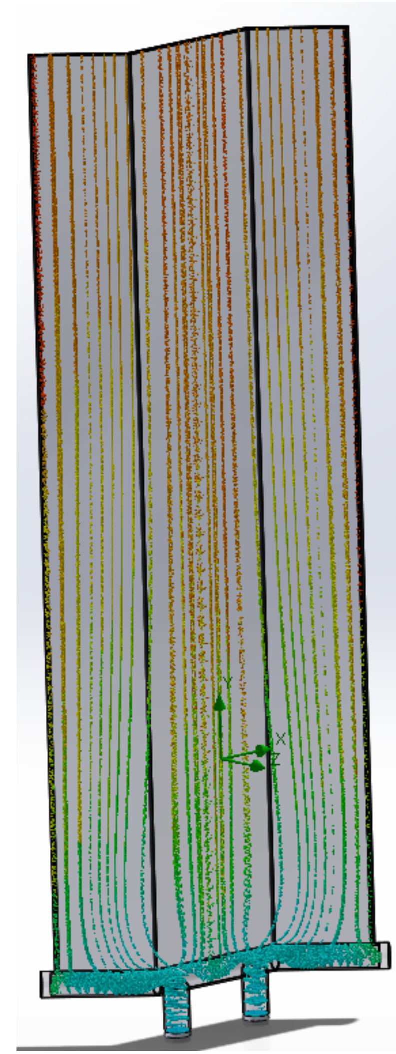
Milestone 3.2–Detailed SOEC Hot Module Design: Complete

- Detailed System Modeling
  - Detailed solid modeling of mechanical components
  - CFD modeling of reactant flows and heat exchange
    - Individual unit operations modeled to verify performance
  - Final mechanical design matches Heat/Material balance
  - Instrumentation, electrical and process connections detailed





Central Multi-Flow Heat Exchanger



Stack Air Heat Exchanger

Proposed Future Work

- Complete a comprehensive techno-economic study of an ultra-high current density SOEC system integrated with renewable energy sources
- Integrate the project's technology development into completing the final Milestone: demonstrating a full size SOEC stack with 250 g/hour hydrogen production and 1000 hour stable operation at a current density of more than 2 A/cm^2

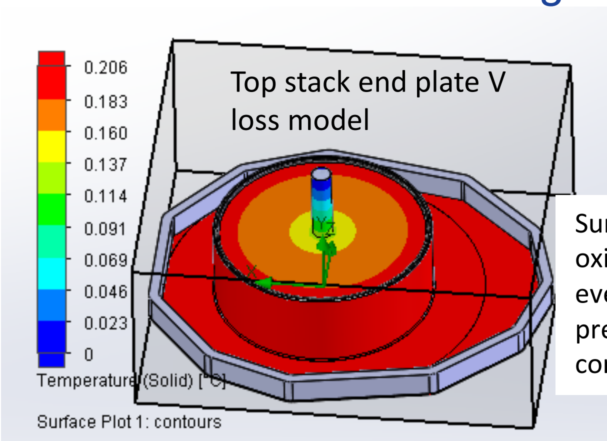
Summary

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 1.3 - Competed the final SOEC cell design, and demonstrated 1.8% per 1000 hour degradation rate with more than 1000 hour stable electrolysis operation at 3 A/cm^2 in single cell test. The result exceeded the project target of <4% per 1000 hours. • Completed Milestone 2.2.2 - Completed detailed full size stack design with all drawings completed and approved; Demonstrated stable short stack operation at 2 A/cm^2. • Completed Milestone 3.2 - Completed in-depth SOEC hot module configuration design, and developed the preliminary ultra-high current density SOEC system conceptual design
Collaboration	NREL, Boeing/DARPA, and DOE SECA

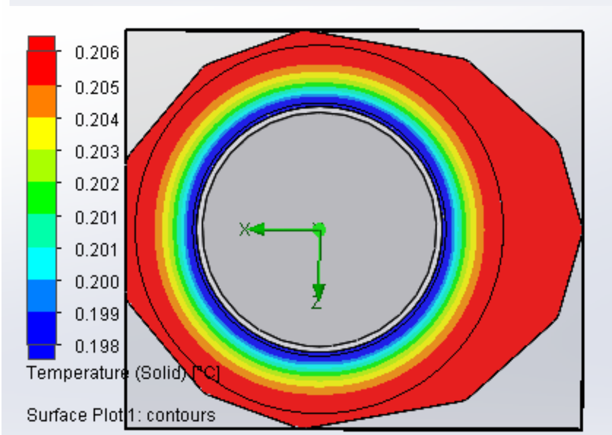
Technical Back-Up Slides

Stack Test Stand Development

- 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