Modular SOEC System for Efficient H_2 Production at High Current Density

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May 30, 2020

2020 DOE Hydrogen and Fuel Cells Program Review

Project ID# TA019

Overview

Timeline

- Project Start Date: 10/01/2016
- Project End Date: 06/30/2020

Barriers

- 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*: $2,911,046

* Estimated as of 4/30/20

Partners

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

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Project Background

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

Relevance

Technology Development Approach

- Cell Technology Improvement
  - Perform single cell tests to establish desirable operating conditions and reduce performance degradation rate
  - Conduct post-test microstructural analysis to improve cell materials stability
- 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
- >4 kg H_2/day Breadboard System Demonstration
  - Design, Fabricate and Test breadboard system:
    - >1000 hours steady state operation
    - >90% electrical & >75% overall (electrical + thermal) system efficiencies
    - Ability to operate intermittently
- Techno-Economic Analysis for a forecourt 1,500 kg H_2/day commercial system
  - Develop flow sheet alternatives to optimize system performance and cost
  - Perform simulation studies using Heat and Mass Balance models
  - Employ H2A analysis model

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FY2019-2020 Milestones

Task / Subtask Title	Milestone #	Milestone Description (Go/No-Go Decision Criteria)	Planned Completion Date	Status (Percent Completed)
Endurance Improvement	M3.1.2	Complete 1000 hr characterization test of SOEC single cell with voltage degradation rate < 1%/1000 hours	12/31/2018	**100%**
Technology Stack Tests	M3.13	Complete demonstration testing of a SOEC stack capable of > 4 kg H2/day for ≥1000 hours and a performance degradation rate of <2%/1000 hours	3/31/2019	**100%**
Demonstration System Testing	M4.2.2	Complete procurement and assembly of >4 kg H2/day SOEC system	3/31/2019	**90%**
	M4.3.1	Complete demonstration of the >4 kg H2/day SOEC system with >1000 hr of steady state operation and with operation on load profiles relevant to intermittent renewable energy sources	9/30/2019	
Detailed System Design	M5.1.1	Complete conceptual process design for forecourt-scale HTWS plant with a system electrical efficiency >90% (based on LHV of H2), an overall system efficiency (electrical + thermal) >75 % and ability to operate intermittently.	6/30/2019	**100%**

Approach

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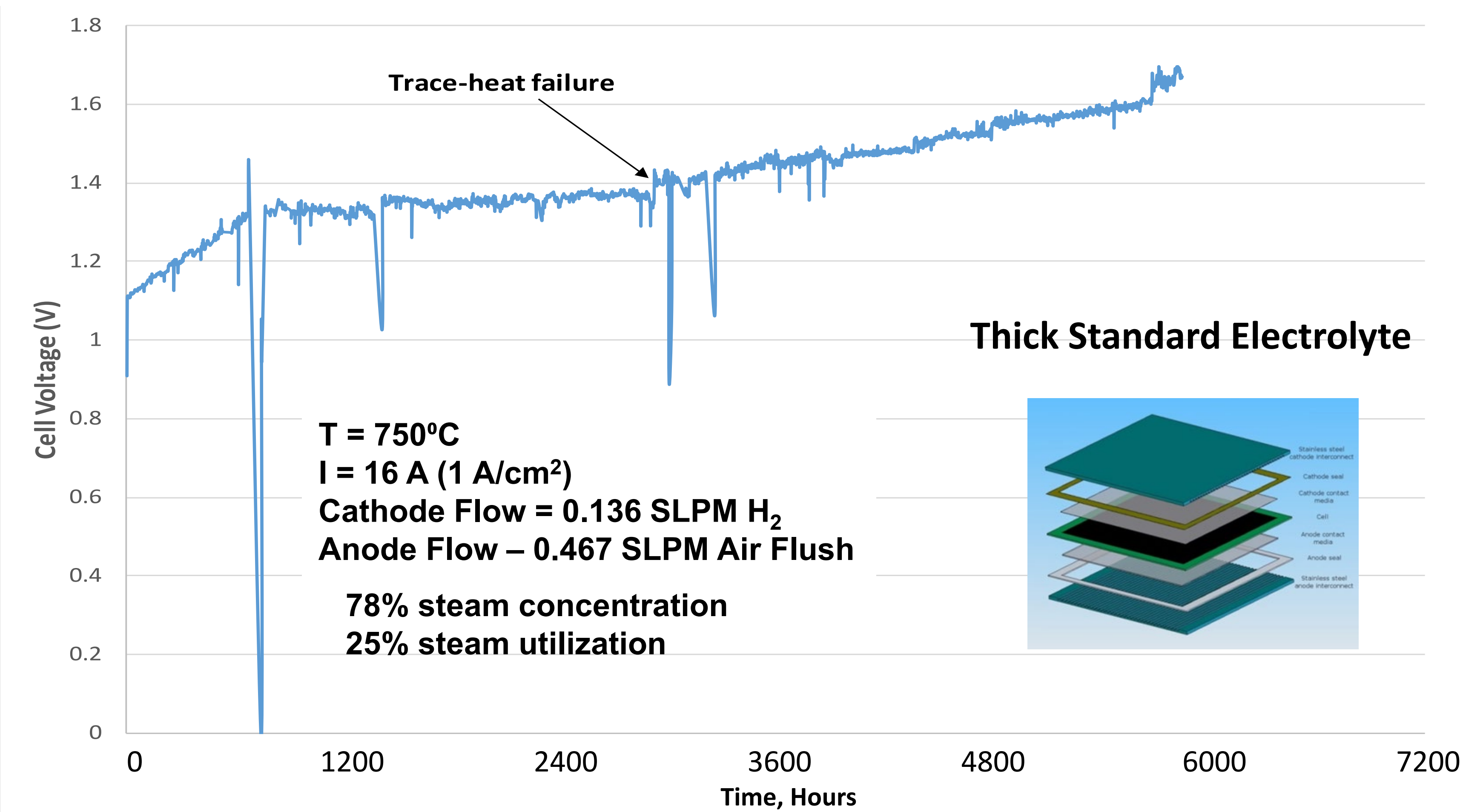
Increased Electrolyte Thickness on Cell Degradation Test at 1 A/cm2

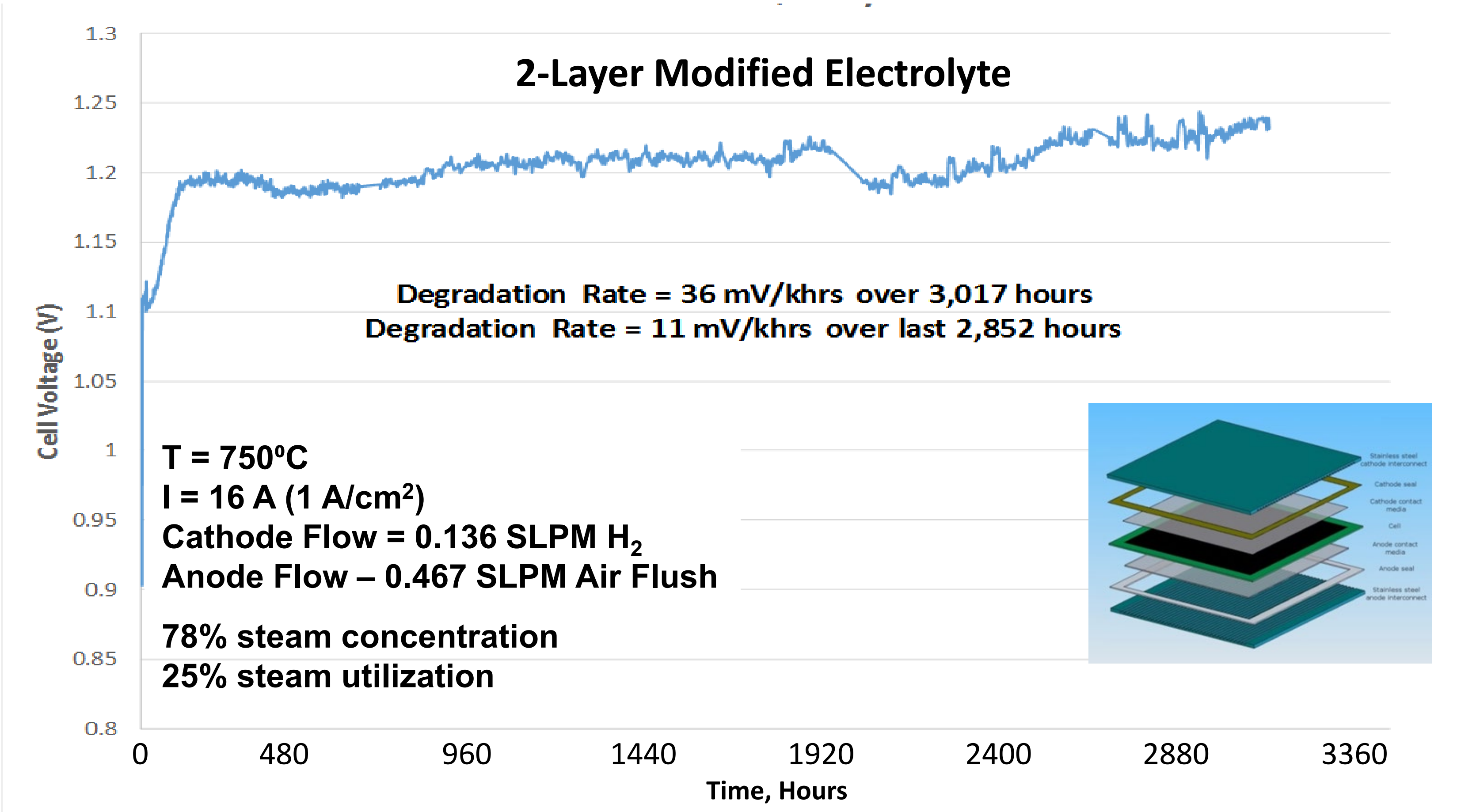
Test of HiPoD (High Power Density) cell (5 cm x 5 cm x 0.03 cm) at 1 A/cm^2



- Standard thick electrolyte showed negligible degradation between 1000-3000 hours of operation before heat tracing element failure caused steam starvation

Modified Electrolyte 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/cm^2



- **Modified electrolyte combined with reduced cathode flow field height achieved the lowest degradation rate of 0.88 %/khrs and met Milestone 3.1.2**

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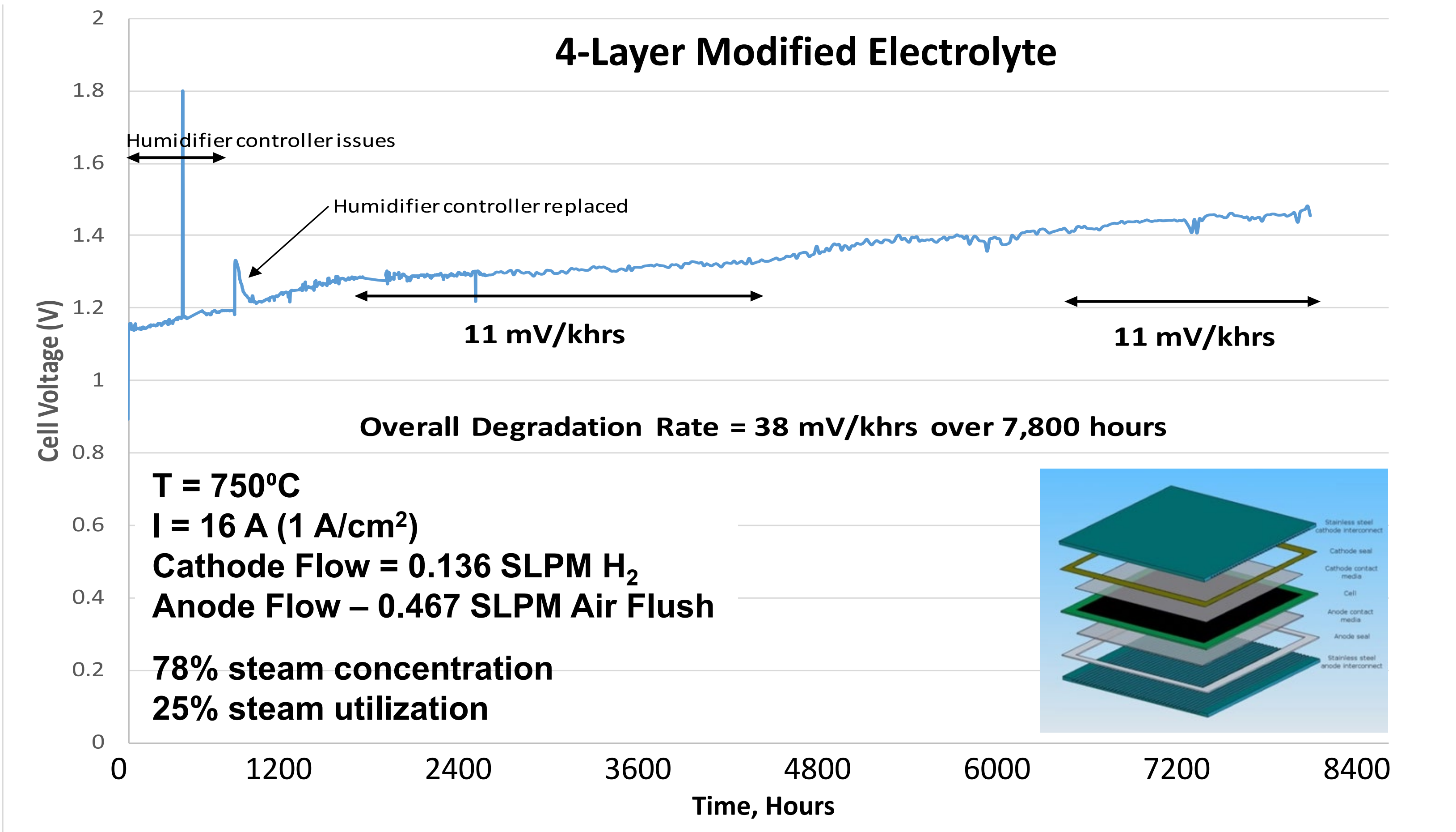
Modified Electrolyte Cell Degradation Test at 1 A/cm2

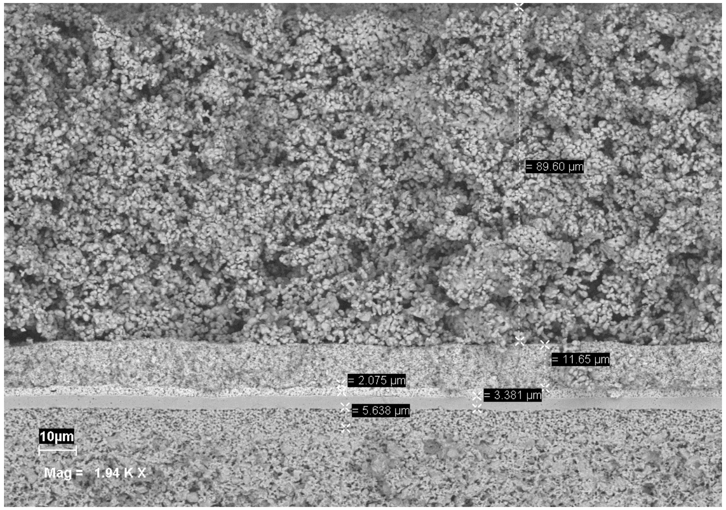
Test of HiPoD (High Power Density) cell (5 cm x 5 cm x 0.03 cm) at 1 A/cm^2



- **Degradation rate of 0.88 %/khrs was repeated in the last 2000 hours of operation by a cell with modified 4-layer electrolyte and reduced cathode flow field height**

SOEC Cell Endurance Summary

- Two key mechanisms of degradation related to cell materials are apparent from autopsies of long-term tests:
  - Ni loss from cathode at or near electrolyte interface
  - Cr deposition on anode side



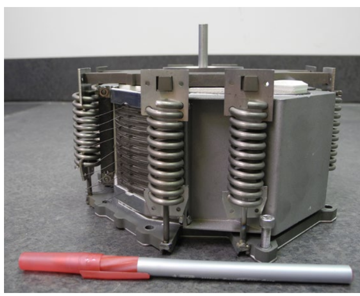
Post Test Analysis After One Year Test

- Overall cell layers look good with no obvious damage
- Electrolyte was dense and ~3.5 microns
- Cr deposited at the anode
- Ni depletion in cathode functional layer

- Operating conditions (e.g. current density, steam concentration and utilization) have significant effects on the SOEC degradation rate
- Modified electrolyte and thicker electrolyte layer have shown to reduce the degradation rate to less than 1%/1000 hr

Compact SOFC Architecture (CSA) Platform

- Newly-developed CSA stacks include very thin (<400 micron thick) cells with active area of 81 cm^2

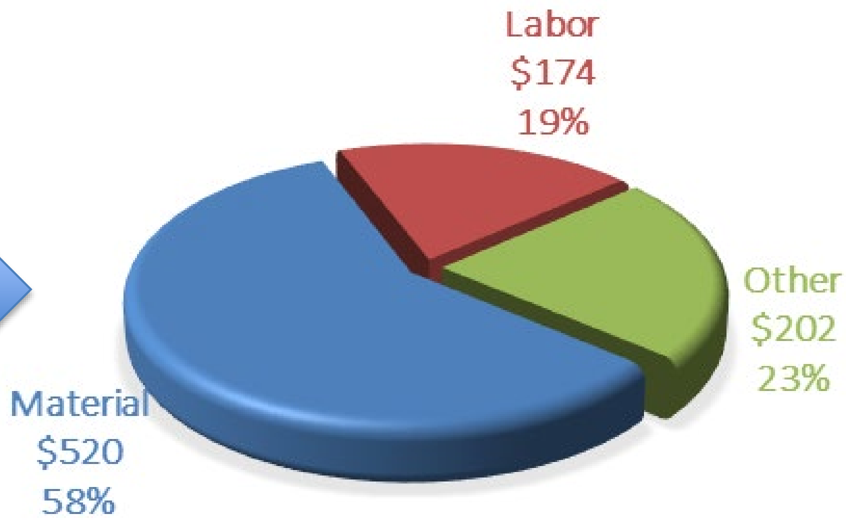


Property	Scale			Comments
	Short	Mid	Full	
Cell count	45	150	350	
Stack voltage, V	58	193	450	At 1.285 V/cell
Stack Power, kW	4.7	15.6	36.4	At -1 A/cm^2
Hydrogen Production, kg/day	3.3	11	25	At -1 A/cm^2
Height, mm (in)	91 (3.6)	211 (8.3)	440 (17.3)	

CSA Stack Factory Cost Estimate

Yr2019 CSA-SOFC Stack Factory Cost Estimate for 1 GW stacks per Year

$ 896 / stack
at
140,080 stacks/year



58% of the estimated cost is due to material

Cost per kW:

- *SOFC @ 250 mW/cm² = $126 $/kWe out*
- *SOEC @ 1.0 A/cm² @ T-N = $25 $/kWe in*
  - *Initial capital cost contribution of ~1 – 2 ¢ / kg H2*

CSA Stack Cost vs. Production Volume

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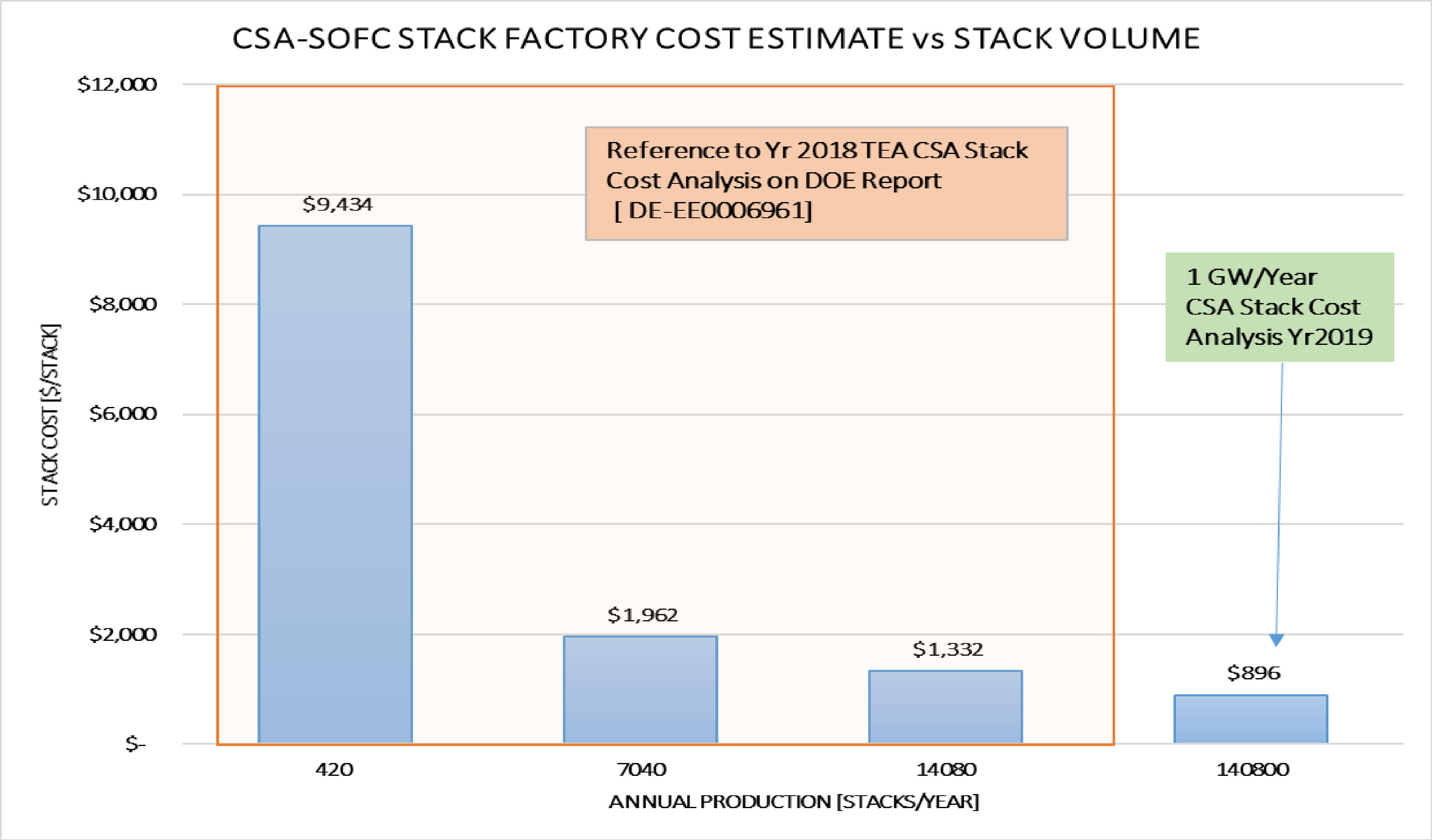
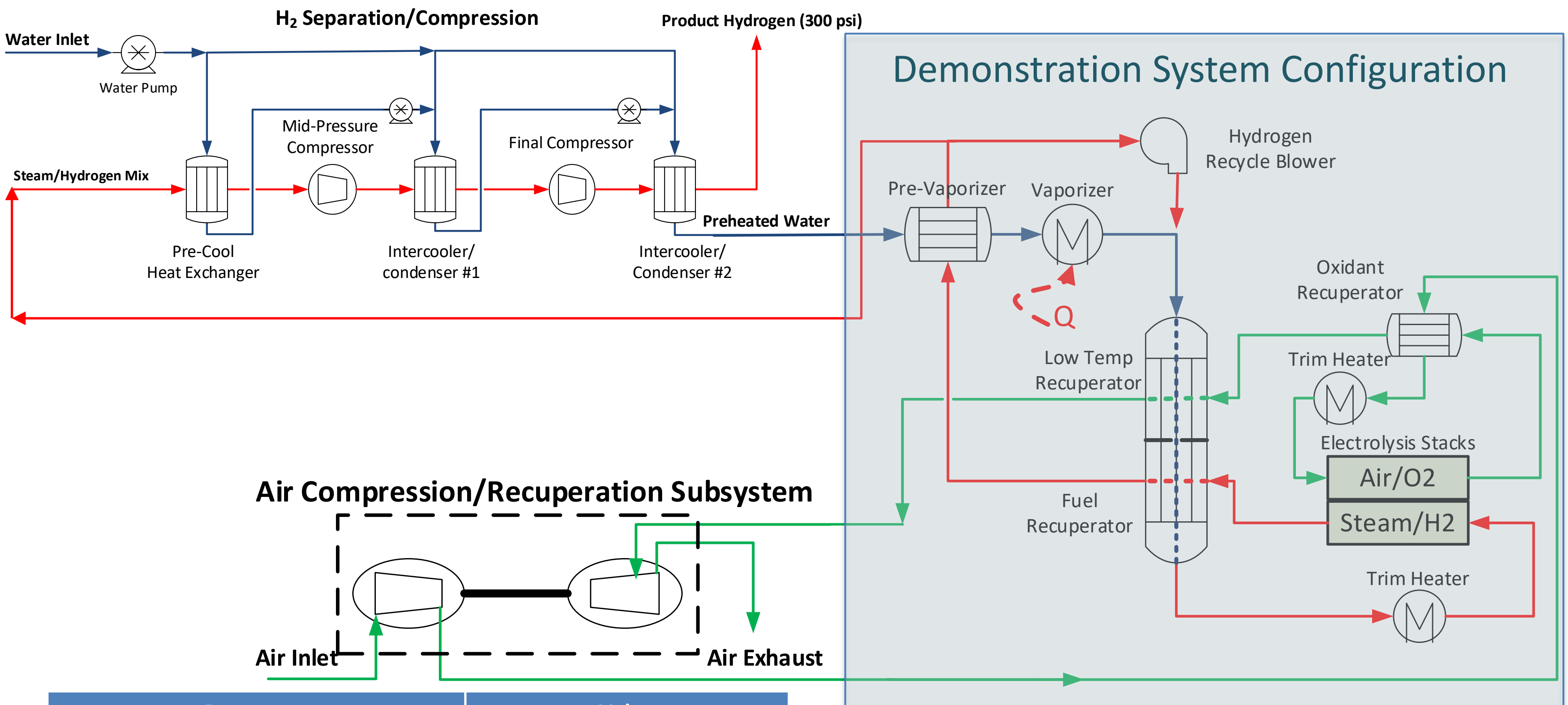


Forecourt Modular Electrolysis System Process Flow Diagram



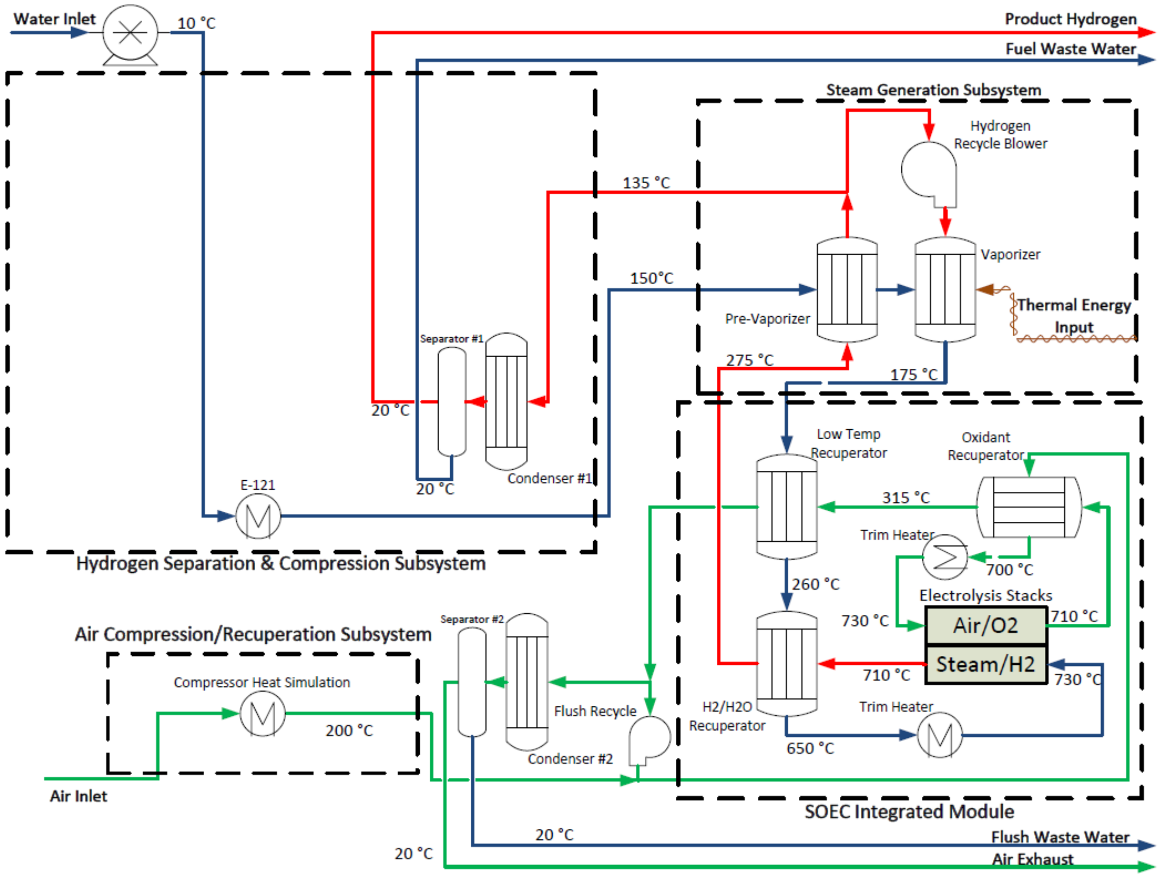
Parameter	Value
Cell Voltage	1.285 V/cell
Current Density	~1 A/cm^2
Operating Temperature	700-750°C
Operating Pressure	5 Bara (60 PSIG)
Inlet Composition	50% H_2, 50% Steam
Steam Utilization	60%
Product Hydrogen Pressure	300 PSIG
Product Composition	99.95% H_2, 0.05% H_2O

System Parameter	Performance
Stack Electrical Eff (LHV)	97.5%
System Electrical Eff (LHV)	90. 9%
System Total Eff (LHV)	78.0%
Electricity Consumption	36.8 kWh/kg
Thermal Consumption (kWh/kg)	5.9 kWh/kg
Total Energy Consumption	42.7 kWh/kg

Demonstration System Overview

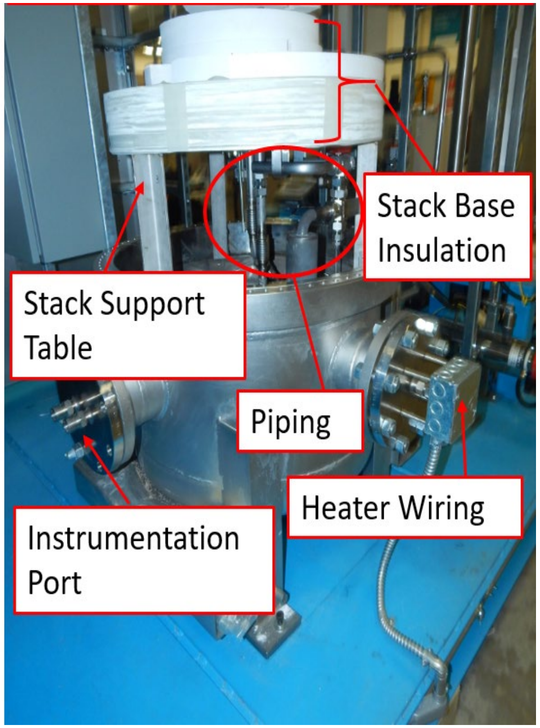
System Characteristics:

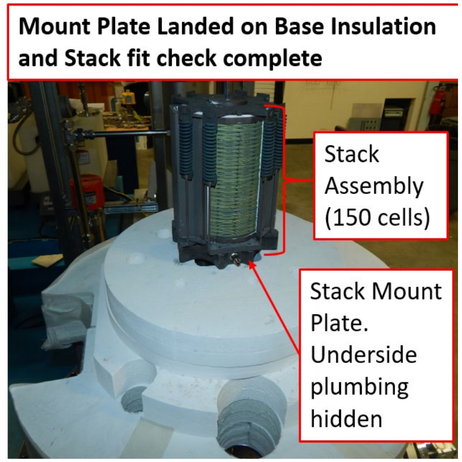
- Nominal 12 kg/day (flexible to achieve 0-20 kg/day)
- 7-32 kWe
- Water Balance System
- 1-5 Bara Operation
- 1 Module (4x ¼ height stacks or 1x ½ height stack)
- Air Compressor simulated by compressed house air and electric preheat
- Thermal input simulated by electric vaporizer system

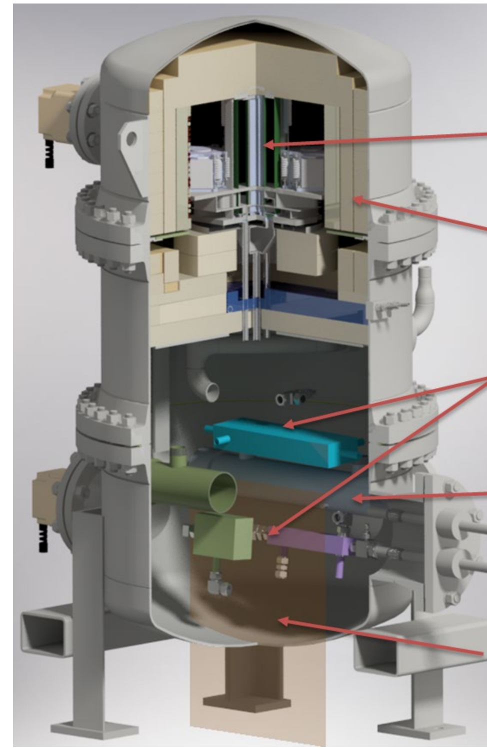


Electrolysis Demonstration System Process Flow Sheet

Demonstration System: SOEC Module

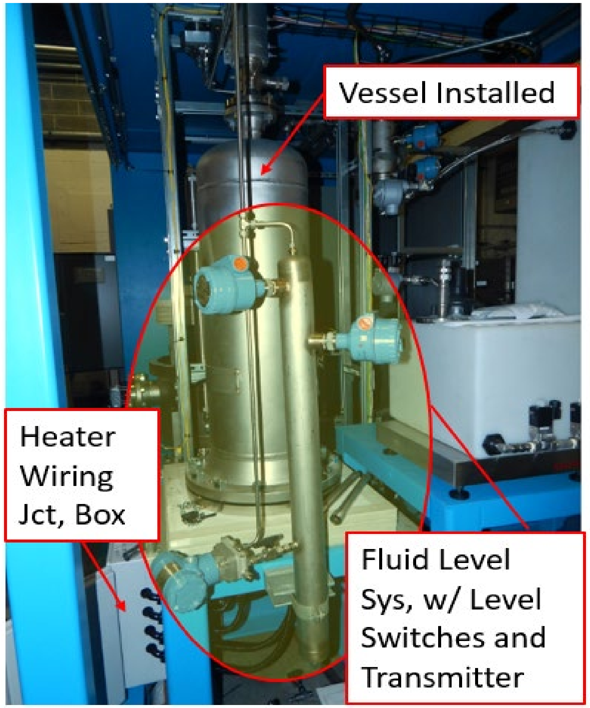






- 125 psig (8.6 barg) design pressure
- Accommodates 1x150-cell stack or 4x45-cell stacks with adapter
- Three thermal zones:
  - Hot zone for the electrolyzer stack
  - Mid-temp zone for BOP components such as electric heaters and heat exchangers
  - Cool Instrument termination zone
- Vessel is designed in accordance with ASME B&PV Code Section VIII Div. II, with internal insulation to allow a touch-safe vessel wall temperature.

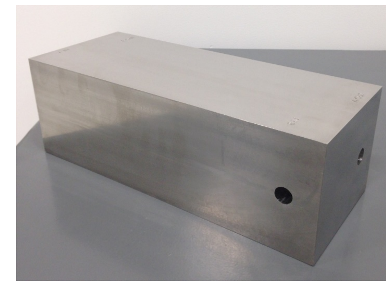
Demonstration System: Key Equipment



- Submerged coil-tube heat exchanger to recover heat from the product hydrogen stream
- Electric cartridge heaters add heat to bring water temperature up to boiling point at the upper level (simulating waste heat recovery)

<u>Heat Exchangers</u>

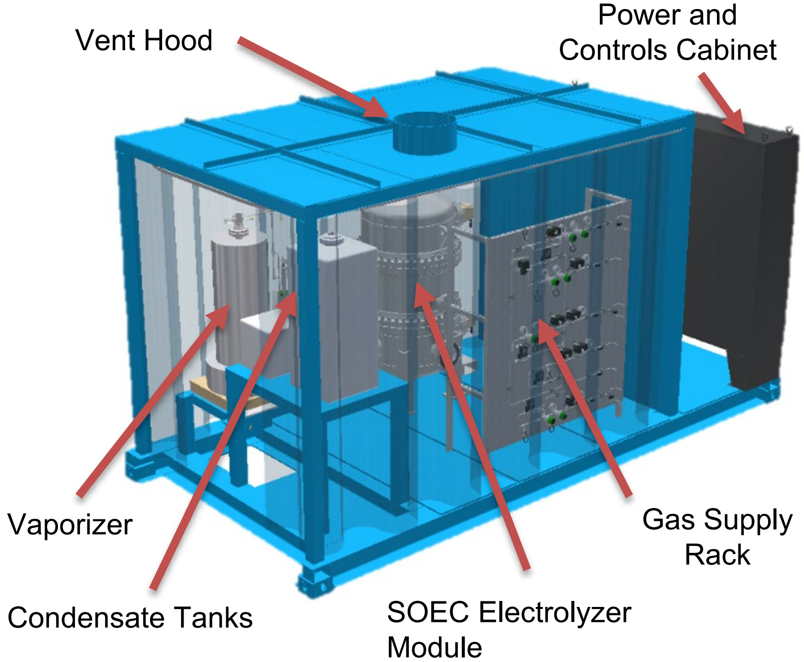
- Diffusion bonded microchannel style
- Compact design with low pressure drop
- 310S materials for corrosion resistance



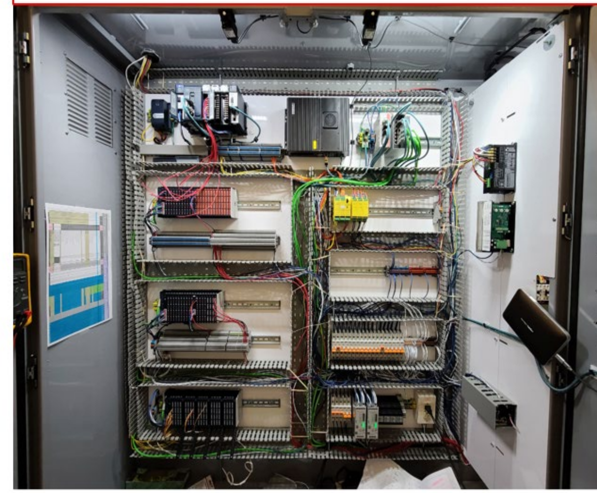
<u>Recycle Blowers</u>

- Scroll-type blowers Semi-custom design based on proven platform
- Installed in the system

Demonstration System Design



Main 24vdc Subpanel Including 24Vdc, I/O, Ethernet distribution, PLC, HMI/IPCs, and Safety Relay Module



DC Disconnect Panel Complete

480V Subpanel Complete

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Responses to Previous Year Reviewers' Comments

- The economic analysis to be completed at a large scale, perhaps 50 tonnes per day or more. Solid oxide electrolysis (SOE) is probably not as suitable for distributed production sites (of 1.5 tonnes per day**). TEA for a large-scale production system is recommended.**
- Possible additions could include stack scale-up and TEA to make the economic case for the technology**. At a minimum, a third-party TEA is strongly encouraged.**
  - Having a third-party system developer is not within the scope and budget. However, FCE's SOEC system was studied under a CRADA, with participants including: Exelon, Idaho National Laboratory, Sandia National Lab tory, Argonne National Laboratory, and National Renewable Energy Laboratory. The study includes independent verification of the TEA results for large commercial SOEC systems.
- The lack of transient response data is a weakness. **Further real-world validation (which can include power outages, thermal excursions, etc.) is recommended to show robustness.**
  - Operation of the demonstration system will include transient data representative of the real-world dynamic responses to intermittent load scenarios.
- This project is highly relevant to H2@Scale. It has the potential to produce low-cost hydrogen. The scale-up and demonstration are needed for H2@Scale. Given the limited time left on the project, unless a no-cost extension is granted, the demonstration will be of minimal impact. **The team should apply for a no-cost extension.**
  - A no-cost extension was applied for and approved by DOE.

Collaborations

- **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

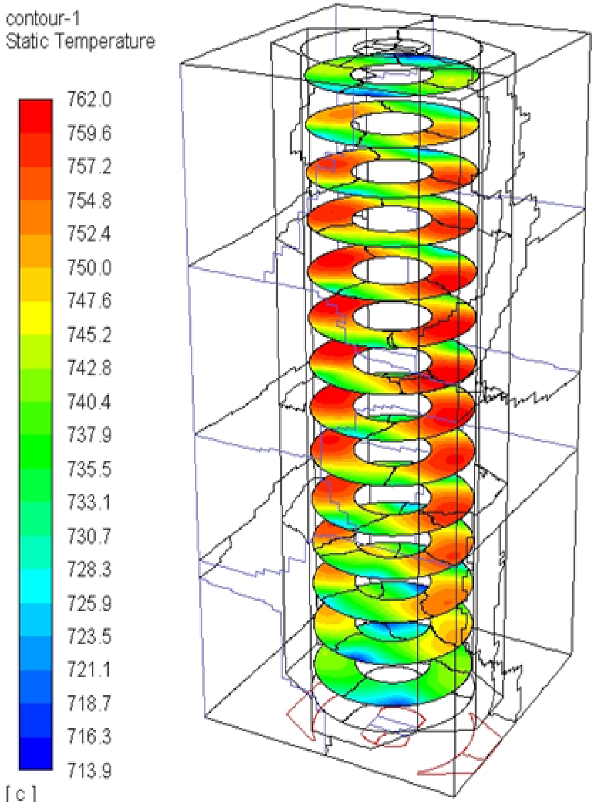
Cell Pilot Manufacturing Processes at VPS: (Tape Casting, Screen Printing, and Co-sintering)

- **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

Collaboration and Coordination

Remaining Challenges and Barriers

- Cell and Stack
  - Operate under pressure of up to 5 bara to increase the efficiency of the overall system
- Forecourt System
  - Verify production cost of \$2/kg H_2 while meeting the overall system efficiency goal of 75% (LHV of H_2)
  - Integrate system with renewable and intermittent power sources
- Demonstration
  - Transient operation and dynamic response of the >4 kg H_2/day demonstration prototype system operating at up to 5 bara



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

Voltage instrumentation

Proposed Future Work

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Future Work

- Cell and Stack
  - Assemble a150-cell stack for tests of 4 kg/day H_2 system demonstrator
- System and Demonstration
  - Complete assembly of the 4 kg/day H_2 prototype system
  - Finish development of system control philosophy and the associated control software
    - State Definition
    - Control logic
    - Alarm documentation
    - Emergency Shutdown Circuit
  - Preform 1000 hour tests of the porotype system meeting the project ultimate target of 4 kg/day H_2 production
  - Determine the economic benefits of forecourt systems using H2A analysis

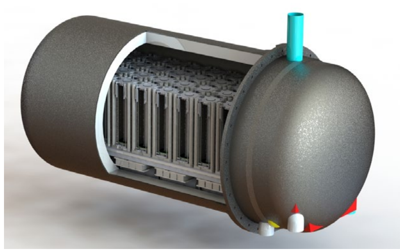
Any proposed future work is subject to change based on funding levels

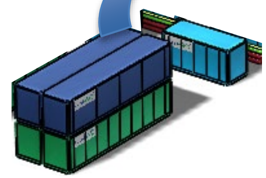
Technology Transfer Activities

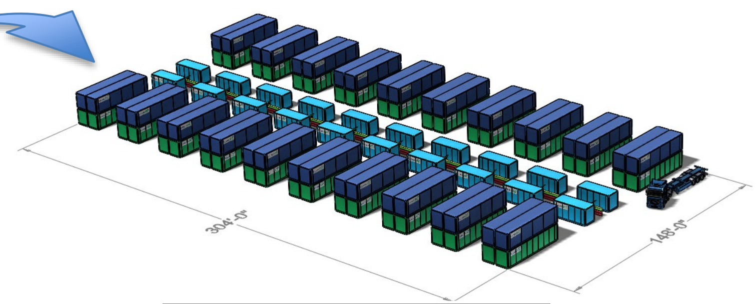
FCE is exploring SOEC systems market opportunities in a variety of applications under a Cooperative Research and Development Agreement (CRADA) with participants including: Exelon, Idaho National Laboratory, Sandia National Laboratory, Argonne National Laboratory, and National Renewable Energy Laboratory.

- Forecourt Refueling – Small Commercial
  - Small, single module system
- 50 MW Block – Mid Industrial/Central
  - 32 MT H_2/day
  - Process Integration (Ammonia, steel, etc)
- 1000 MW Block – Large Industrial/Nuclear
  - 640 MT H_2/day
  - Thermal Integration – coupled with industry

System Parameter	Performance
Stack Electrical Eff (LHV)	97.5%
System Electrical Eff (LHV)	90. 9%
System Total Eff (LHV)	78.0%
Electricity Consumption	36.8 kWh/kg
Thermal Consumption (kWh/kg)	5.9 kWh/kg
Total Energy Consumption	42.7 kWh/kg







Single Module	
# of Stacks	40
Production Rate	1 MT/day
Gross Power	1.43 MWe
Physical Size	4'x4'x8'

50 MW Block	
# of Stacks	1280
Production Rate	32 MT/day
Gross Power	50 MWe
Physical Size	20'x80'x16'

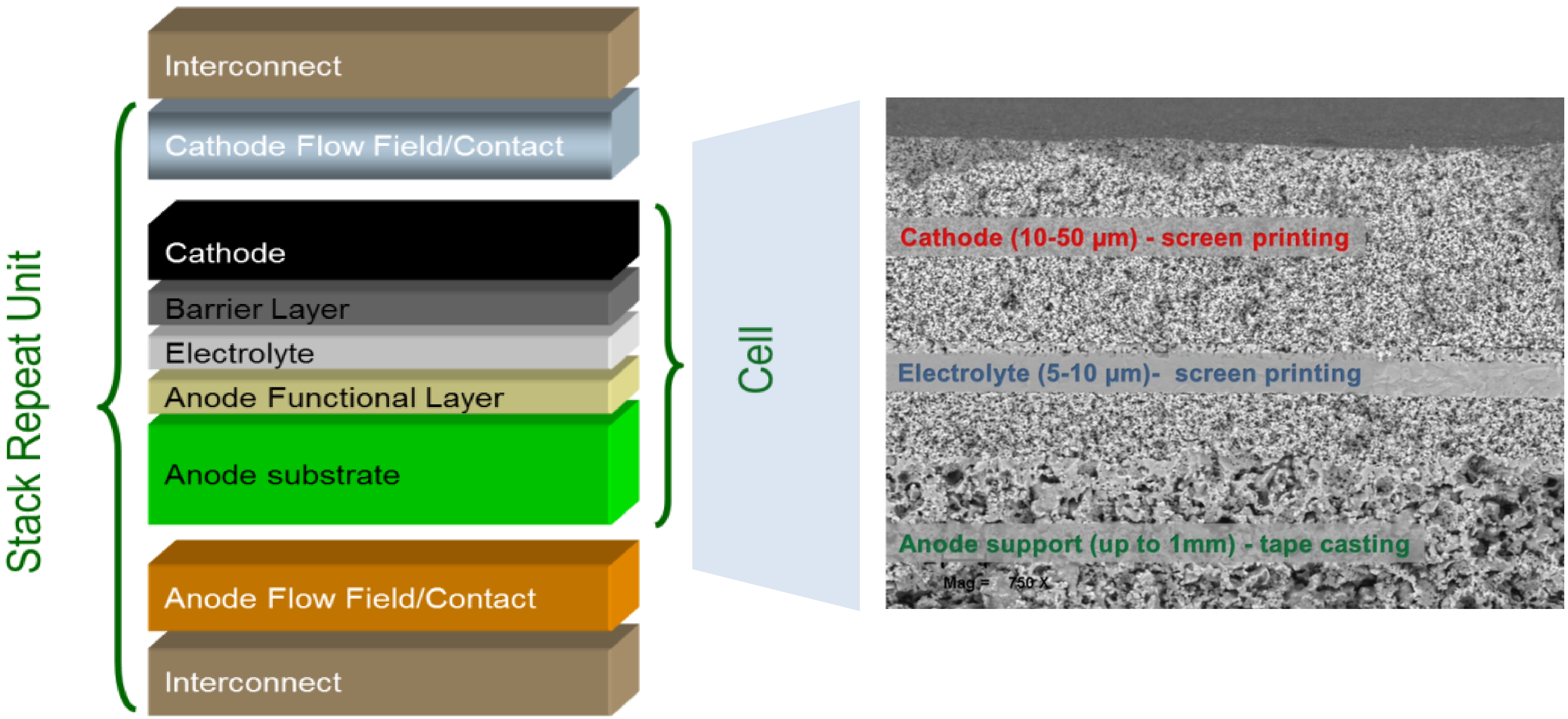
1000 MW System	
# of Stacks	25600
Production Rate	640 MT/day
Gross Power	1000 MWe
Physical Size	~ 1 Acre

Summary

- Met Q1 through Q10 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/cm^2
  - 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
  - Performance of a 45-cell CSA stack, capable of producing > 4 kg H_2/day, was verified with virtually no degradation in ≥3500 hours of tests under simulated system conditions with electrical efficiency >95% (based on LHV of hydrogen) at ≥1 A/cm2
  - Design of a >4 kg H_2/day prototype unit was completed for future demonstration of the system efficiency metrics and the operability of SOEC using intermittent renewables
  - Construction of the components for the >4 kg H_2/day prototype system is near completion

Technical Back-up Slides

HiPoD Cell Technology Used as Fuel Cell



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

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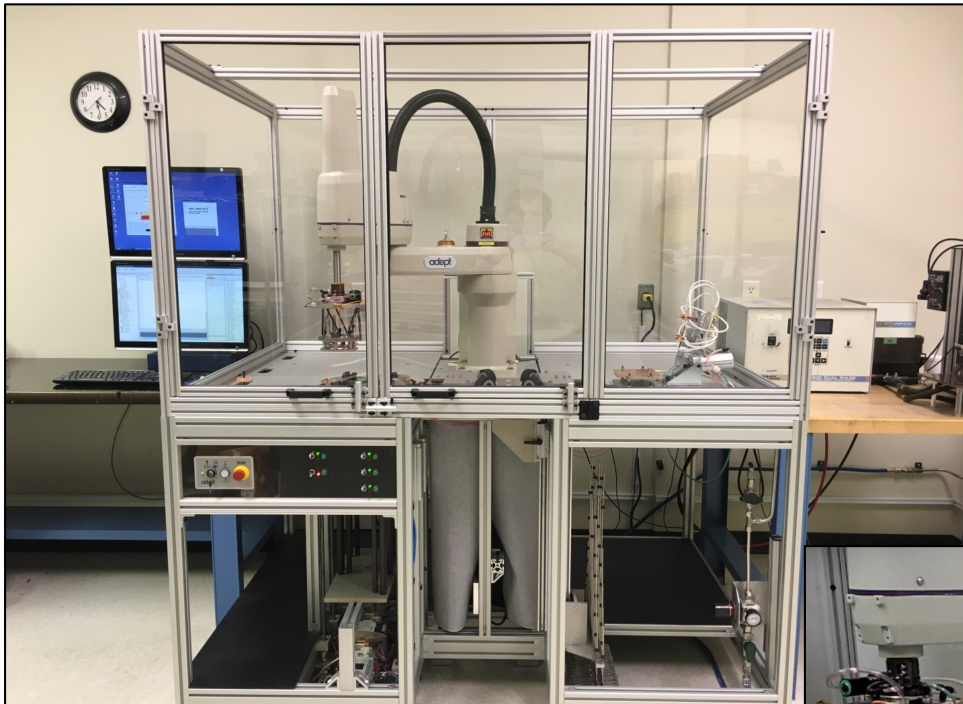
Automated Work Cell

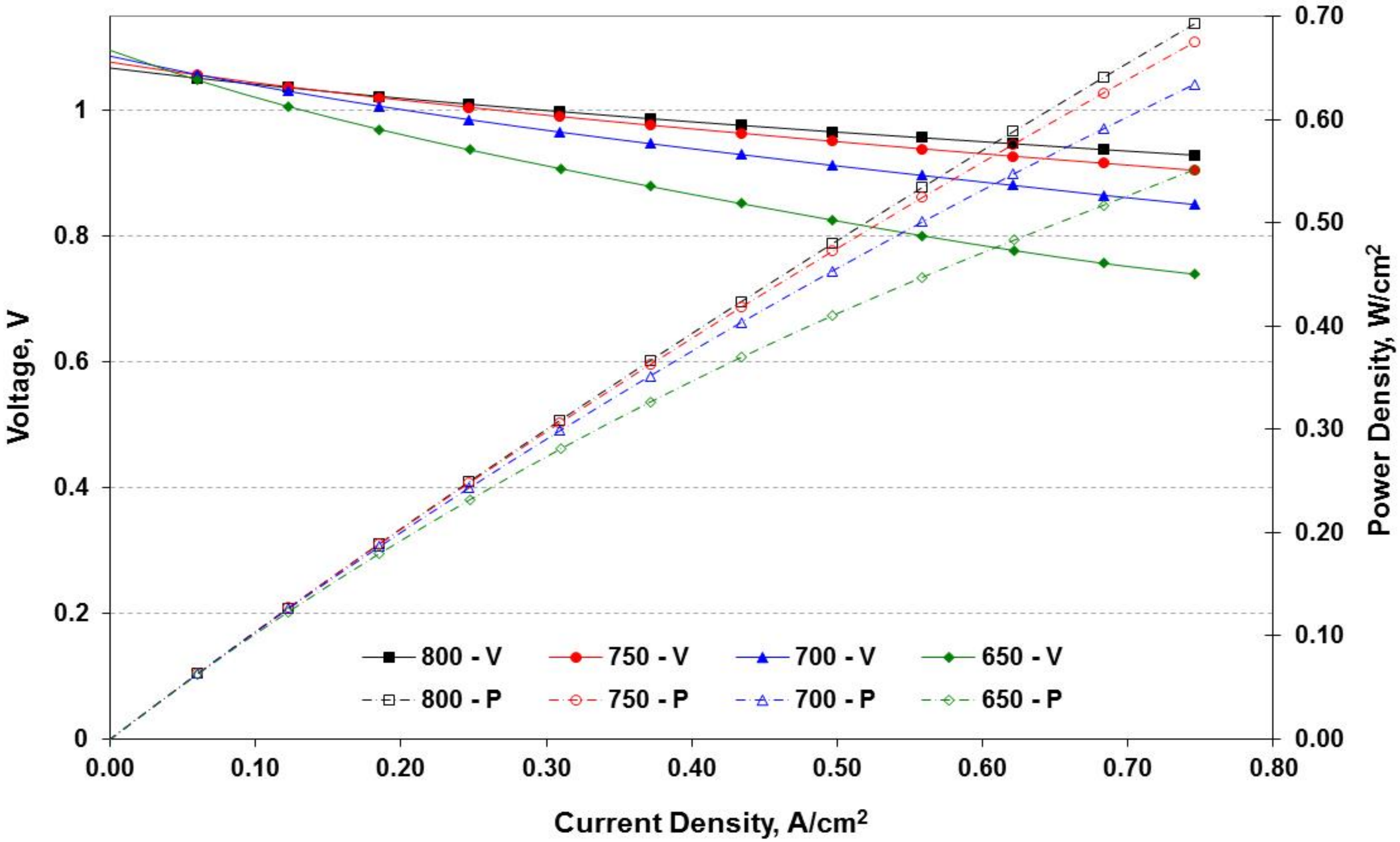


Automated work cell commissioned and performs:

- Stack builds
- Cell and interconnect QC

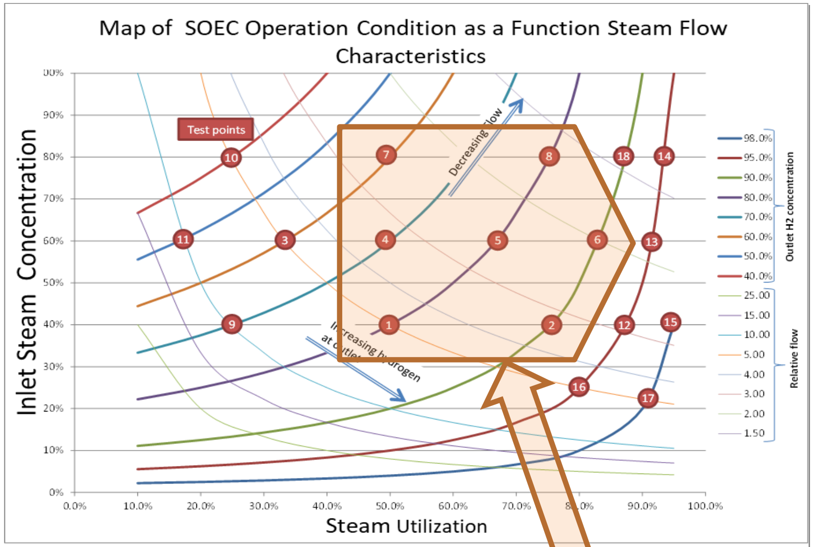
Demonstrated production rate of up to 4 stacks per 8-hour work shift

HiPoD Fuel Cell Performance

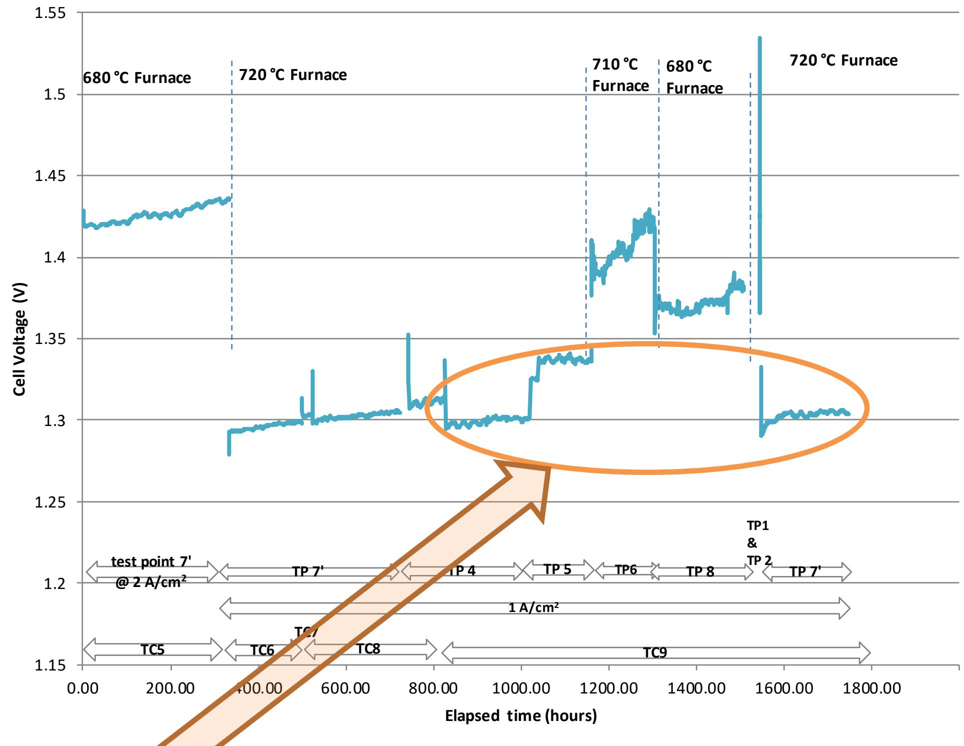


- **Baseline HiPoD Cell Performance Characteristics in Fuel Cell Mode**

Milestone 1.4.1: Parametric stack testing



Test conditions explored

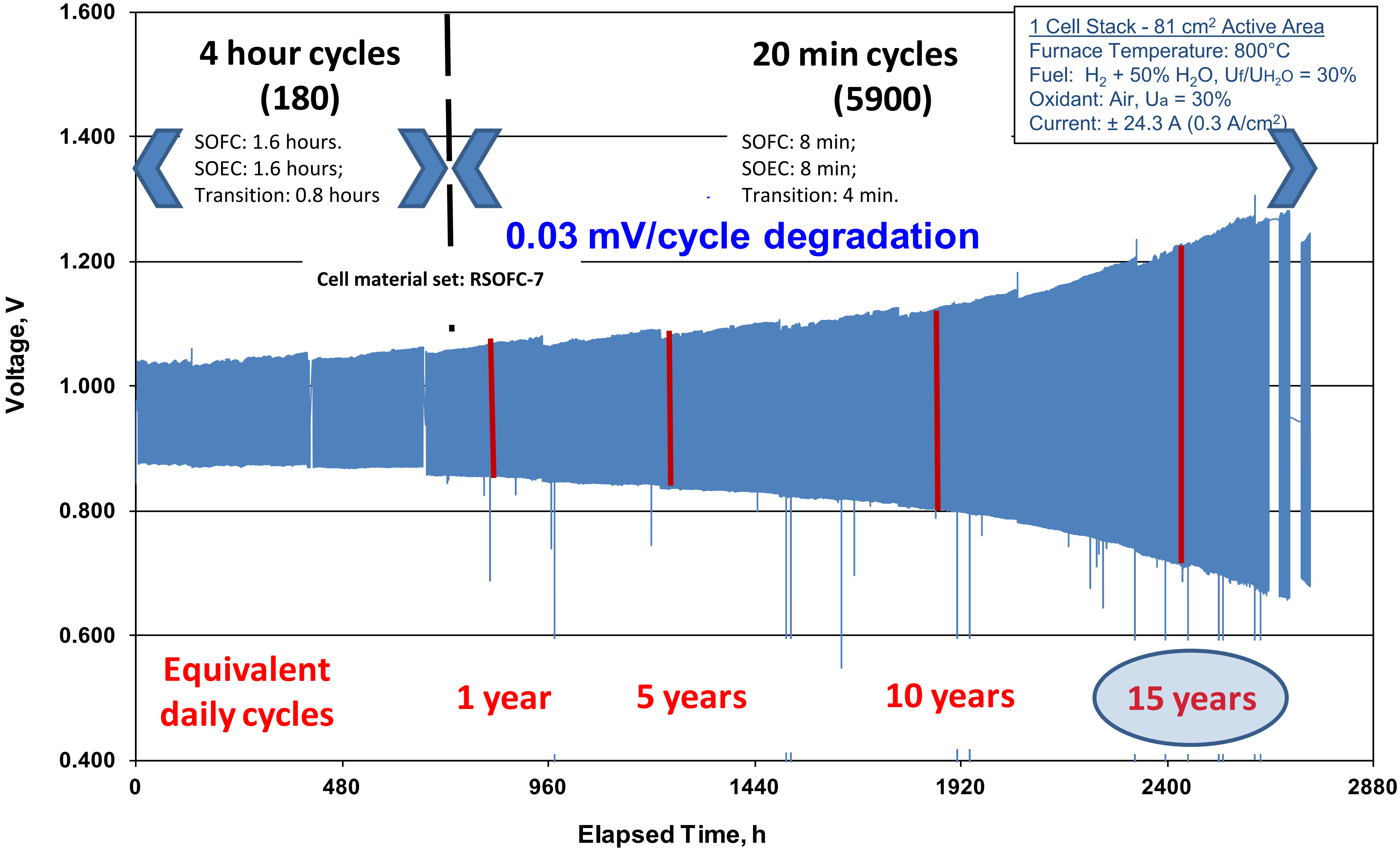


20 cell stack:

- **Test point 7: Degradation of 7 mV/khr = 0.6%/khr, Stack voltage of 1.303 V, Efficiency of 96.1% LHV**

Milestone targets	**Results**
>500 hours parametric testing	>1700 hours parametric testing ✓
System relevant conditions	System relevant conditions ✓
At least 5 operating points	8 operating points ✓

Accelerated Cycling (6,080 Cycles)



Publications and Presentations

1. Hossein Ghezel-Ayagh; "Modular SOEC System for Efficient H_2 Production at High Current Density", 2018 DOE Hydrogen and Fuel Cell Program Review, Washington, DC, June 13, 2018, https://www.hydrogen.energy.gov/pdfs/review18/tv041_hossein_2018_o.pdf
2. 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", 2017 DOE Hydrogen and Fuel Cell Program Review, Washington, DC, June 7, 2017, https://www.hydrogen.energy.gov/pdfs/review17/pd124_petri_2017_o.pdf
3. Hossein Ghezel-Ayagh, Randy Petri, Micah Casteel, Stephen Jolly, and Casey Brown, "Solid Oxide Electrolysis Cell Development for Hydrogen Production and Energy Storage", Presented at 2017 Fuel Cell Seminar & Energy Exposition, Long Beach, California, November 8, 2017
4. 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
5. 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