Modular SOEC System for Efficient H_2 Production at High Current Density

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2017 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: $3,750,000.00
- 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:

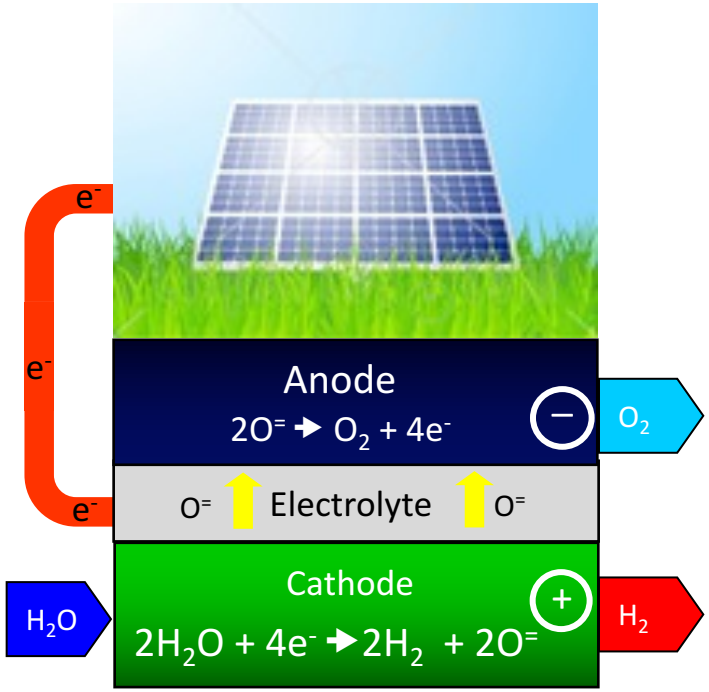
- Demonstrate the potential of Solid Oxide Electrolysis Cell (SOEC) systems to produce hydrogen at a cost of <$2 /kg H_2 exclusive of delivery, compression, storage, and dispensing

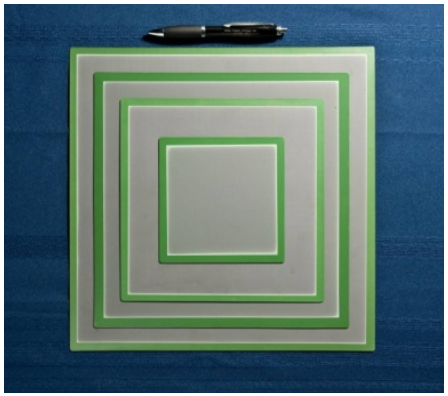
Project Goals:

- 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



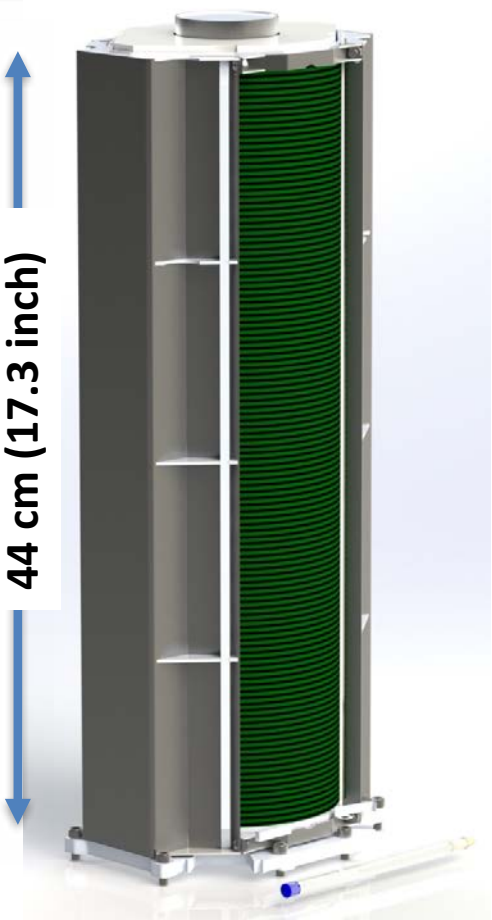


Anode-Supported Solid Oxide Electrolysis Cell

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

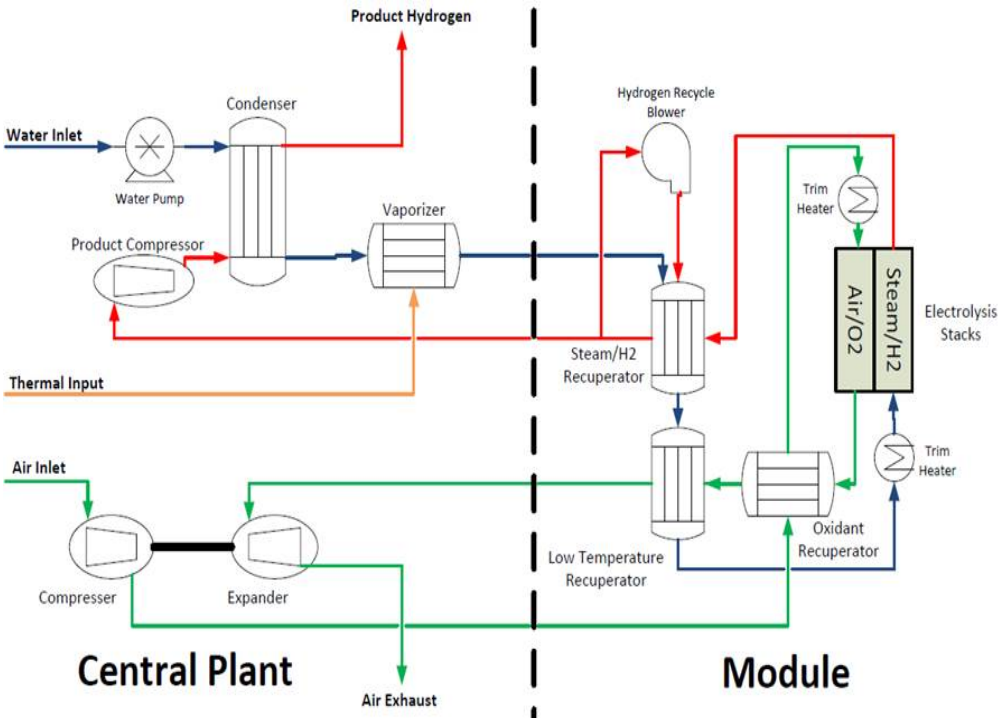
Approach: Breadboard System Demonstration

- 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

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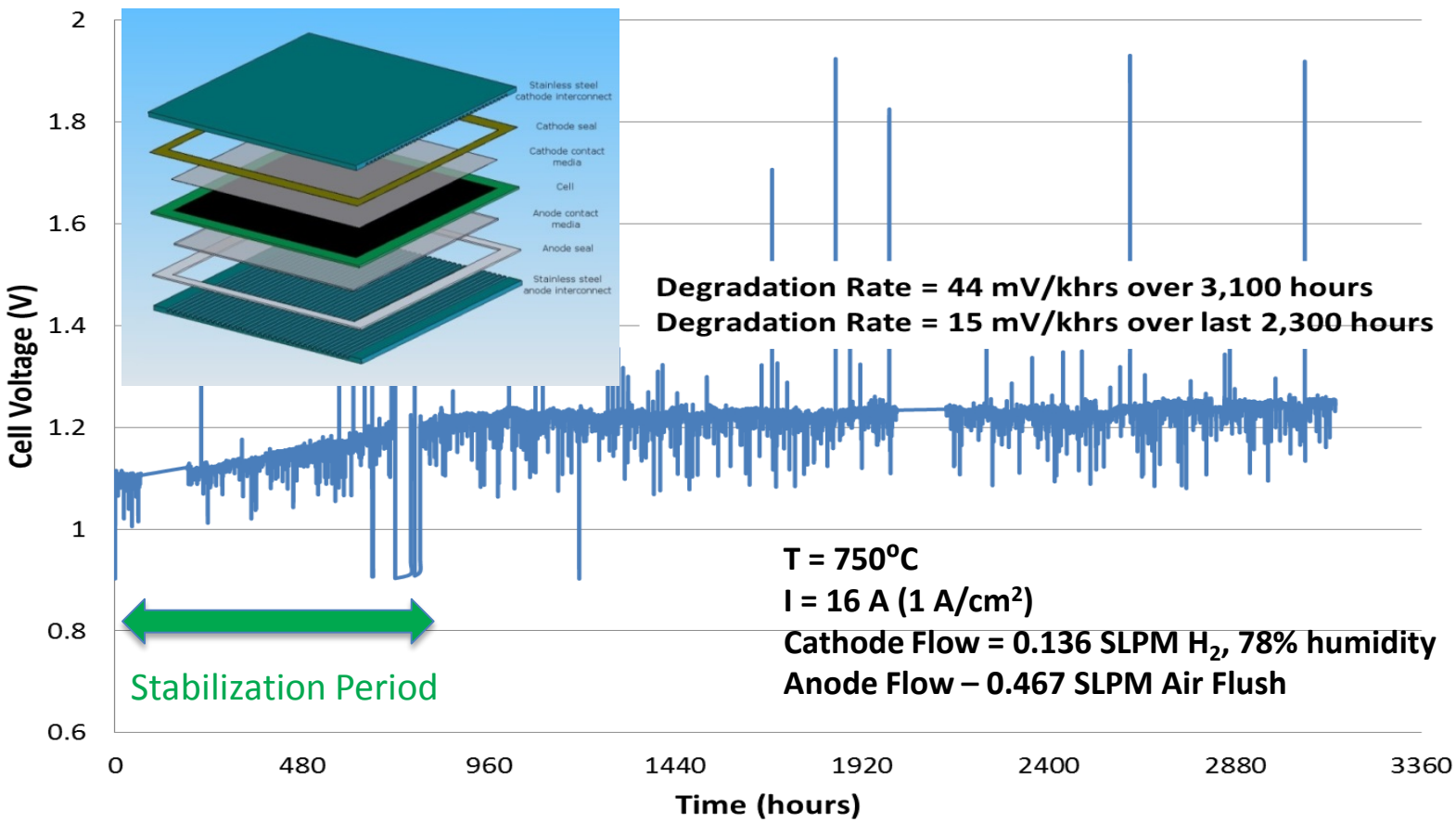
Approach: Milestones FY2017 and FY2018

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 ***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% **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/cm^2

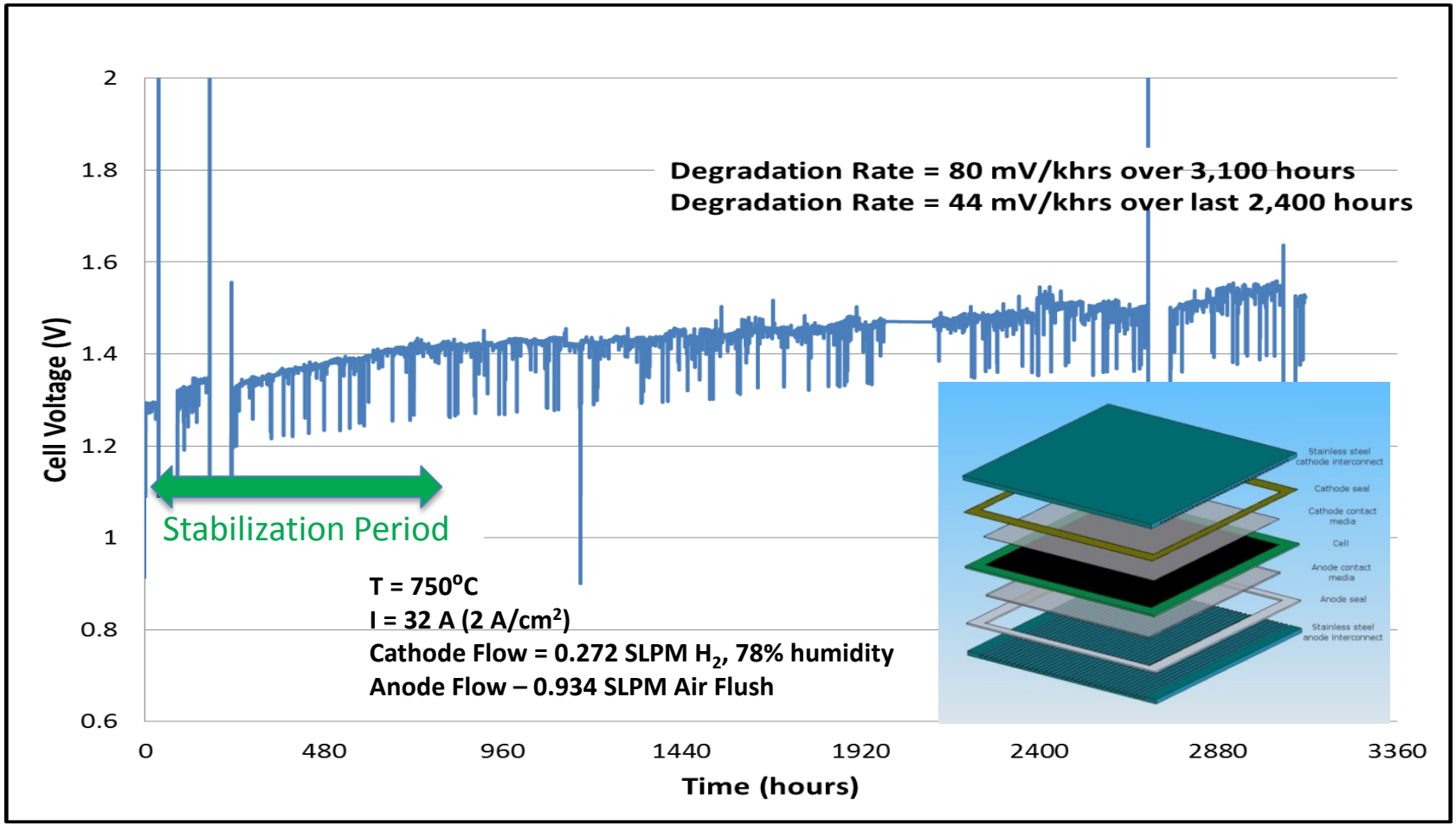
Test of HiPoD (High Power Density) cell (5 cm x 5 cm x 0.03 cm) at 1 A/cm^2



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

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



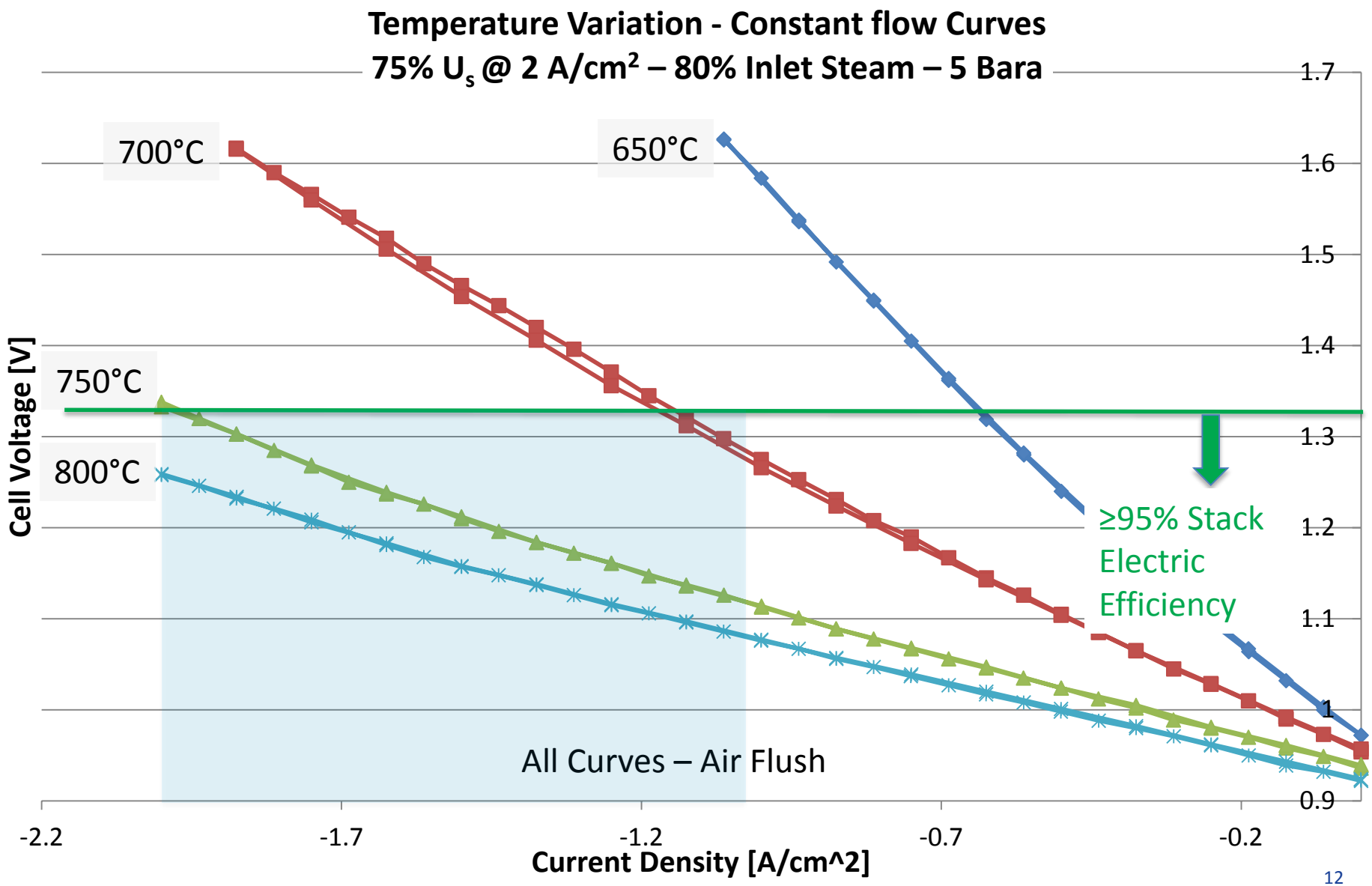
- **Demonstrated voltage degradation rate of <44 mV/1000h or 3.5%/1000h over the last 2,400 hours after initial stabilization**

Accomplishments and Progress: Operation Window Exploration

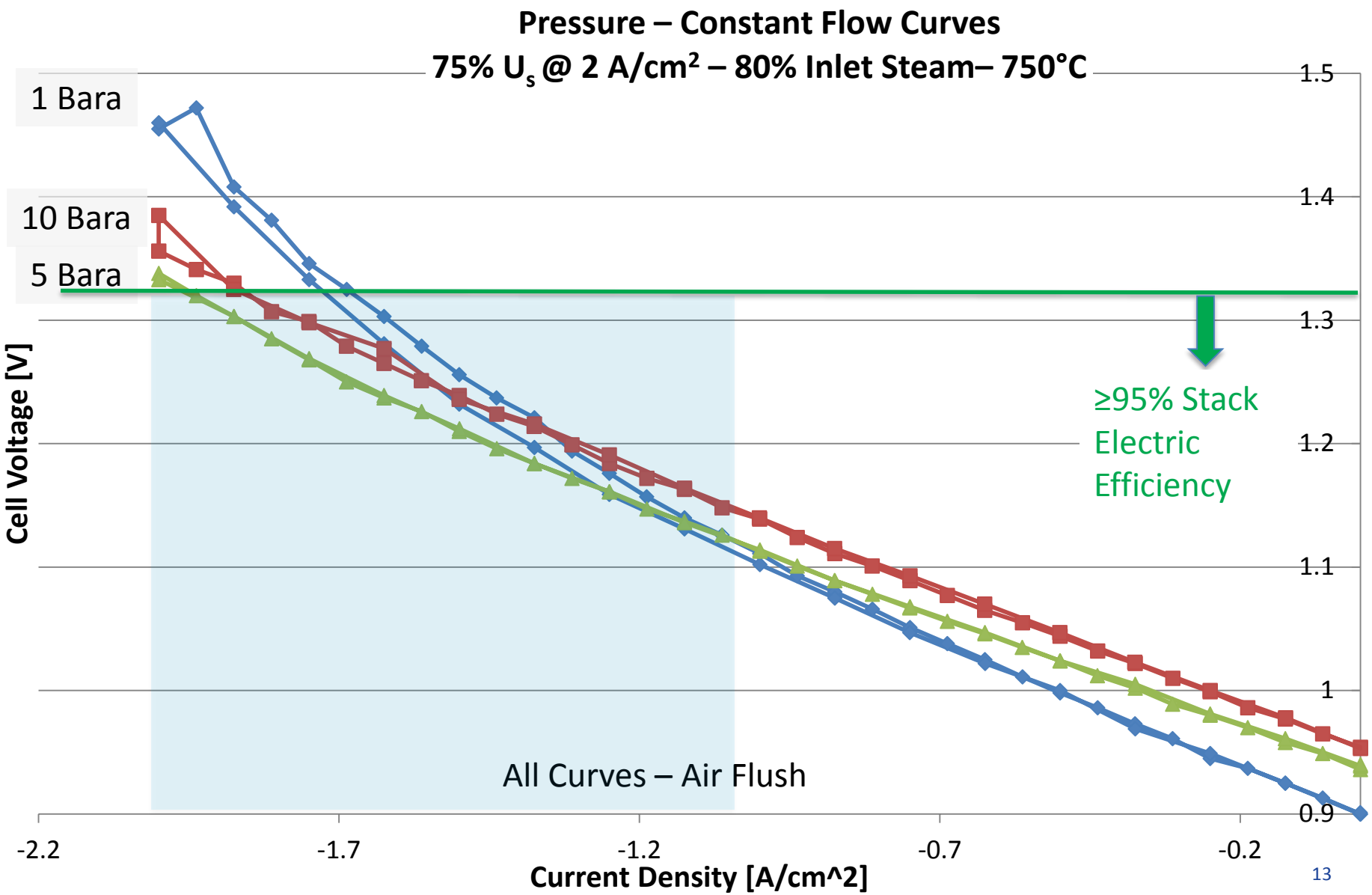
Operating Parameter	Range	System Impacts at Higher End of Range
Current	1-2 A/cm^2 (Target 1.1-1.32 V/cell)	1- Reduced Stack Cost 2- Higher Stack Exit Temperature for Heat Recovery 3- Lower Stack Efficiency 4- Life Impact
Steam Utilization (Stack)	50%-95%	1- Simpler H_2 Purification 2- Lower Stack Efficiency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

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

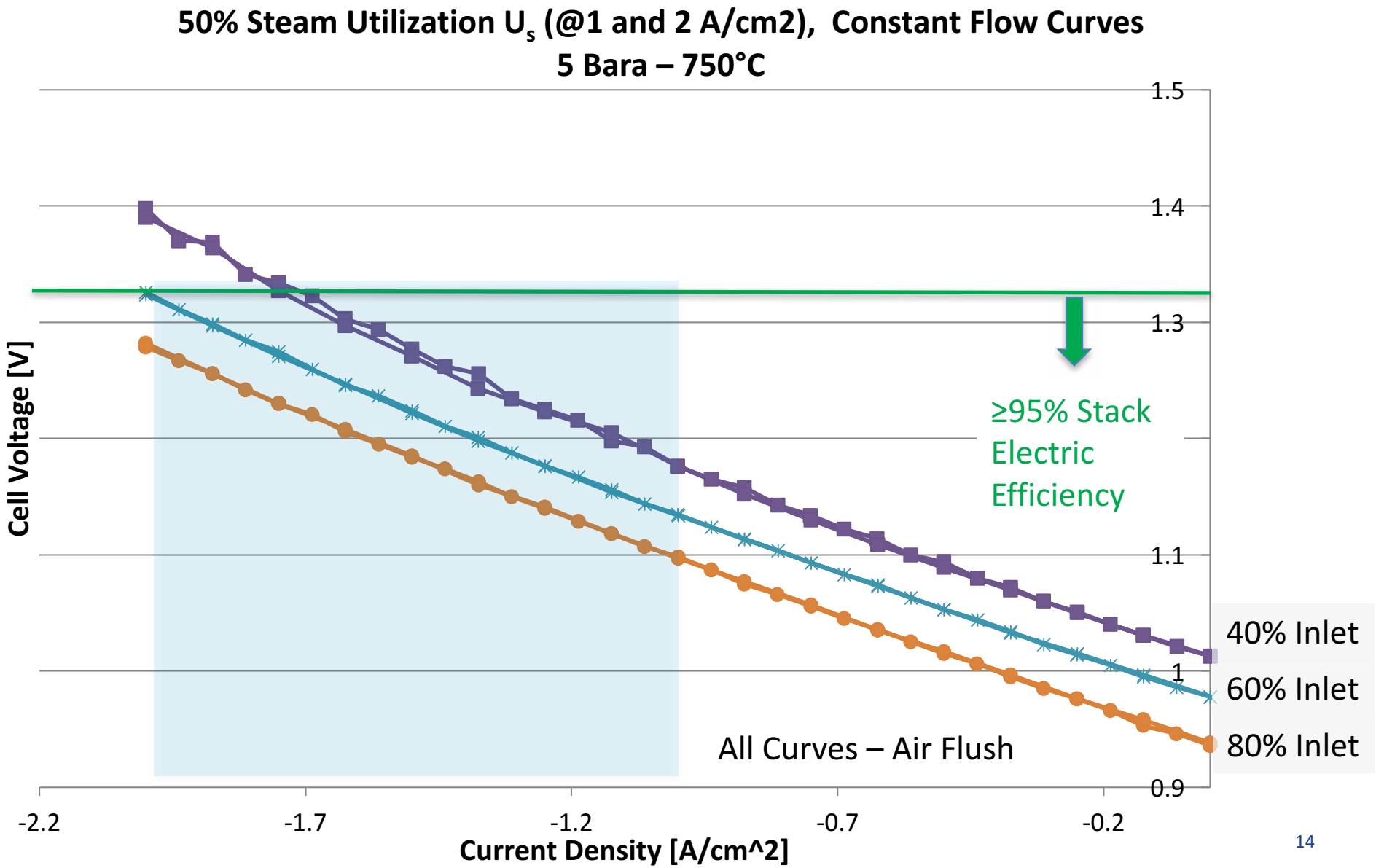
Accomplishments and Progress: Temperature Effect on Performance



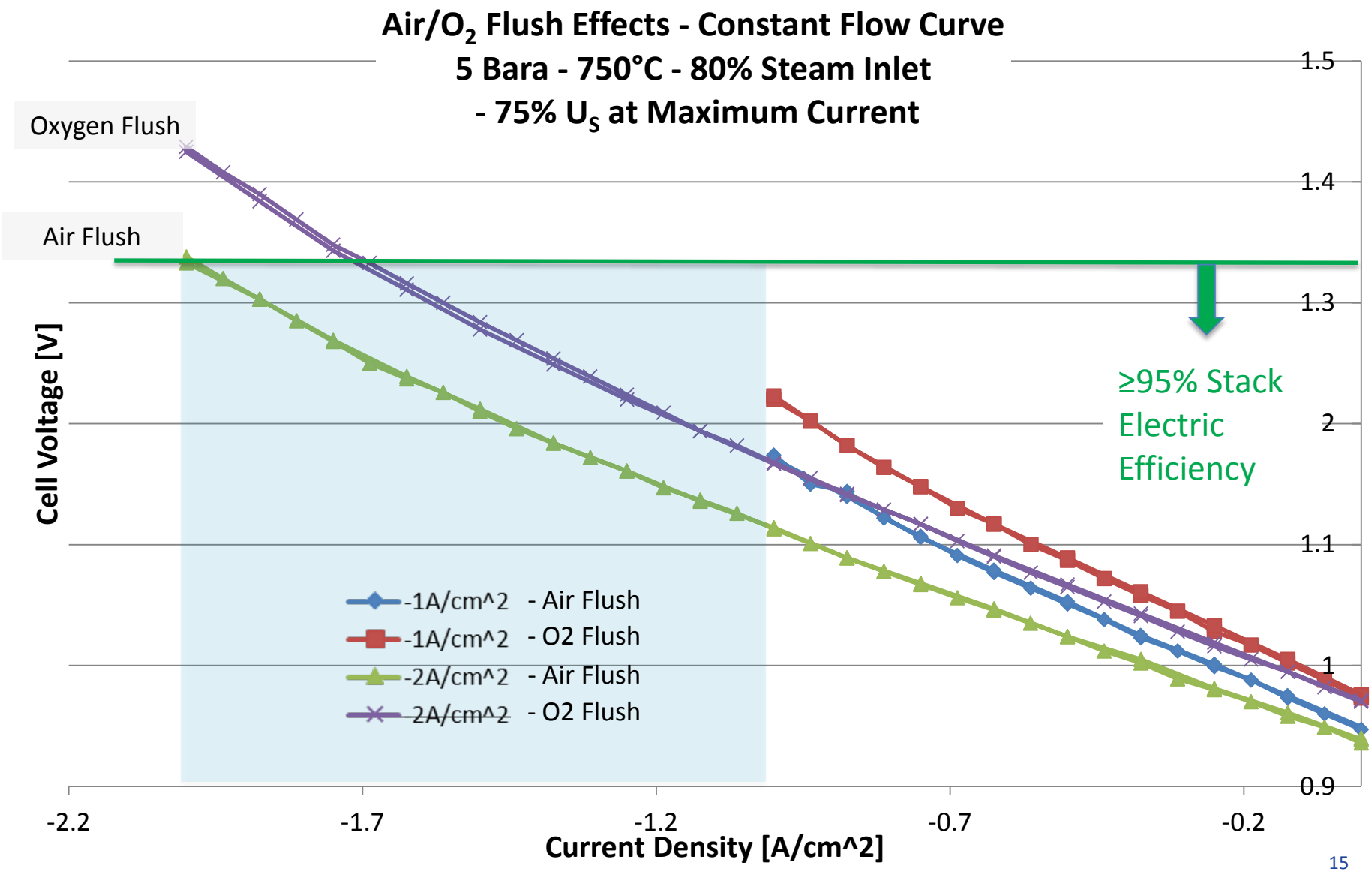
Accomplishments and Progress: Pressure Effect on Performance



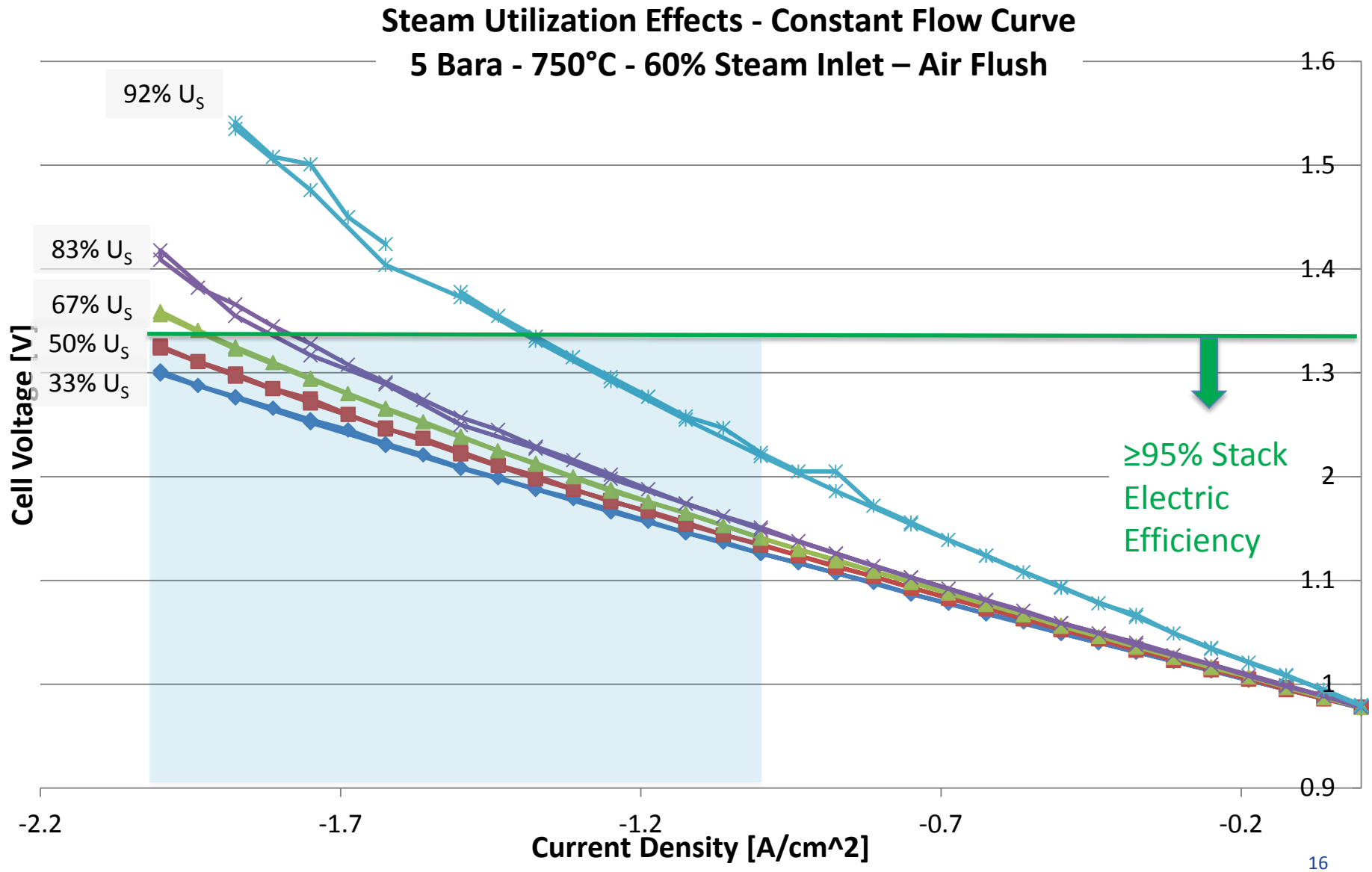
Accomplishments and Progress: Inlet Conc. Effect on Performance



Accomplishments and Progress: Air/O_2 Effect on Performance



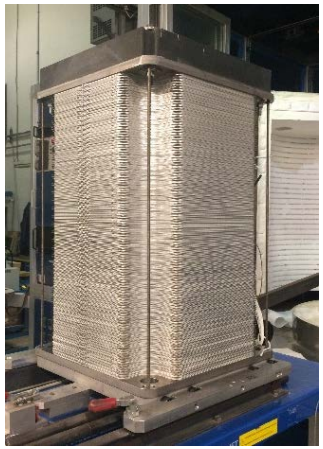
Accomplishments and Progress: Steam Utilization Effects on Performance



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 cm^2 Active Area per Cell)

50 kW System: Natural Gas Fuel (8'x20'x8'6")

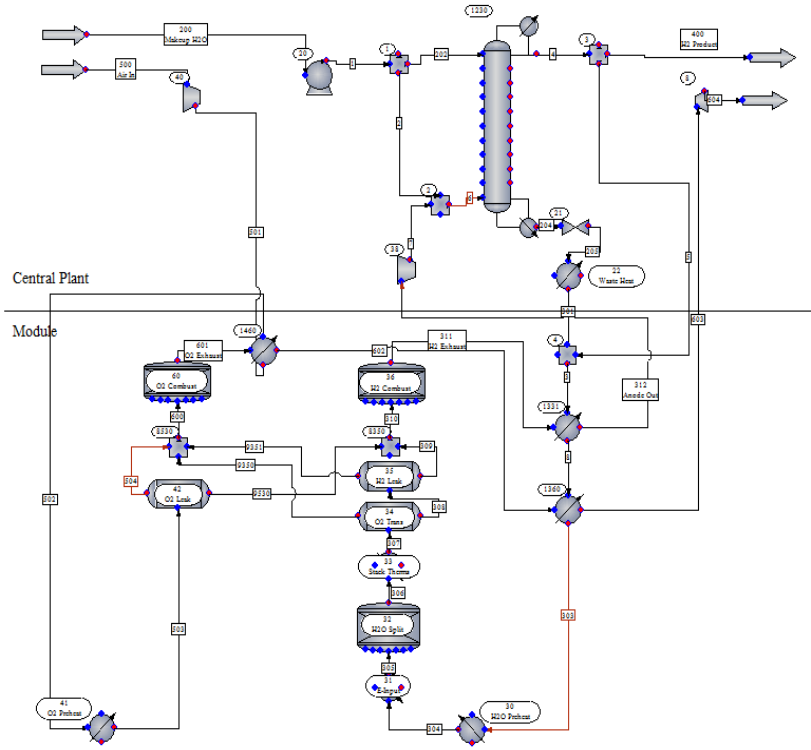
Remaining Challenges and Barriers

- 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

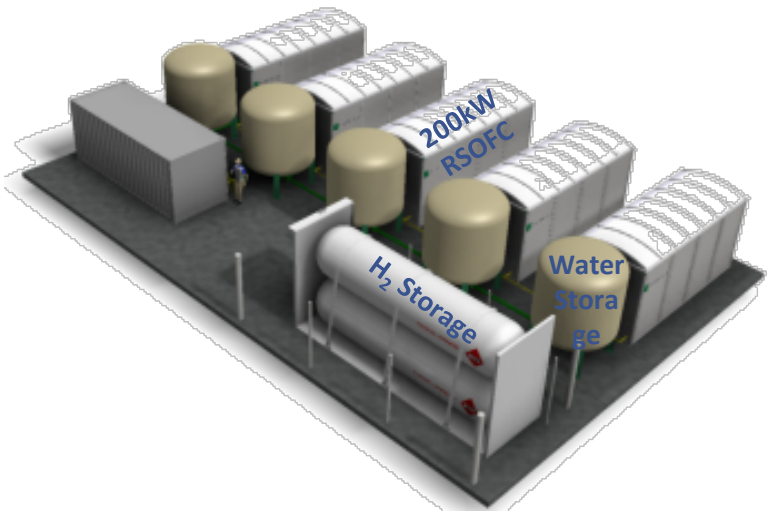


Any proposed future work is subject to change based on funding levels

Technology Transfer Activities

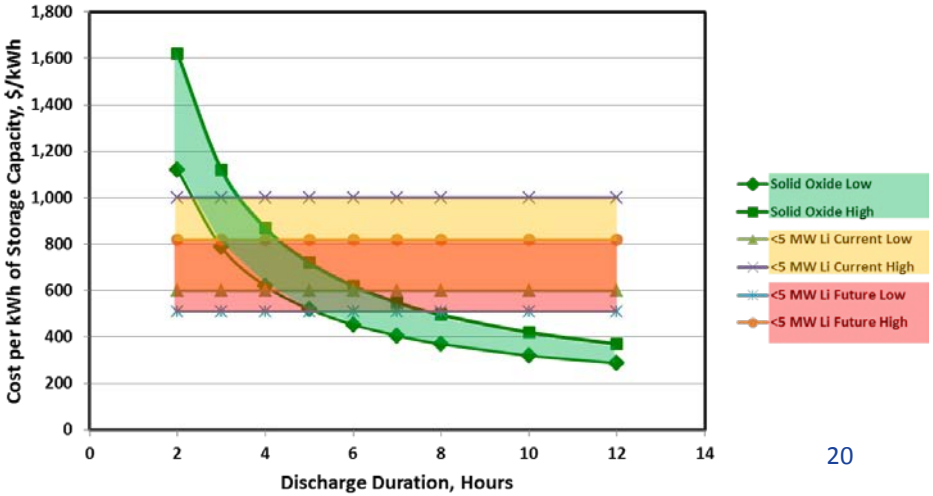
Reversible SOFC (RSOFC) System for Energy Storage

- 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



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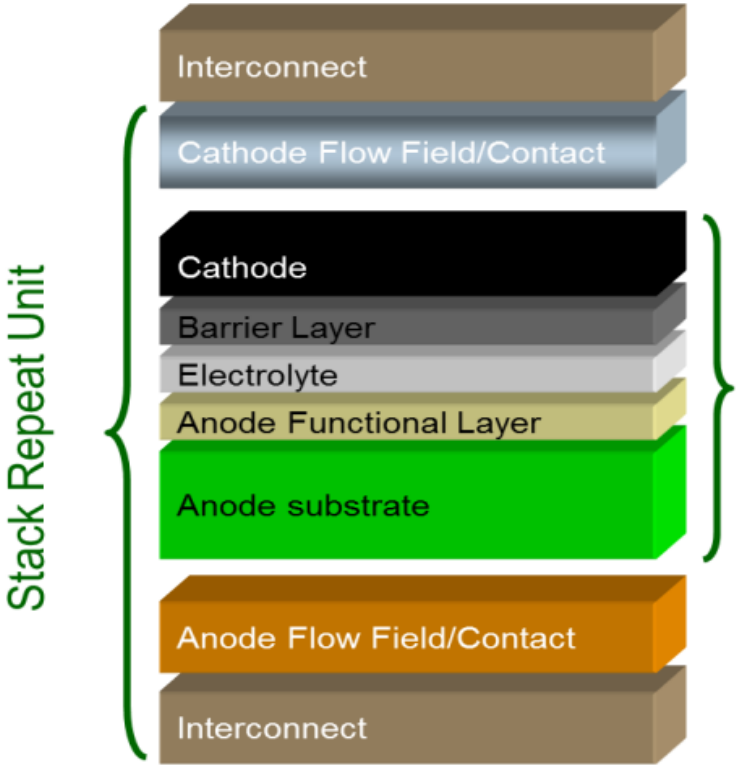
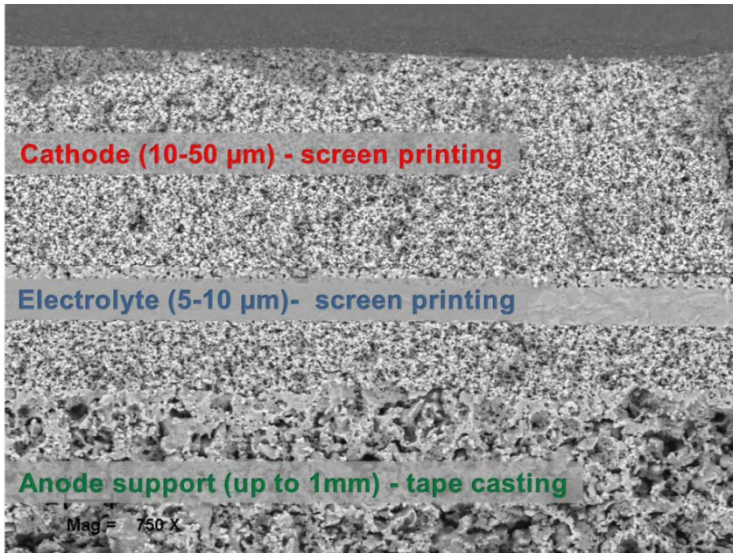
Summary

- 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

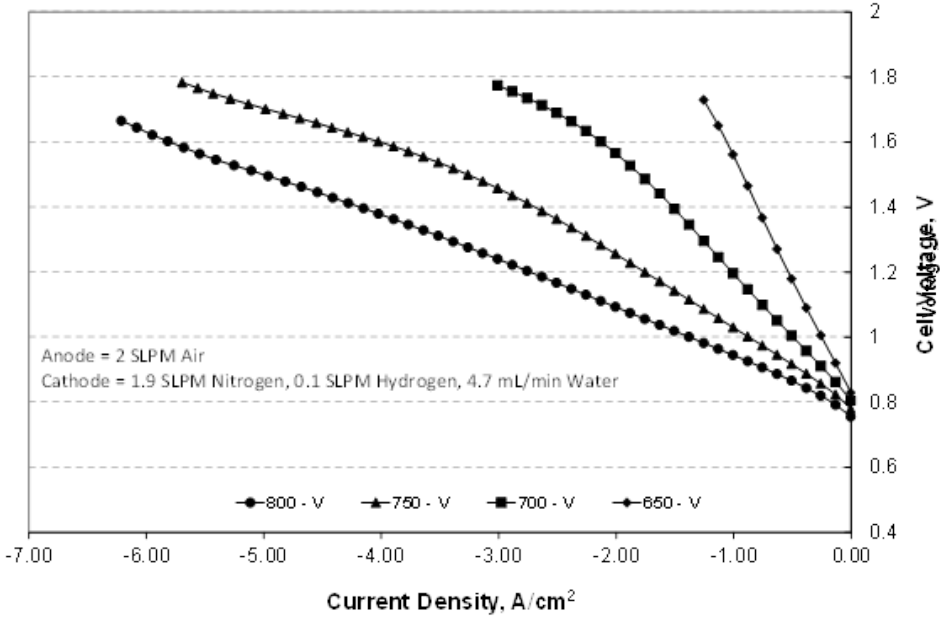


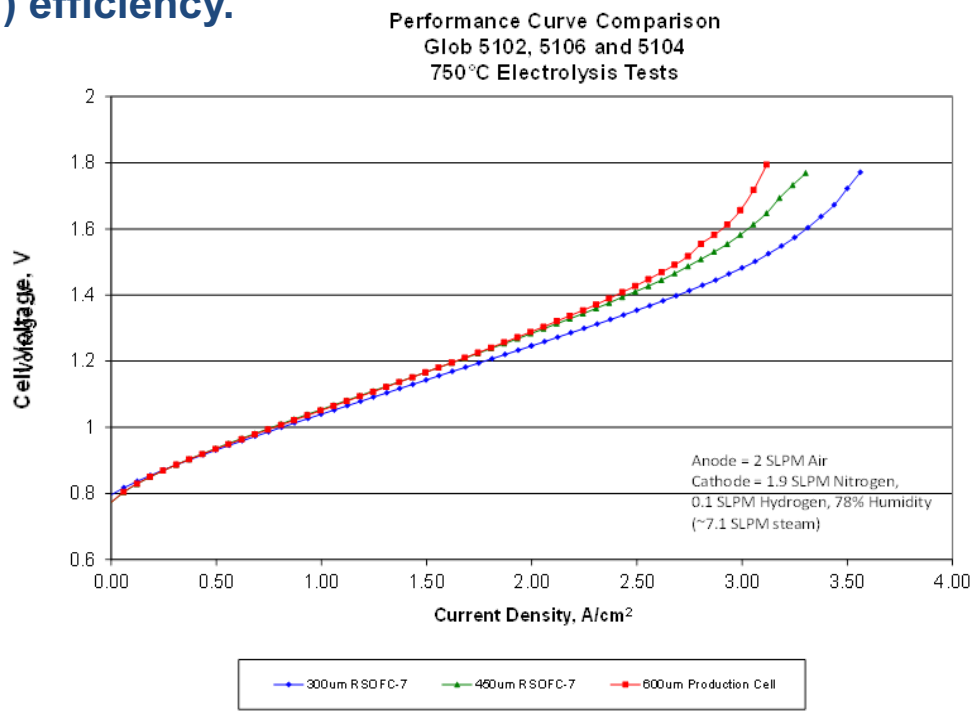


Component	Materials	Thickness	Porosity	Process
Anode	Ni/YSZ	0.3 mm	~ 40%	Tape casting
Electrolyte	YSZ	5 - 10 µm	< 5%	Screen printing
Cathode	Conducting ceramic	10 - 50 µm	~ 30%	Screen printing

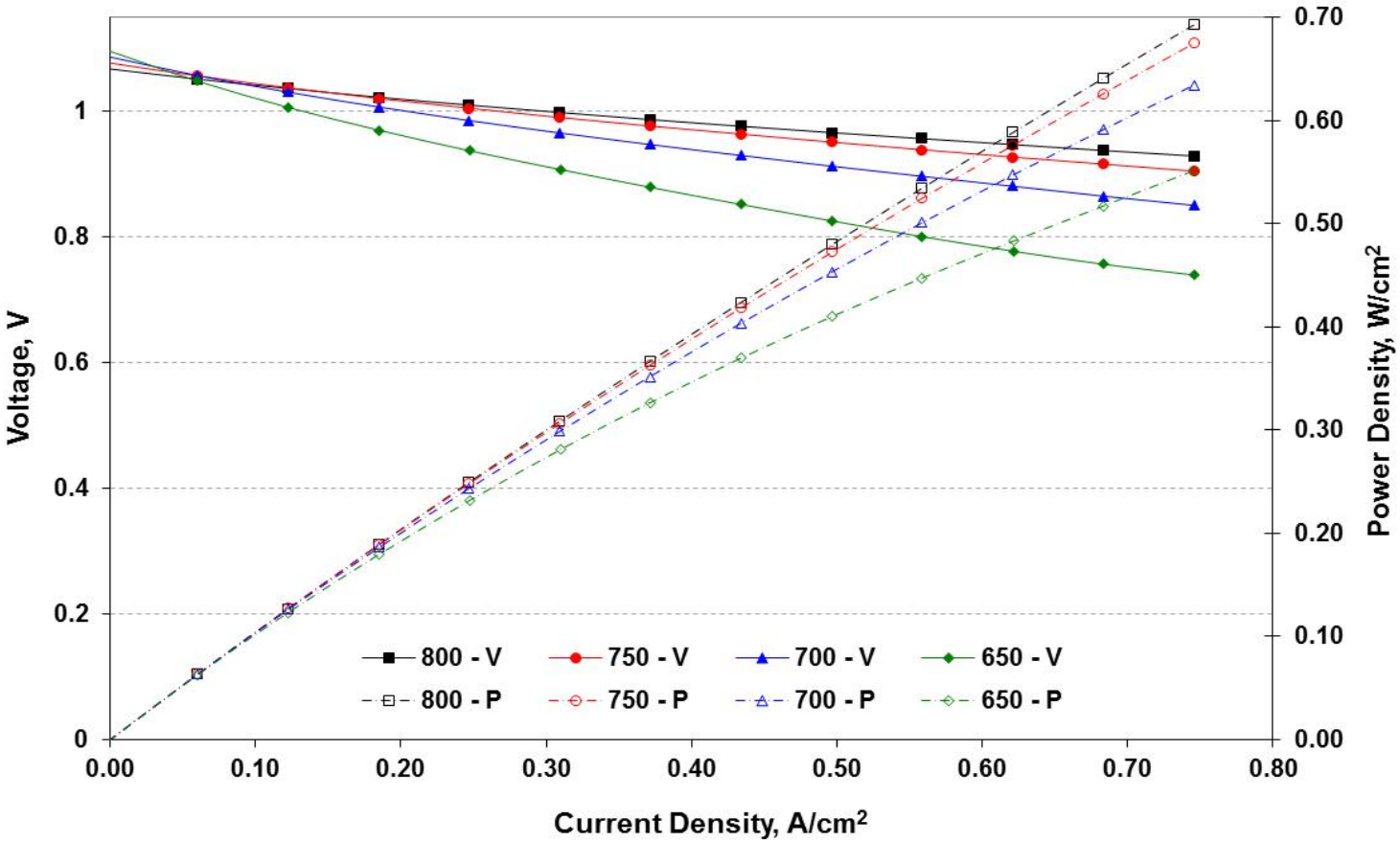
HiPoD Electrolysis Performance

- 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/cm^2 in a single cell test at 78% (LHV) efficiency.**





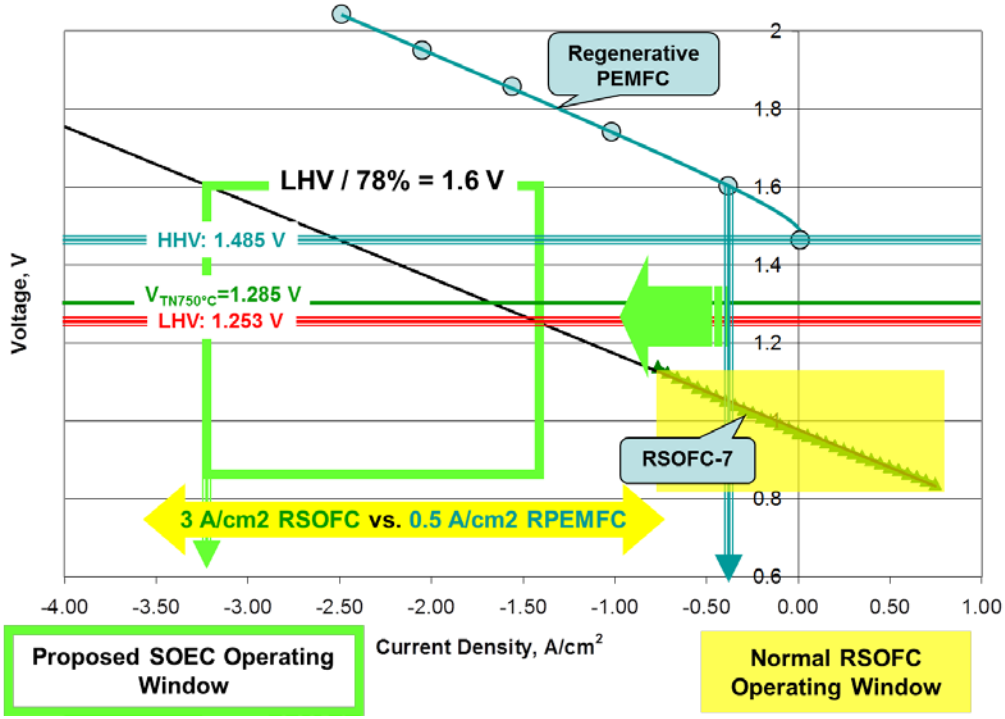
HiPoD Fuel Cell Performance



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

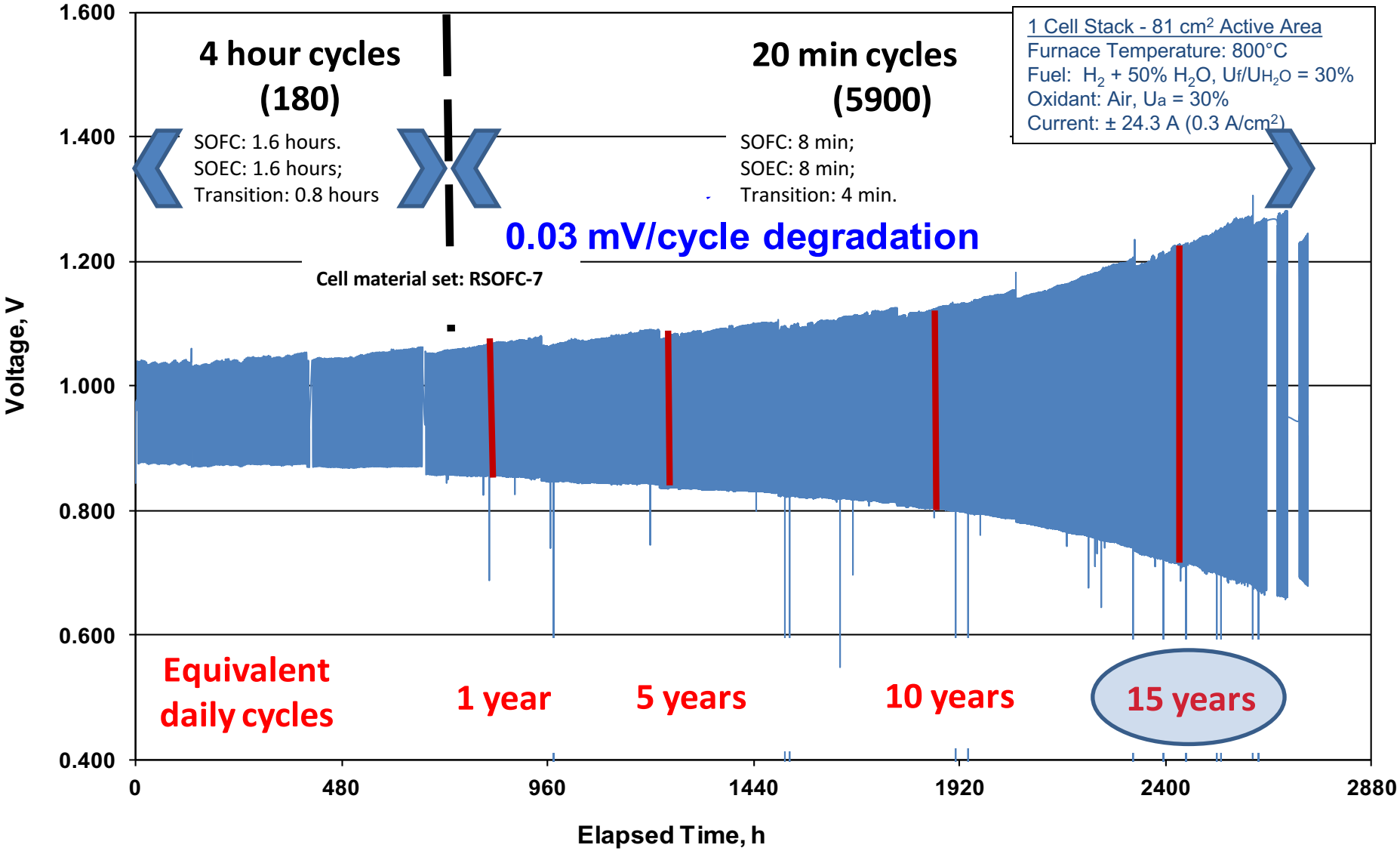
SOEC Compared to PEM

- 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)



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