# Modular SOEC System for Efficient $H_2$ Production at High Current Density

fuelcellenergy

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Project ID# TV041

# 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: $3,750,000.00
- Total Recipient Share: $750,000.00
- Total Federal Share: $3,000,000.00

- Total DOE Funds Spent*: $77,039.00

* Estimated as of 3/31/17

## Partner

- Versa Power Systems (VPS)
- DOE/FE, National Energy Technology Laboratory (NETL)

# Relevance

**Objective:**

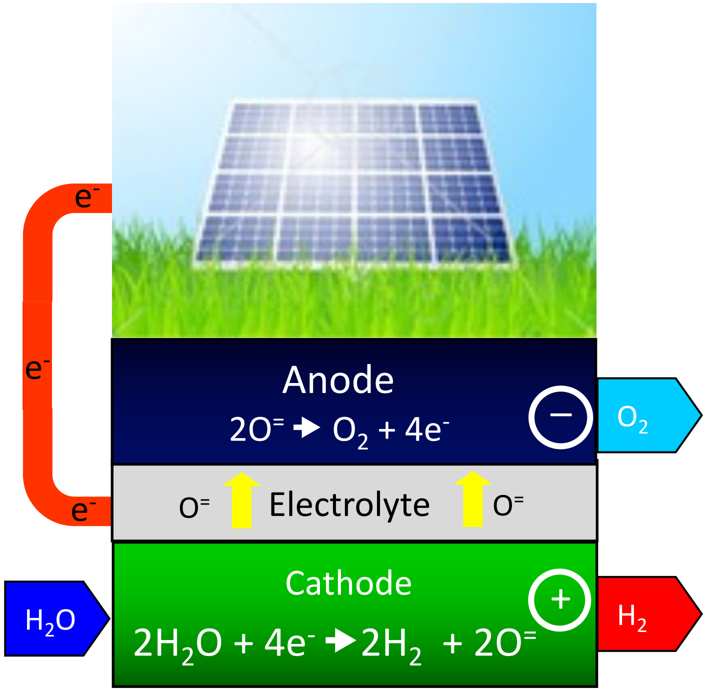
- Demonstrate the potential of Solid Oxide Electrolysis Cell (SOEC) systems to produce hydrogen at a cost of <$2 /kg $H_2$ exclusive of delivery, compression, storage, and dispensing

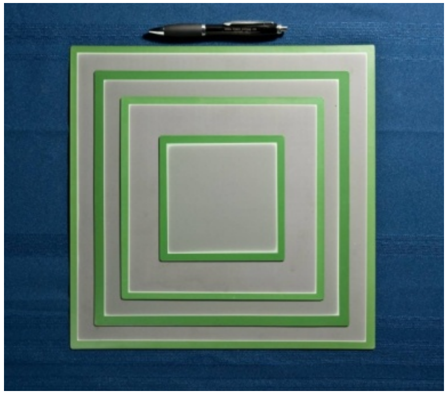
**Project Goals:**

- Improve SOEC performance to achieve >95% stack electrical efficiency based on LHV of $H_2$ (>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

# Approach: 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



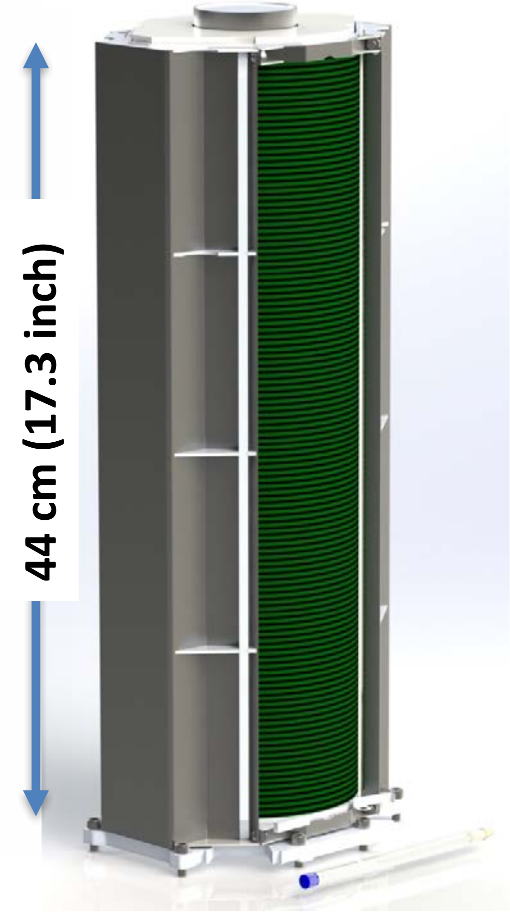


Anode-Supported Solid Oxide Electrolysis Cell

# *Approach: Stack Technology Development*

- 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 38 kg $H_2$/day at a current density of 1.5 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 test

**Full size CSA stack:**
**38 kg $H_2$/day**
**10 liter stack volume**



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

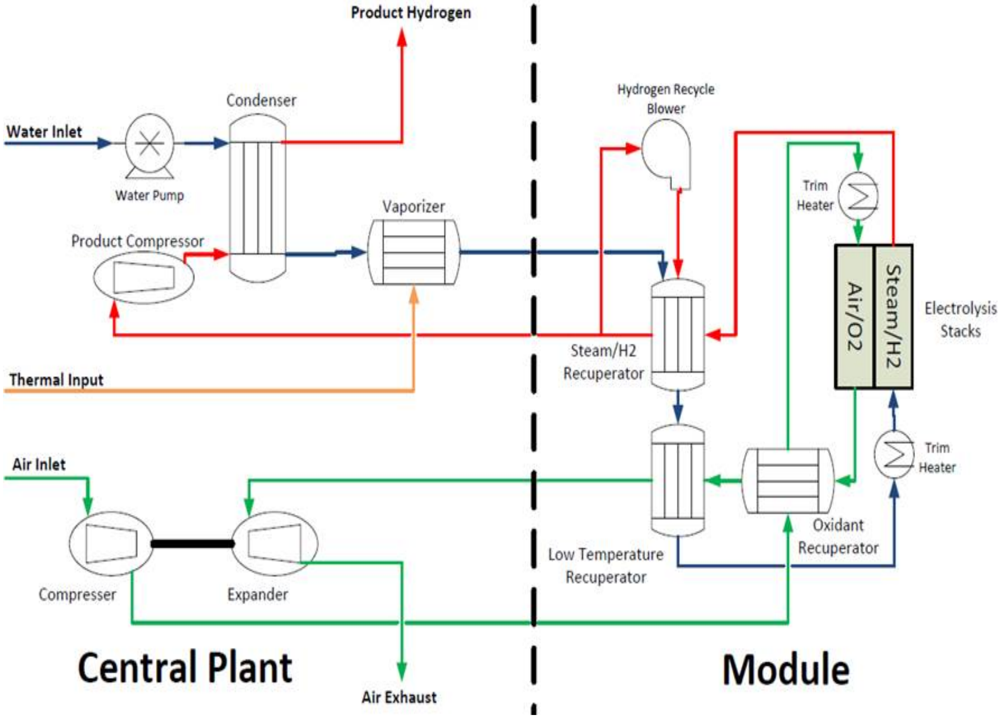
# Approach: Breadboard System Demonstration

- Develop bases of design and operation for a breadboard demonstration prototype:
  - >4 kg $H_2$/day capacity
  - Operating current density 1 to 2 A/cm$^2$
  - 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

**Example of a thermally self-sustained stack module design**

# Approach: Techno-Economic Analysis

- 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 $H_2$/day commercial system
  - Utilize CSA stack design architecture
- Develop flow sheet alternatives to optimize system performance and cost
- Perform simulation studies using first principle conservation laws
- 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



Electrolysis Process Flow Sheet

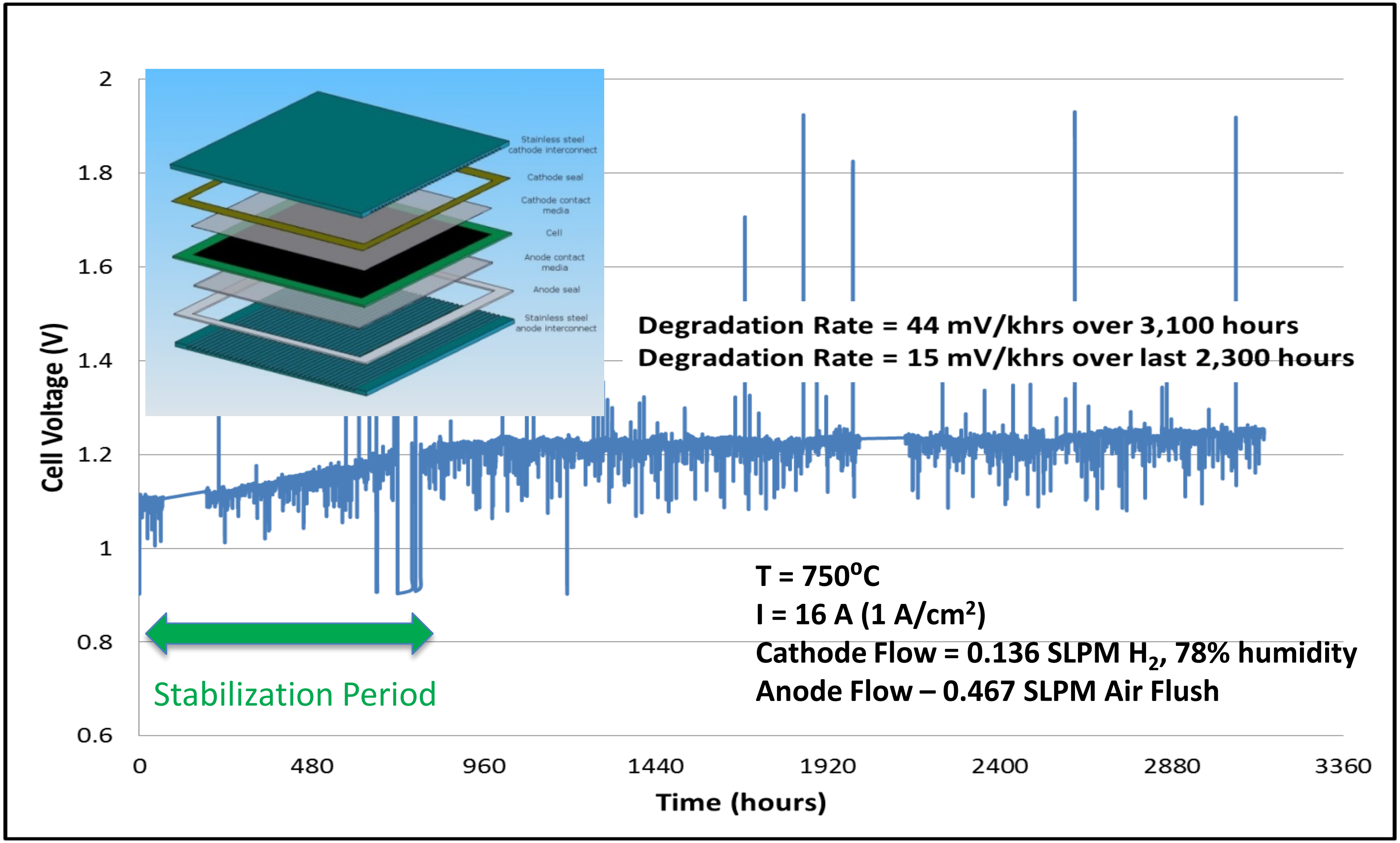
200 kW SOFC System BOP

# Approach: Milestones FY2017 and FY2018

| Task / Subtask Title | Milestone Description (Go/No-Go Decision Criteria) | Completion Date | Status (Percent Completed) |
|---|---|---|---|
| **Endurance Improvement** | Complete 1000 hr test of single cell with voltage degradation rate ≤4%/1000 hrs | 12/31/2016 | **100%** |
| | Complete 1000 hr test of single cell with voltage degradation rate of ≤2%/1000 hrs | 12/31/2017 | |
| **Technology Stack Tests** | Complete >500 hours testing of a stack across a matrix of ≥5 operating points to identify design improvements | 6/30/2017 | **25%** |
| | *Stack testing (≥1000 hours) with electrical efficiency ≥95% (LHV based) at ≥1 A/cm$^2$ & degradation rate ≤4%/1000 hrs*<br>***Go-No-Go Decision: Success criteria for continuation to BP2*** | 3/31/2018 | |
| | Complete post-test analysis of the metric stack to be utilized in further reduction of the stack degradation rate | 6/30/2018 | |
| **System Configuration and Parametric Analysis** | Develop electrolysis performance characteristic maps of system operating parameters to be used for optimization | 3/31/2017 | **100%** |
| | Develop system configuration and operational parameters for achieving >75% overall system efficiency | 9/30/2017 | **5%** |
| | Create conceptual design of a > 4 kg $H_2$ / day SOEC demonstration system with estimated overall efficiency >75%<br>**Go-No-Go Decision: Success criteria for continuation to BP2** | 3/31/2018 | |
| **Detailed System Design** | Complete detailed system design for >4kg $H_2$/day demonstration | 9/30/2018 | |

# *Accomplishments and Progress: 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**



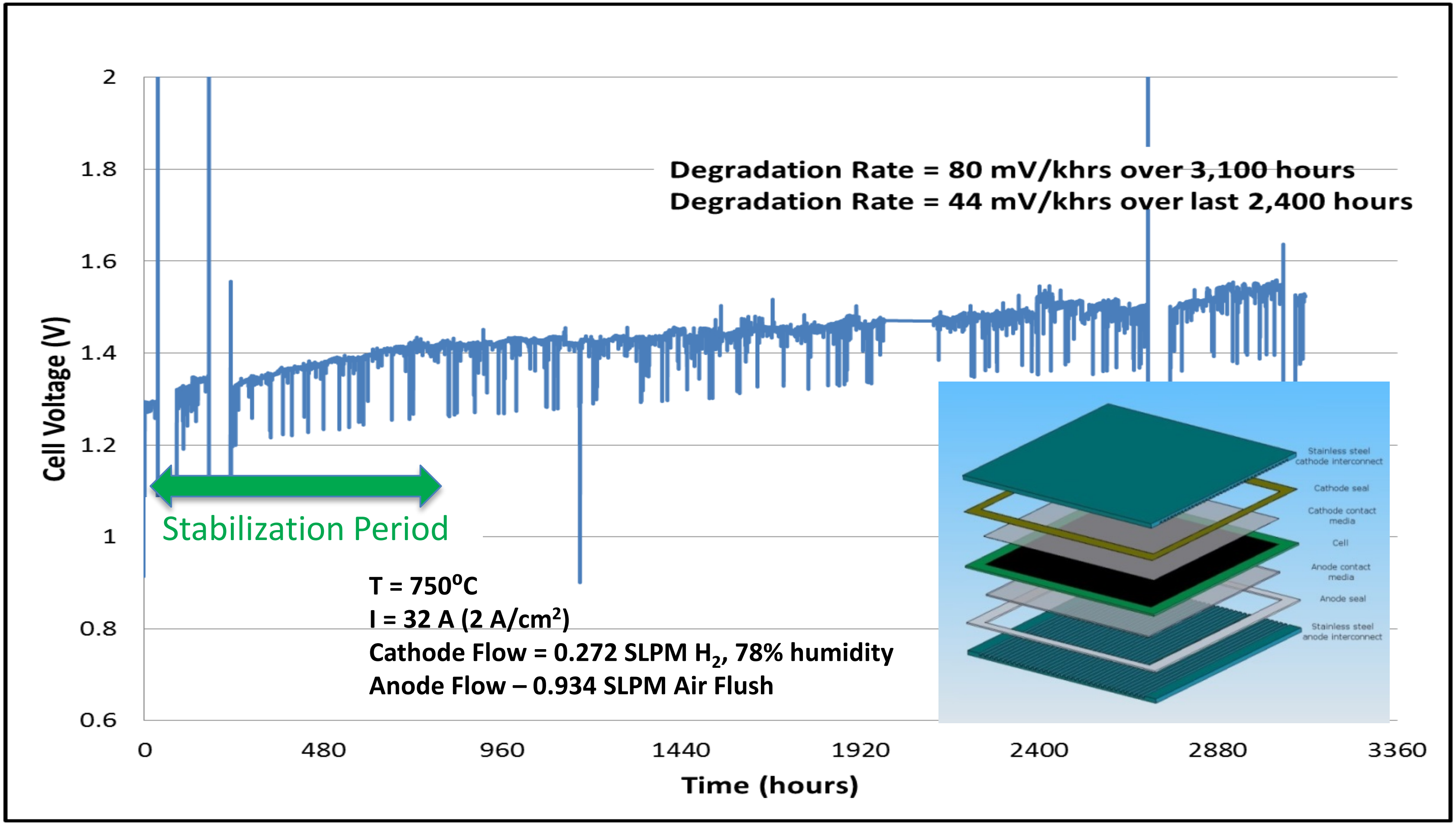
Degradation Rate = 44 mV/khrs over 3,100 hours
Degradation Rate = 15 mV/khrs over last 2,300 hours

T = 750°C
I = 16 A (1 A/cm²)
Cathode Flow = 0.136 SLPM $H_2$, 78% humidity
Anode Flow – 0.467 SLPM Air Flush

- **Demonstrated voltage degradation rate of <15 mV/1000h or 1.3 %/1000h over the last 2,300 hours after initial stabilization** fuelcellenergy

# Accomplishments and Progress: Cell Degradation Test at 2 A/cm$^2$

## Test of HiPoD (High Power Density) cell (5 cm x 5 cm x 0.03 cm) at 2 A/cm$^2$



Degradation Rate = 80 mV/khrs over 3,100 hours
Degradation Rate = 44 mV/khrs over last 2,400 hours

Stabilization Period

T = 750°C
I = 32 A (2 A/cm$^2$)
Cathode Flow = 0.272 SLPM $H_2$, 78% humidity
Anode Flow – 0.934 SLPM Air Flush

- **Demonstrated voltage degradation rate of <44 mV/1000h or 3.5%/1000h over the last 2,400 hours after initial stabilization**

# Accomplishments and Progress: Operation Window Exploration

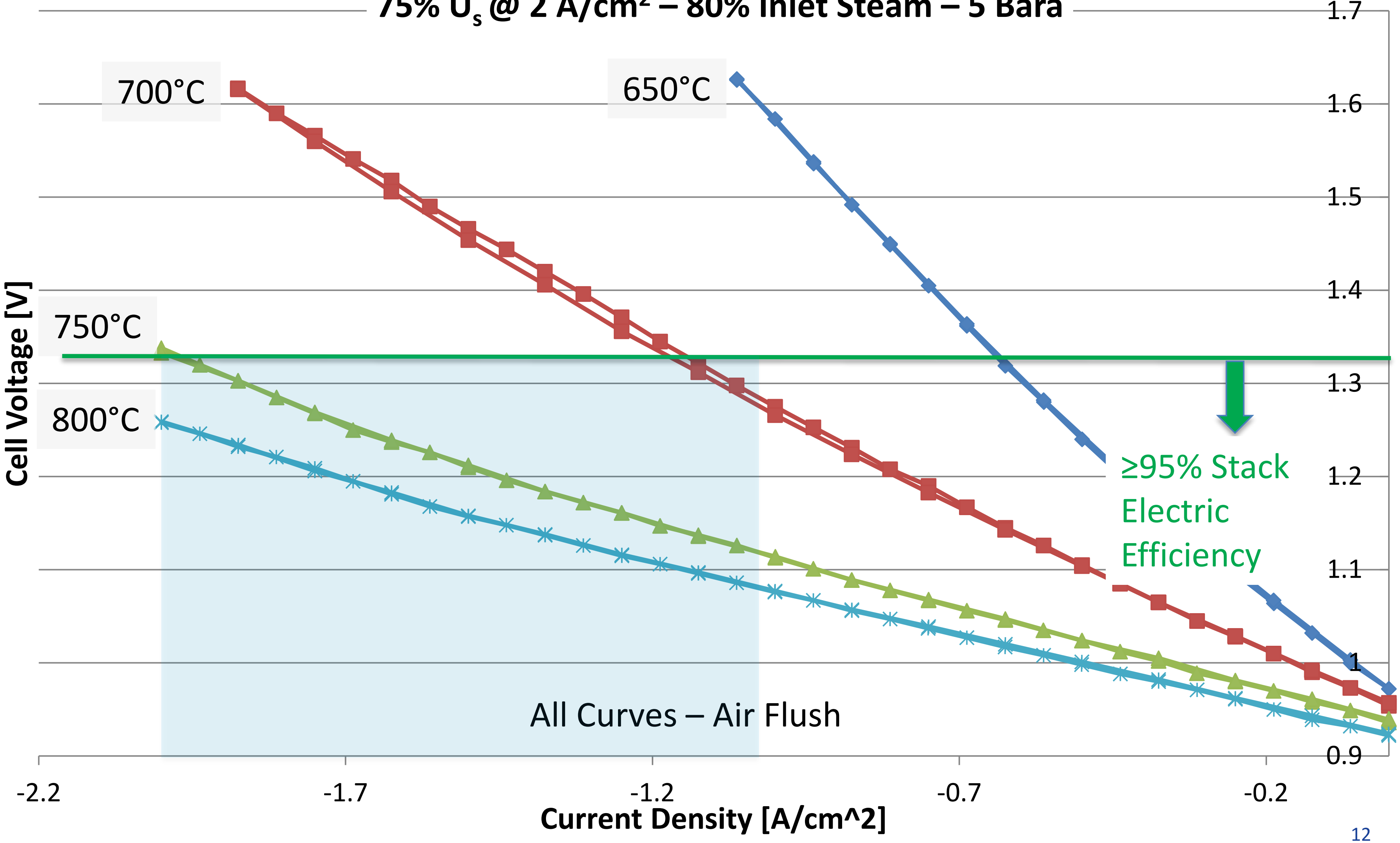
| Operating Parameter | Range | System Impacts at Higher End of Range |
|---|---|---|
| Current | 1-2 A/cm$^2$<br>(Target 1.1-1.32 V/cell) | 1- Reduced Stack Cost<br>2- Higher Stack Exit Temperature for Heat Recovery<br>3- Lower Stack Efficiency<br>4- Life Impact |
| Steam Utilization (Stack) | 50%-95% | 1- Simpler $H_2$ Purification<br>2- Lower Stack Efficiency |
| Steam Inlet Concentration | 40%-100% | 1- Higher Stack Efficiency<br>2- Less Recycle (Reduced BoP Cost)<br>3- Harder $H_2$ Purification<br>4- Potential Life Impact |
| Cell Pressure | 1-10 bara | 1- Higher Stack Efficiency (First ~4 bar)<br>2- Simpler $H_2$ Purification<br>3- Lower Stack Efficiency (Above ~ 5 bar)<br>4- Potential Life Impact |
| Anode $O_2$ Concentration (outlet) | 40%-100% | 1- Less Air Flow to Anode (Less BoP Cost)<br>2- Simpler for Pressurized Operation (Less BoP Cost)<br>3- Higher Voltage (Less Efficient) |
| Operating Temperature | 650 °C to 800 °C | 1- Higher Stack Efficiency<br>2- Potential Life Impact |

- Large number of experiments across the above ranges were completed (> 500 test conditions)
- Degradation testing at select points planned

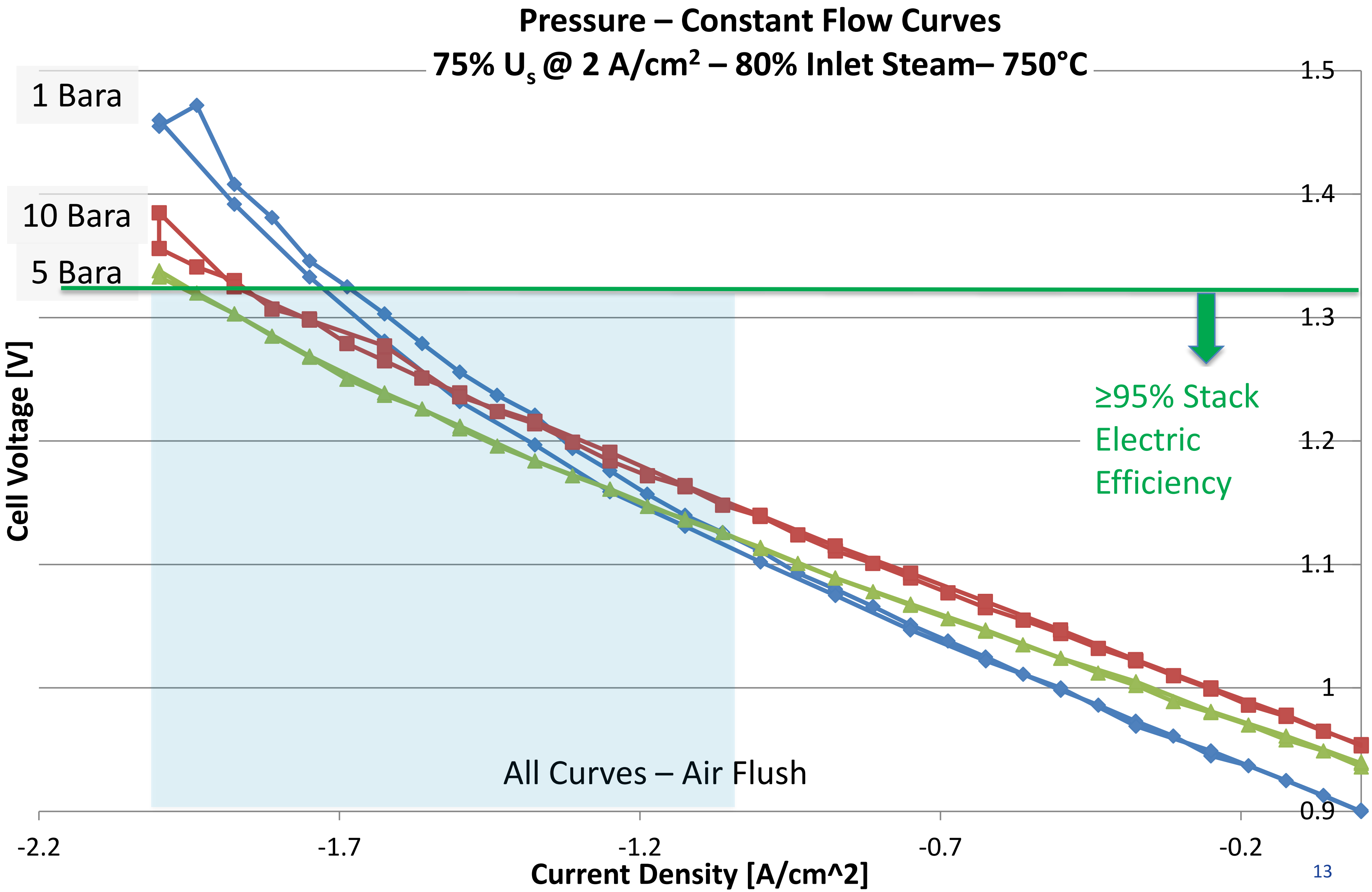
# Accomplishments and Progress: Temperature Effect on Performance

Temperature Variation - Constant flow Curves

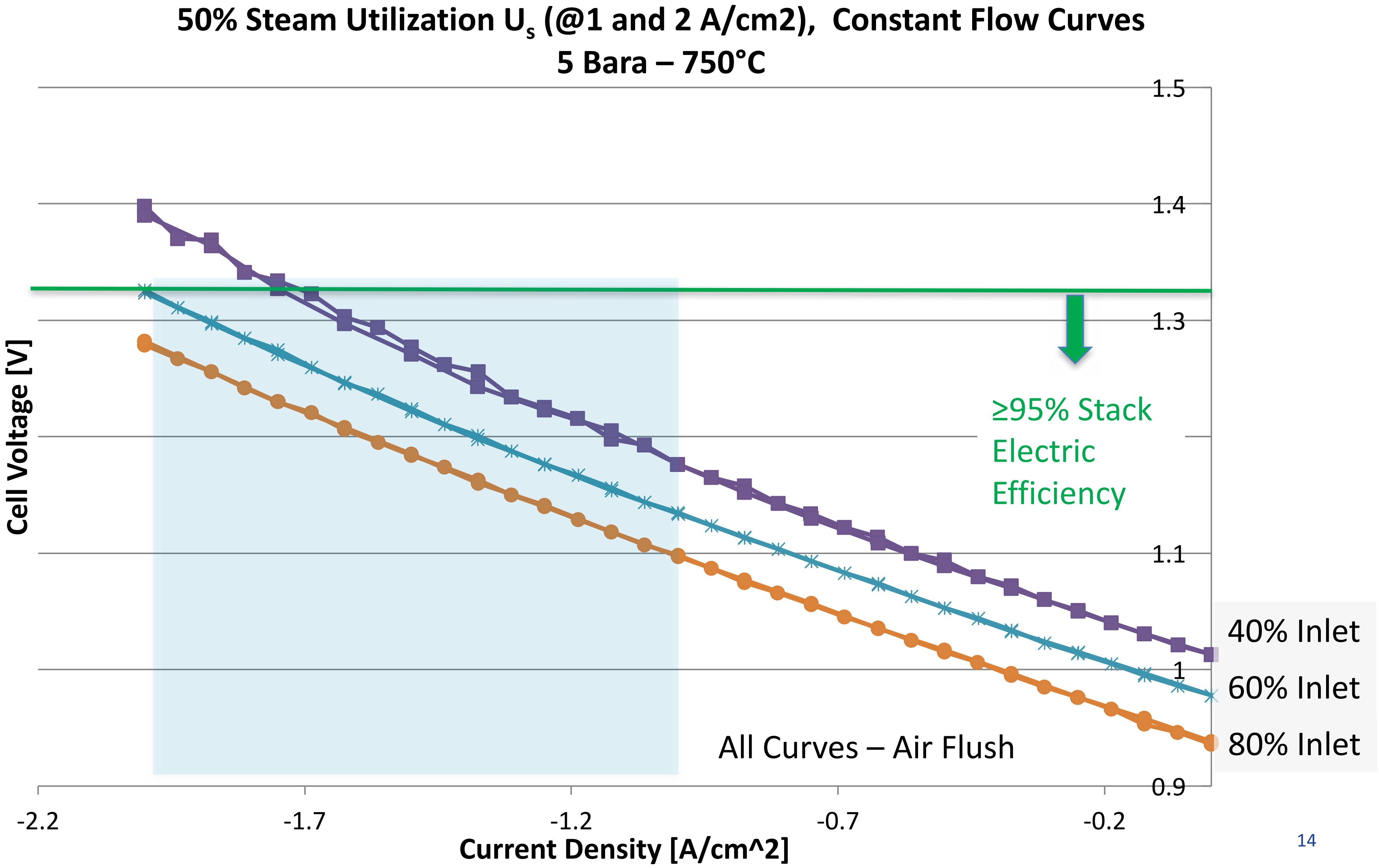
75% $U_s$ @ 2 A/cm² – 80% Inlet Steam – 5 Bara



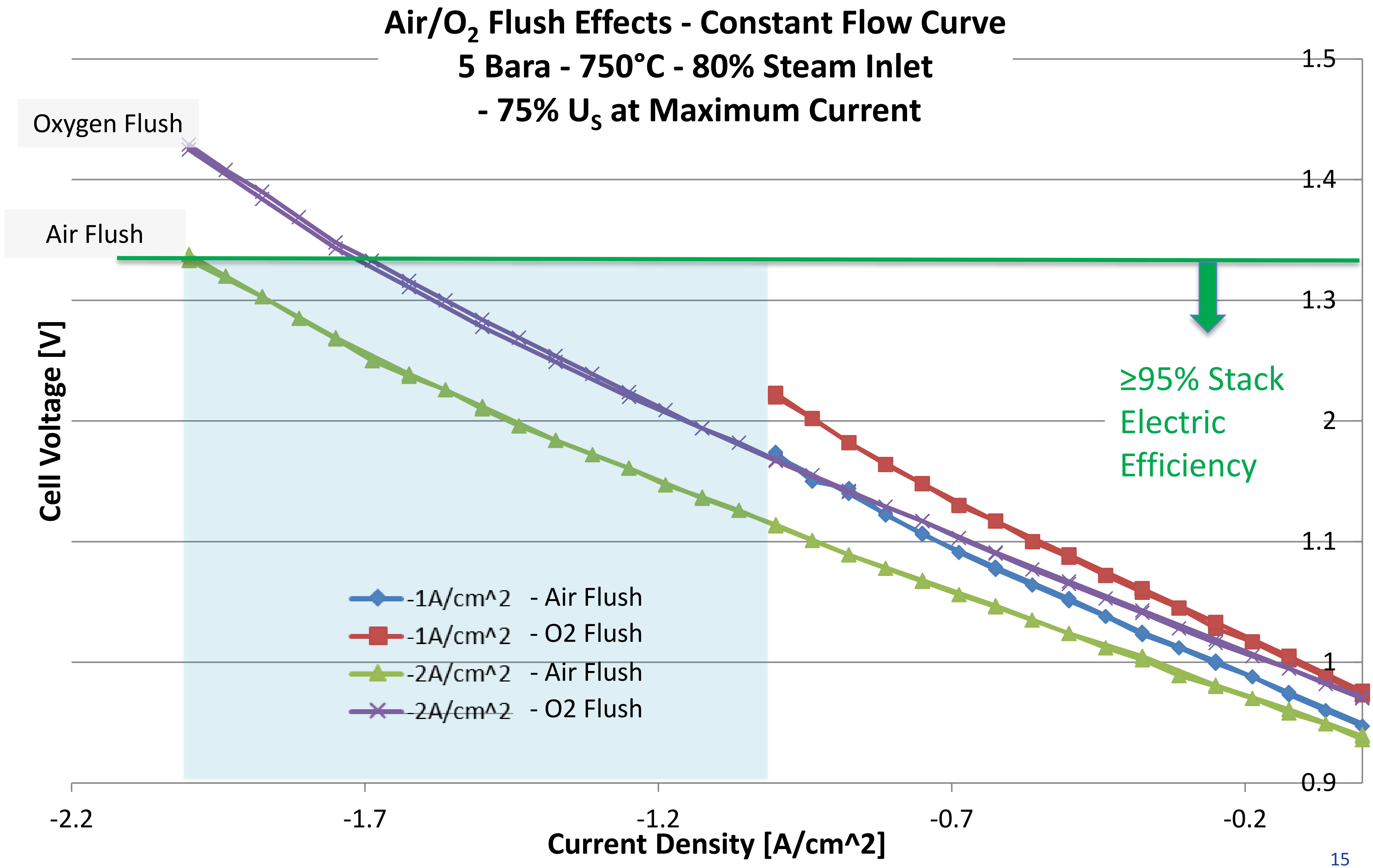
# Accomplishments and Progress: Pressure Effect on Performance



# *Accomplishments and Progress: Inlet Conc. Effect on Performance*



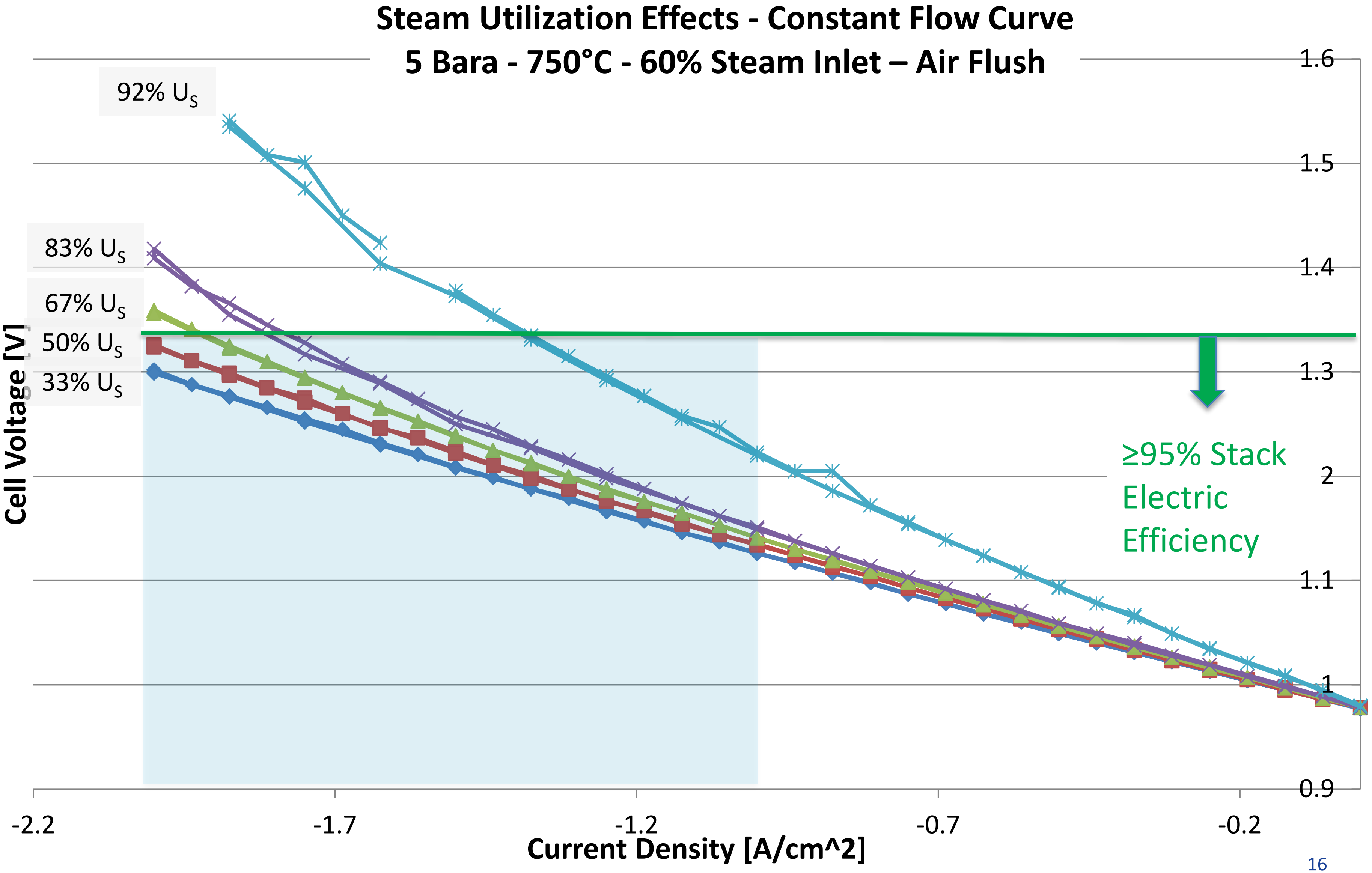
# Accomplishments and Progress: Air/$O_2$ Effect on Performance



Air/$O_2$ Flush Effects - Constant Flow Curve
5 Bara - 750°C - 80% Steam Inlet
- 75% $U_S$ at Maximum Current

≥95% Stack Electric Efficiency

# Accomplishments and Progress: Steam Utilization Effects on Performance

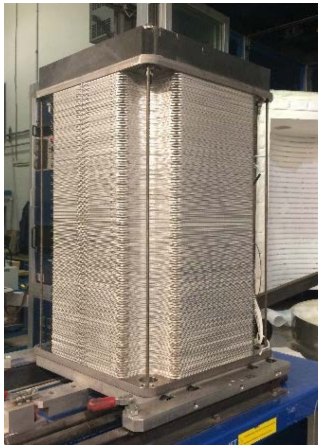


≥95% Stack Electric Efficiency

# Collaborations

- Versa Power Systems (VPS)
  - Provides expertise in:
    - SOFC materials & components R&D
    - Stack design
    - Cell/stack pilot manufacturing and QC
- DOE/NETL
  - Supports development of SOFC technology for power generation focused on:
    - Increased SOFC endurance
    - Stack/system scale-up and cost reduction
    - Power system integration and demonstration

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



16 kWe Stack: 120-cells ($550 \text{ cm}^2$ Active Area per Cell)

50 kW System: Natural Gas Fuel (8’x20’x8’6”)

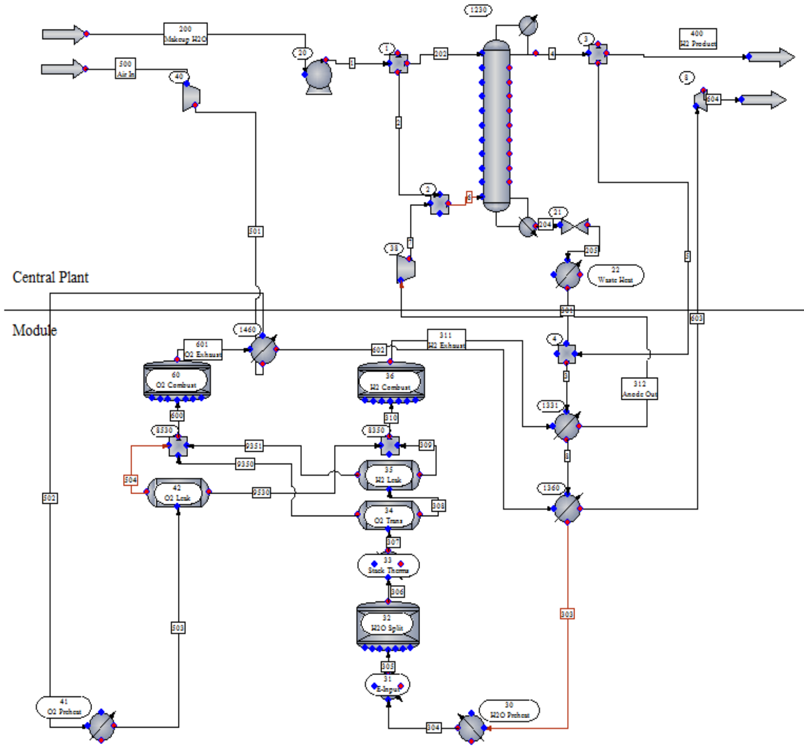
# Remaining Challenges and Barriers

- Cell and Stack
  - Degradation reduction at high current density
  - Determination of operating parameters impacts on cell endurance
  - Scale up of stack architecture and manufacturing process
- System and Demonstration
  - System efficiency target of 75% (LHV of $H_2$)
  - High pressure solid oxide system design and demonstration
  - Development of cost optimized system to meet \$2/kg $H_2$ target

45-Cell stack (>4 kg $H_2$/ day) for demonstration tests

# Proposed Future Work

- Cell and Stack
  - Degradation characterization
  - Cell and stack fabrication for testing and demonstration of milestone targets
  - Cell performance model development
  - Development of system flowsheet and model in Chemcad simulation platform
- System and Demonstration
  - Tradeoff analysis considering wide ranges of operating parameters
  - Detailed system design and performance optimization
  - Demonstration of highly efficient and power dense SOEC in a breadboard system
  - H2A Analysis

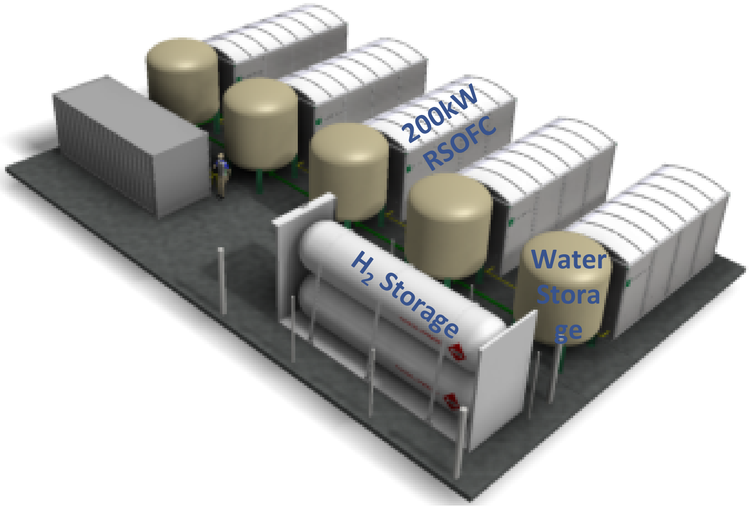


**Any proposed future work is subject to change based on funding levels**

# Technology Transfer Activities

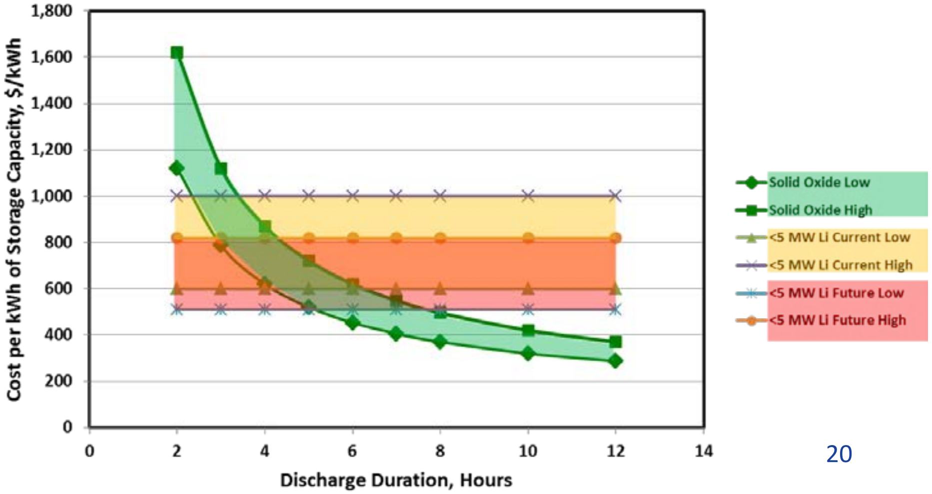
## *Reversible SOFC (RSOFC) System for Energy Storage*

- In addition to the opportunities for low-cost $H_2$ production, SOEC technology is an enabler for development of RSOFC for electric energy storage
- Advantage over conventional storage:
  - Long duration achieved by adding hydrogen storage, without adding stacks
- Advantage over other Hydrogen based storage:
  - Efficiency advantage- due to higher efficiency of SOFC in fuel cell and electrolysis modes of operation



***6 MWh RSOFC System:***

1MW x 6 h, SOFC Power Delivery

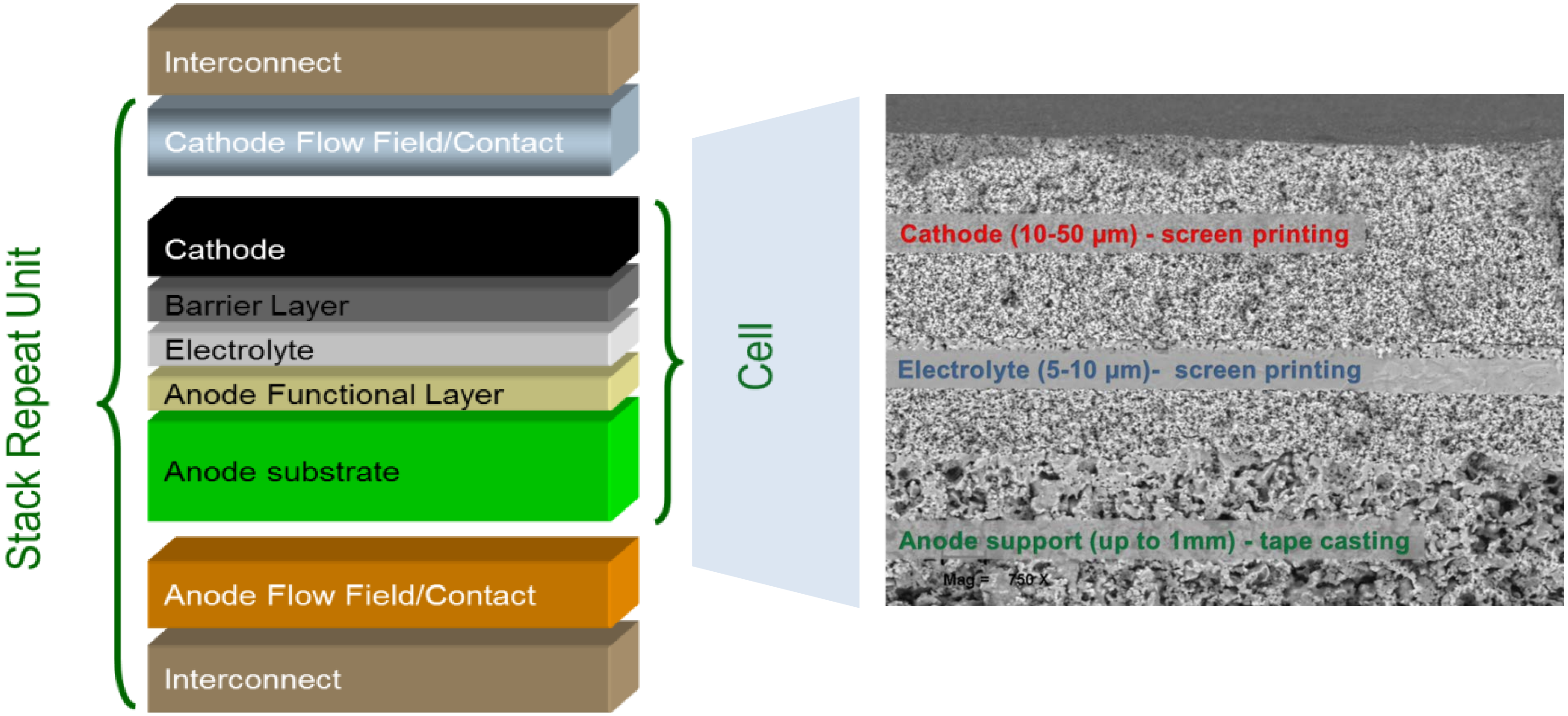


# Summary

- Met Q1 and Q2 Milestone targets as planned:
  - Long term cell performance degradation rate of ≤4%/1000 was demonstrated at 1 & 2 A/cm$^2$
  - Cell operating parameter investigation was completed to determine stack operational windows to be used in system design
    - >500 test conditions evaluated
- Initiated >500hr test of a 20 HiPoD cell stack to establish design improvements
- Initiated preliminary system flowsheet design:
  - Develop alternative configurations for heat recovery
  - Perform mass and energy balances at the operating parameters selected in Q2 milestone for optimum system performance

# TECHNICAL BACK-UP SLIDES

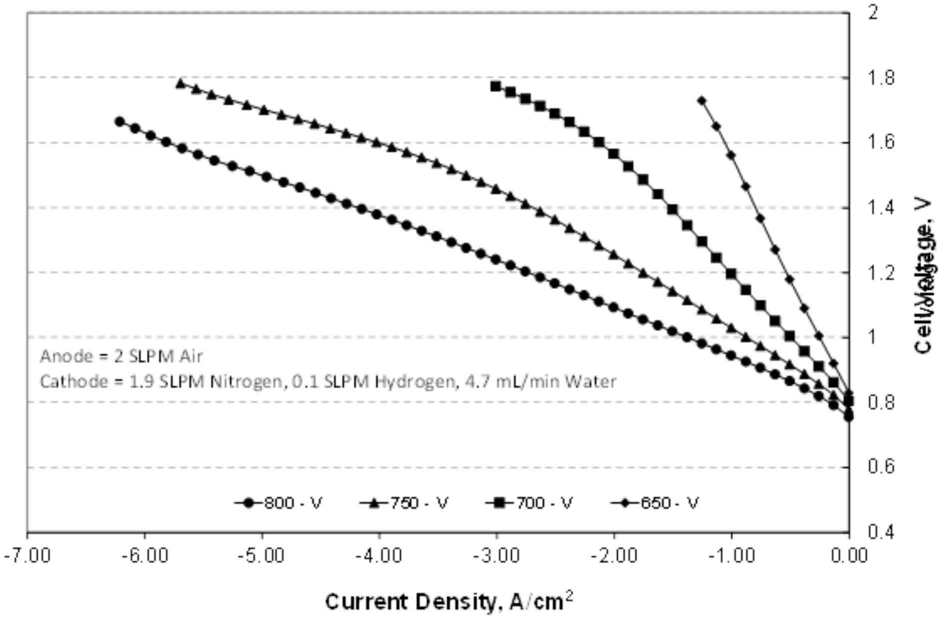
# HiPoD Cell Technology

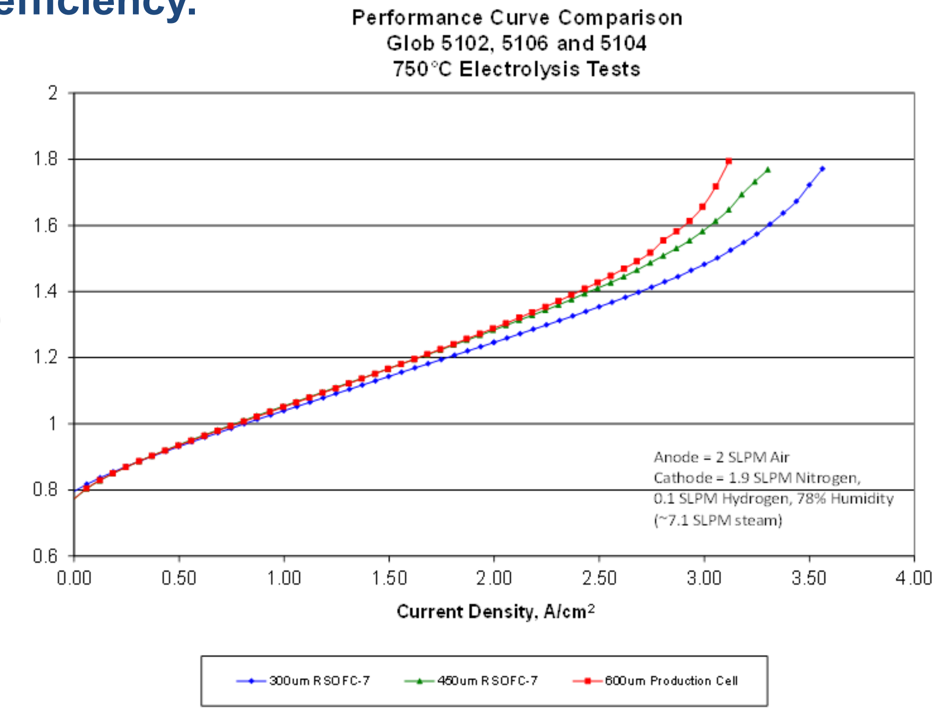


| Component | Materials | Thickness | Porosity | Process |
|---|---|---|---|---|
| Anode | Ni/YSZ | 0.3 mm | ~ 40% | Tape casting |
| Electrolyte | YSZ | 5 - 10 µm | < 5% | Screen printing |
| Cathode | Conducting ceramic | 10 - 50 µm | ~ 30% | Screen printing |

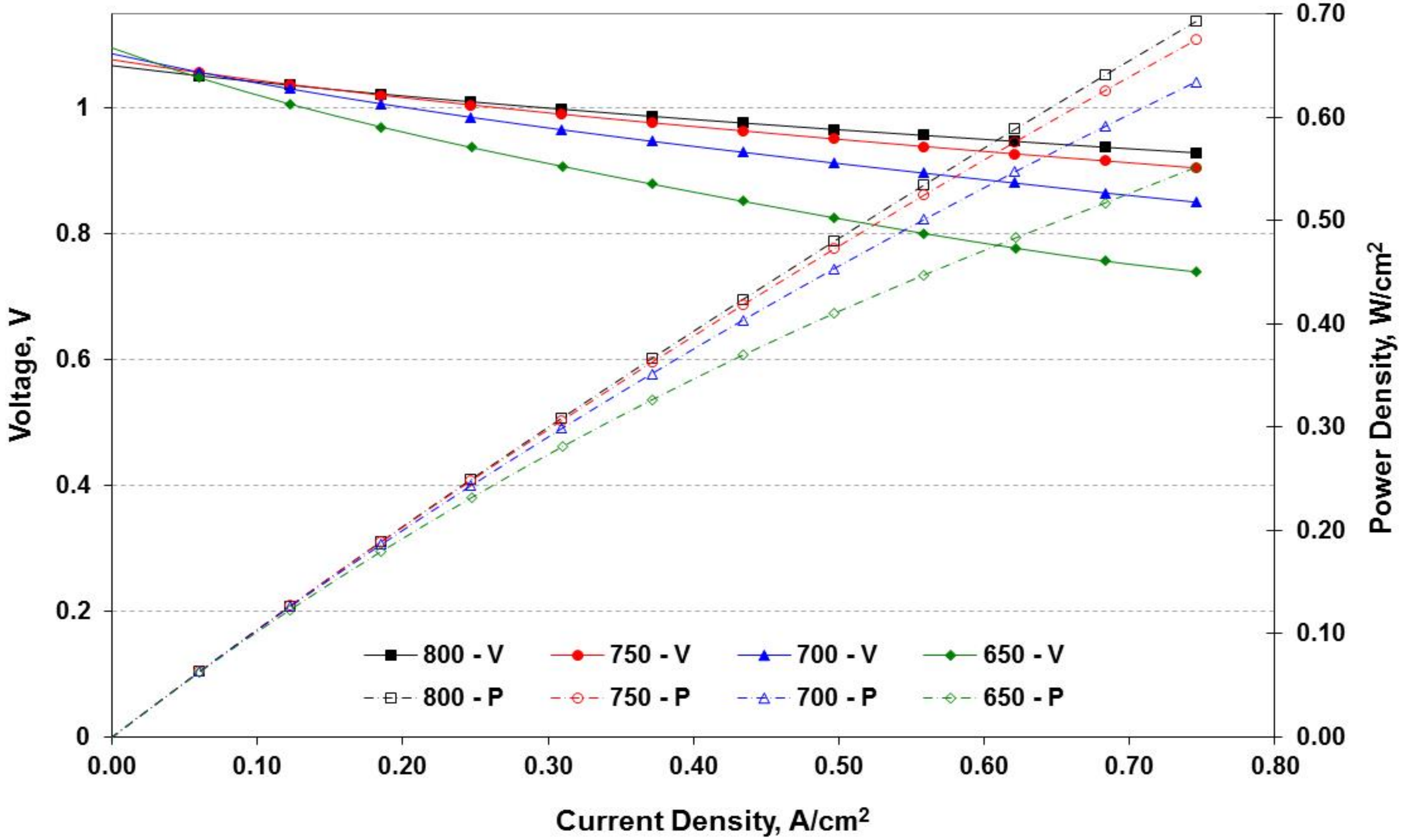
# HiPoD Electrolysis Performance

- 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.
- **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.**



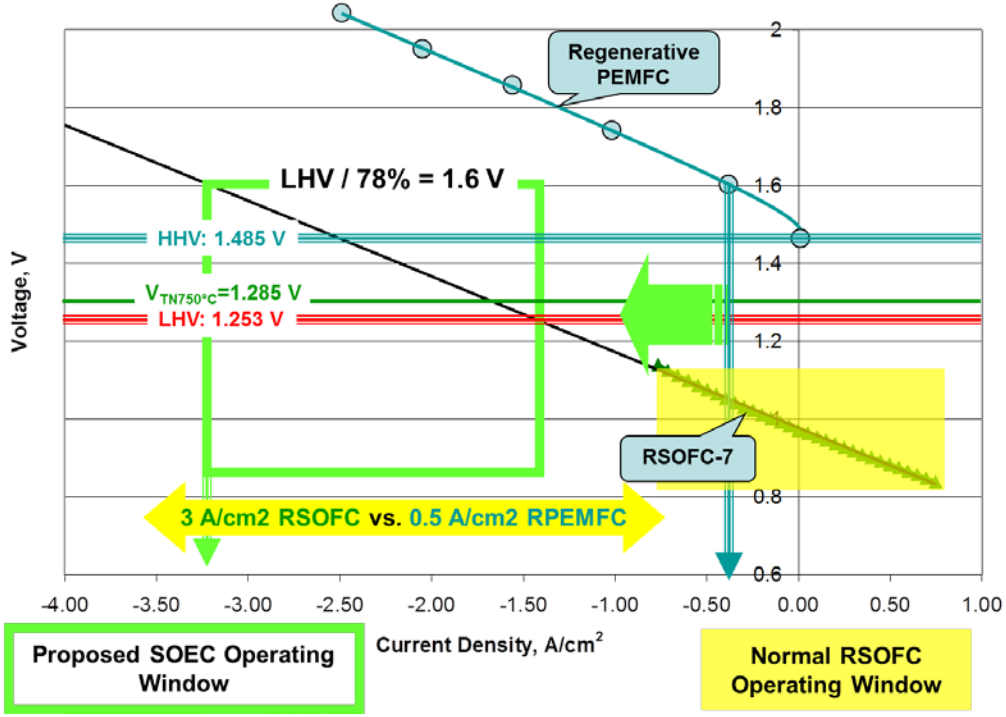


# HiPoD Fuel Cell Performance



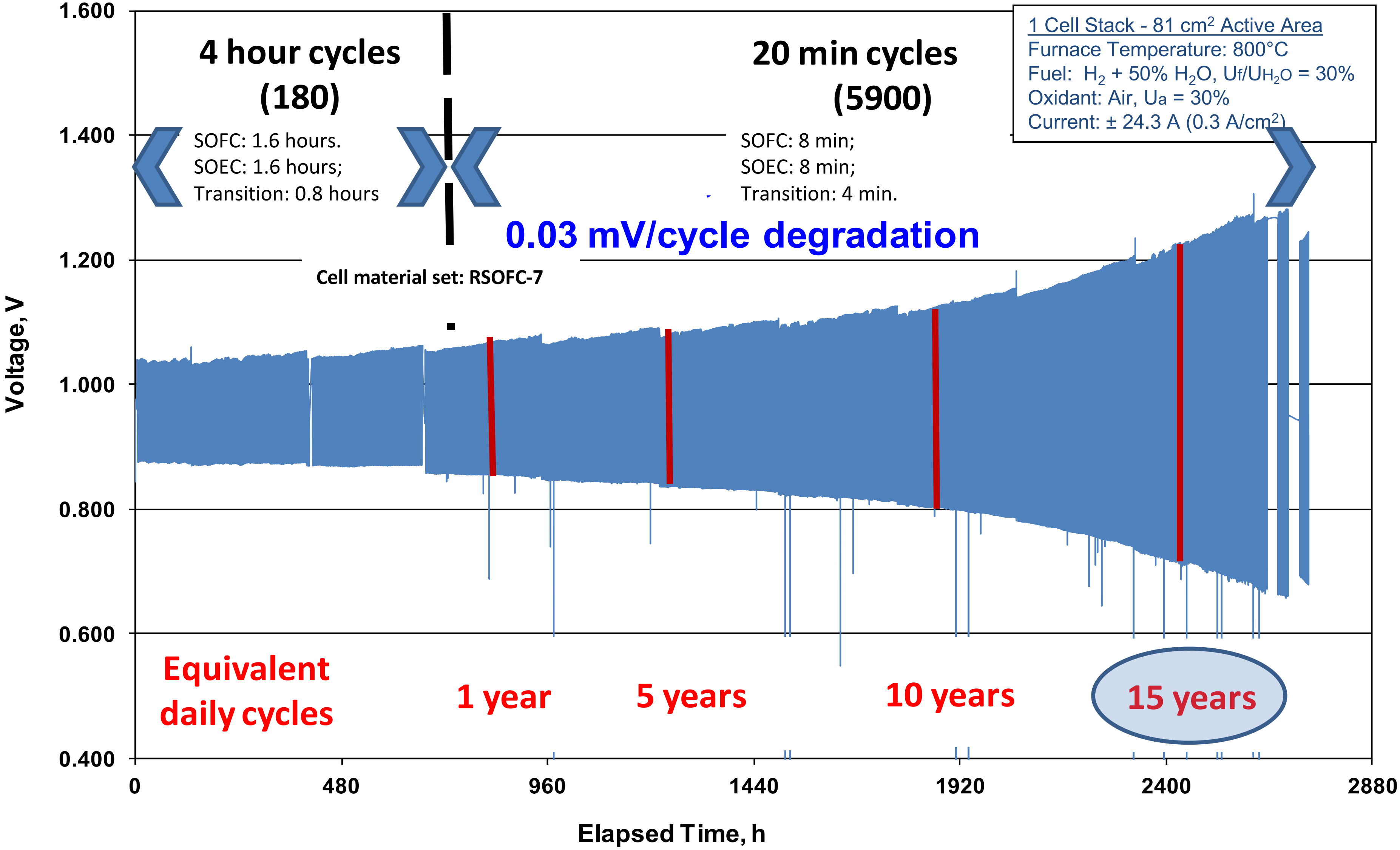
- **Baseline HiPoD Cell Performance Characteristics in Fuel Cell Mode**

# 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/cm$^2$.
- In comparison, a PEM-based regenerative cell will have a much lower current density of less than 0.5 A/cm$^2$ 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)



1 Cell Stack - 81 cm² Active Area
Furnace Temperature: 800°C
Fuel: $H_2$ + 50% $H_2O$, Uf/$U_{H_2O}$ = 30%
Oxidant: Air, Ua = 30%
Current: ± 24.3 A (0.3 A/cm²)

**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**

**Cell material set: RSOFC-7**

**Equivalent daily cycles**

**1 year**

**5 years**

**10 years**

**15 years**

# Publications and Presentations

1. A. Wood, H. He, T. Joia, M. Krivy, D. Steedman; “Communication—Electrolysis at High Efficiency with Remarkable Hydrogen Production Rates”, Journal of Electrochemical Society, 2016 volume 163, issue 5, F327-F329
2. Eric Tang, Tony Wood, Sofiane Benhaddad, Casey Brown, Hongpeng He, Jeff Nelson, Oliver Grande, Ben Nuttall, Mark Richards, Randy Petri, “Advanced Materials for RSOFC Dual Operation with Low Degradation”, Final Report, https://www.osti.gov/scitech/servlets/purl/1058912
3. Eric Tang, Tony Wood, Casey Brown, Micah Casteel, Michael Pastula, Mark Richards, and Randy Petri, “Solid Oxide Based Electrolysis and Stack Technology with Ultra-High Electrolysis Current Density (>3A/cm2) and Efficiency,” 2016 DOE Hydrogen and Fuel Cell Program Review, June 8, 2016, Washington, DC, https://www.hydrogen.energy.gov/pdfs/review16/pd124_petri_2016_o.pdf
4. H. Ghezel-Ayagh, “Advances in SOFC Power System Development”, 17th Annual Solid Oxide Fuel Cell (SOFC) Project Review Meeting, Pittsburgh, PA, July 19-21, 2016, https://www.netl.doe.gov/File%20Library/Events/2016/sofc/Ghezel-Ayagh.pdf