Modular SOEC System for Efficient H_2 Production at High Current Density

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2019 DOE Hydrogen and Fuel Cells Program Review

Project ID# ta019

Overview

Timeline

- Project Start Date: 10/01/2016
- Project End Date: 09/30/2019

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*: $1,666,536

* Estimated as of 3/1/19

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

Approach

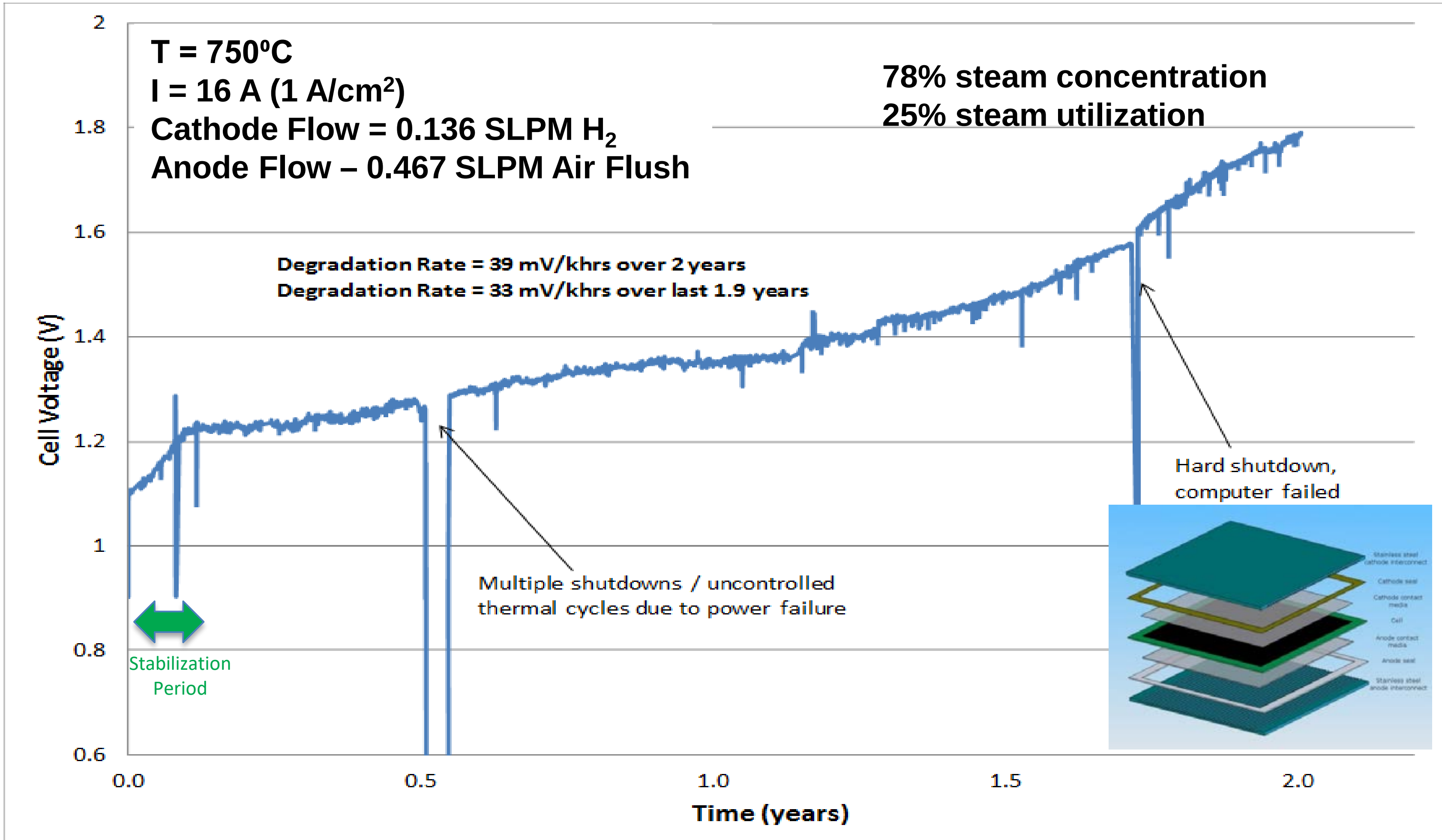
FY2019 Milestones

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	**40%**
	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	**30%**

Approach

2 Year SOEC Testing @ 1 A/cm²

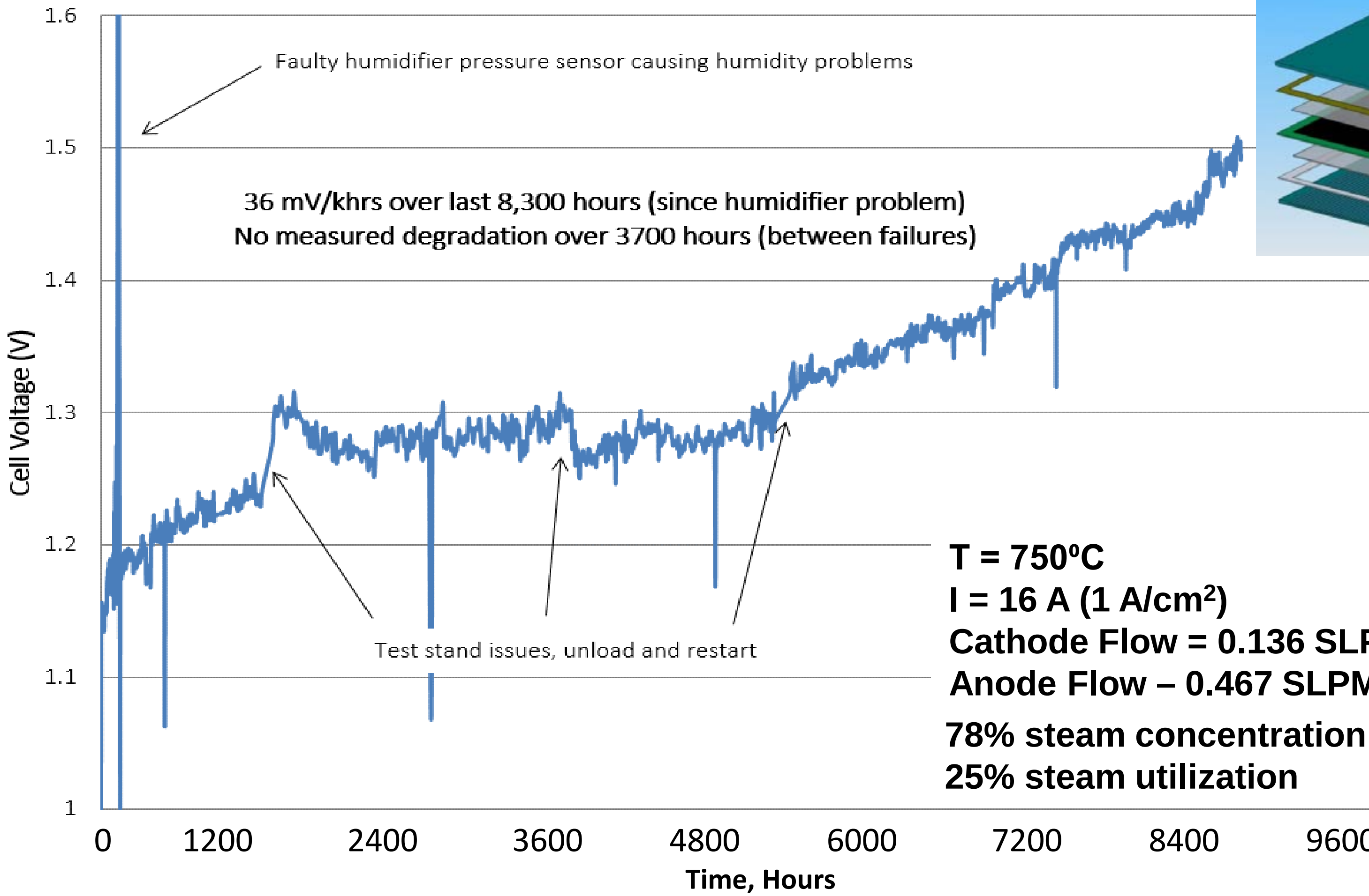
Test of HiPoD (High Power Density) cell (5 cm x 5 cm x 0.03 cm) at 1 A/cm²

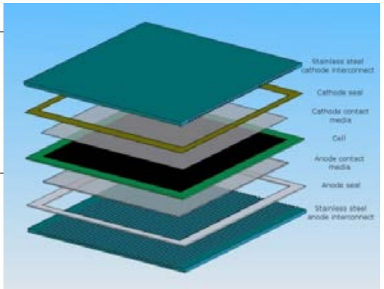


Demonstrated voltage degradation rate of 18 mV/1000h or 1.4 %/1000h over 7,350 hours between test stand failures, meeting milestone target

Additional Long Term SOEC Testing

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





T = 750°C
I = 16 A (1 A/cm^2)
Cathode Flow = 0.136 SLPM H_2
Anode Flow – 0.467 SLPM Air Flush
78% steam concentration
25% steam utilization

Repeat cell test showed similar degradation rate after one year of testing

Technical Accomplishments and Progress

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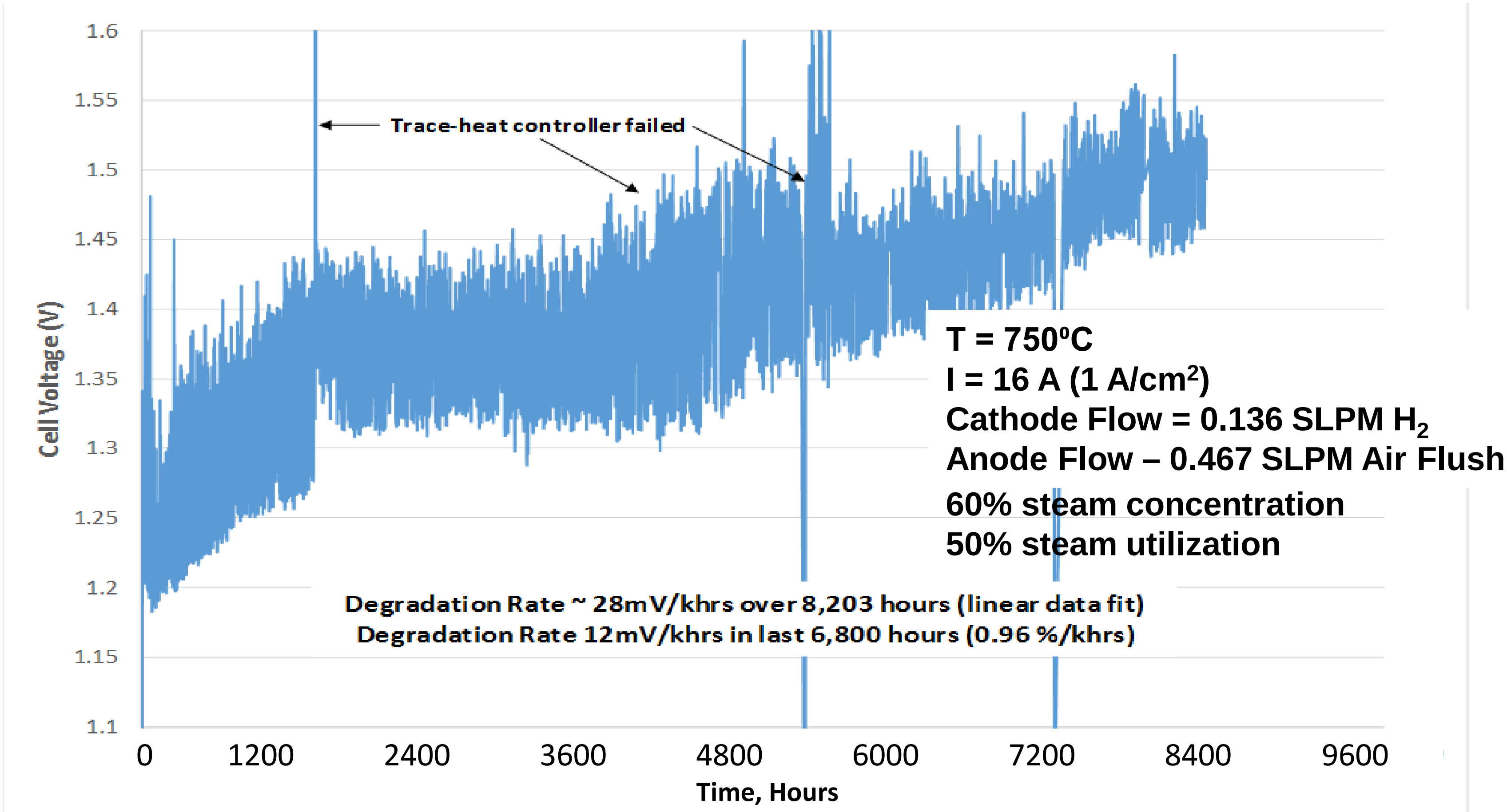
Effect of Operating Conditions on Cell Degradation Test at 1 A/cm^2

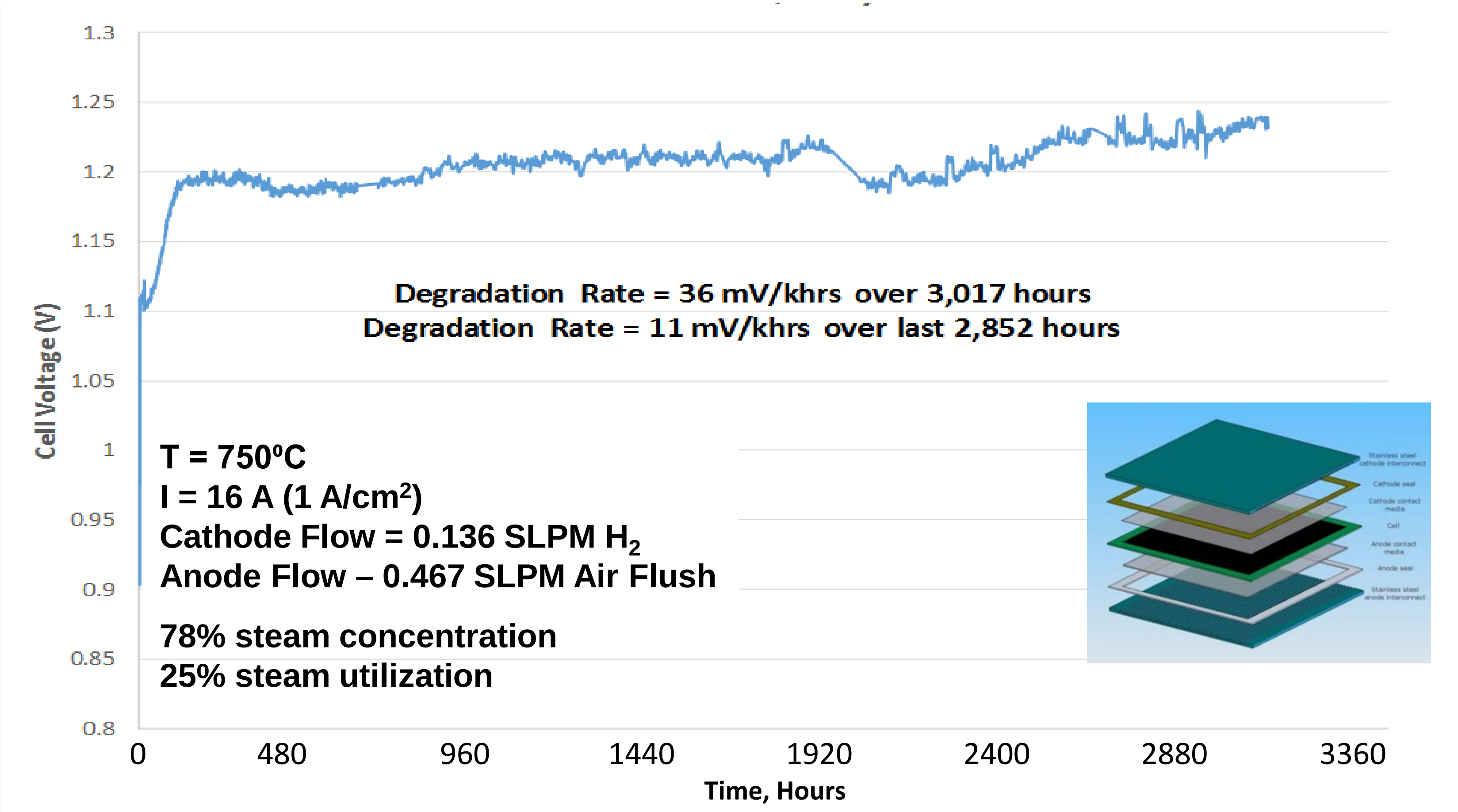
Test of HiPoD (High Power Density) cell (5 cm x 5 cm x 0.03 cm) at 1 A/cm^2



Alternative test condition (lower steam concentration, higher steam utilization) and coated cell hardware achieved degradation rate < 1.0 %/khrs

Effect of Modified Electrolyte on Cell Degradation Test at 1 A/cm2

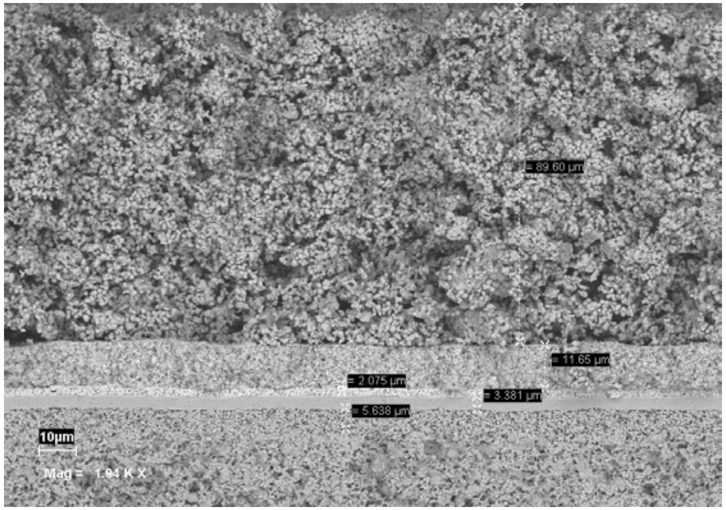
Test of HiPoD (High Power Density) cell (5 cm x 5 cm x 0.03 cm) at 1 A/cm^2



- **Modified electrolyte (10YSZ) combined with reducing cathode flow field height achieved the lowest degradation rate of 0.88 %/khrs and met Milestone 3.1.2**

SOEC Cell Endurance Summary

- Operating conditions (e.g. current density, steam concentration and utilization) have significant effects on the SOEC degradation rate
- 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
- Investigations to date aimed at evaluating the relative importance of these mechanisms



Post Test Analysis After One Year Test

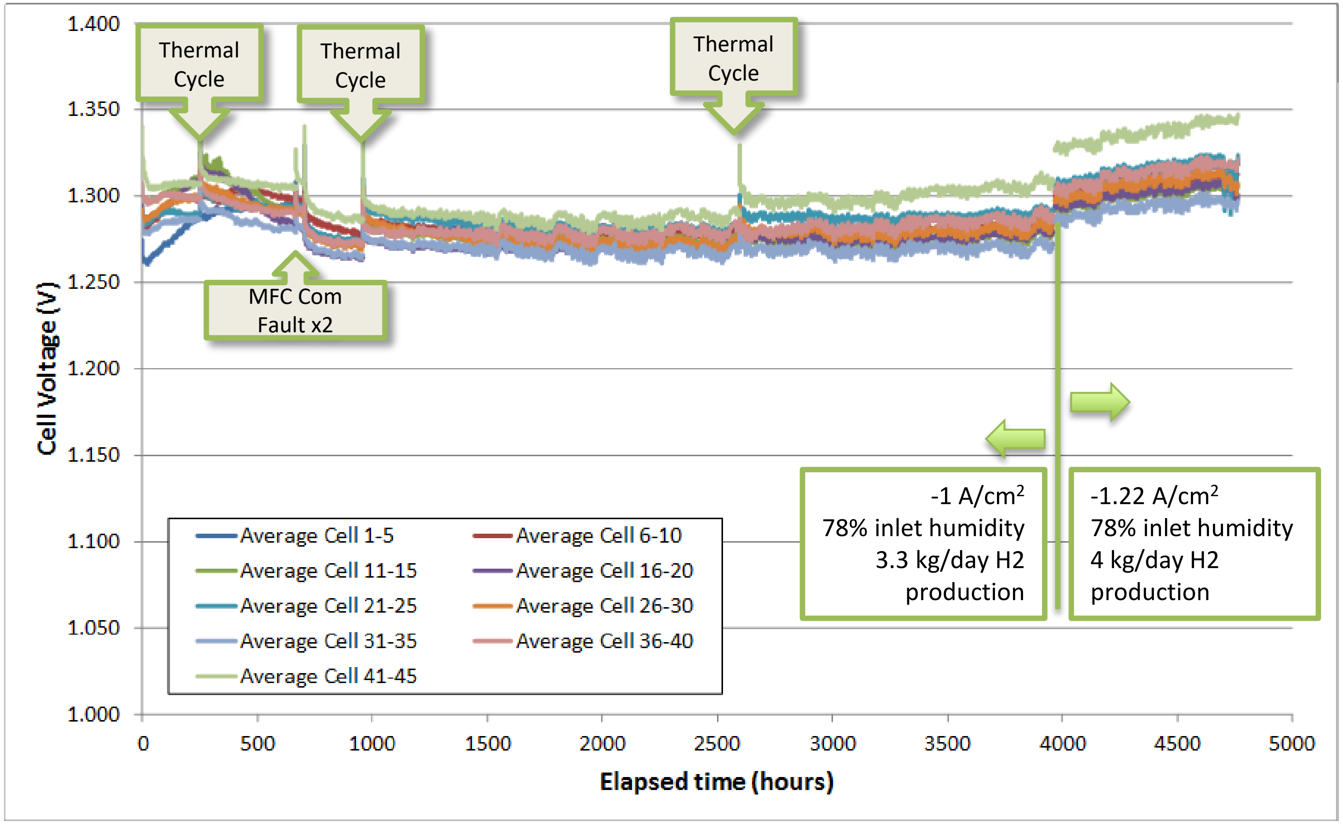
- Overall cell layers look good with no obvious damage
- Electrolyte was dense and ~3.5 microns
- Cr deposited at the anode
- Ni depletion in cathode functional layer

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)	

Long Term Testing of 45-Cell CSA Stack



45-Cell Stack Tests Met Milestone 3.1.3

Milestone 3.1.3 Targets	Demonstrated	Comment
4 kg H_2/day H_2 production ✓	4 kg/day H_2 production	
<2% /khr performance degradation ✓	18 mV/khr (1.4% /khr) degradation at 4 kg/day (-1.22 A/cm^2)	Approximately **no degradation over 3959 hours electrolysis** at 3.3 kg/day (-1 A/cm^2)
>1000 hours operation ✓	4,765 hours demonstrated at or above 3.3 kg/day, including 800 hours at 4 kg/day	

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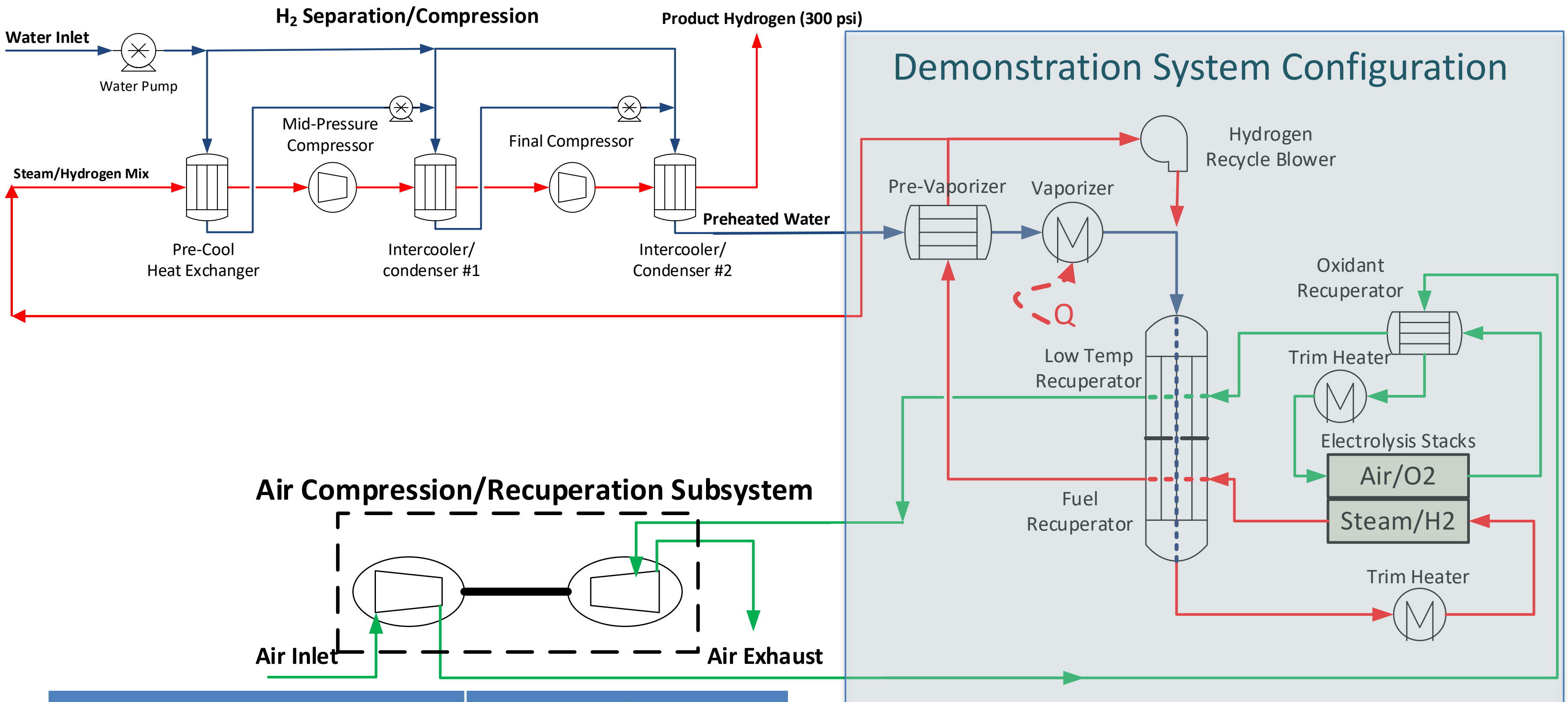
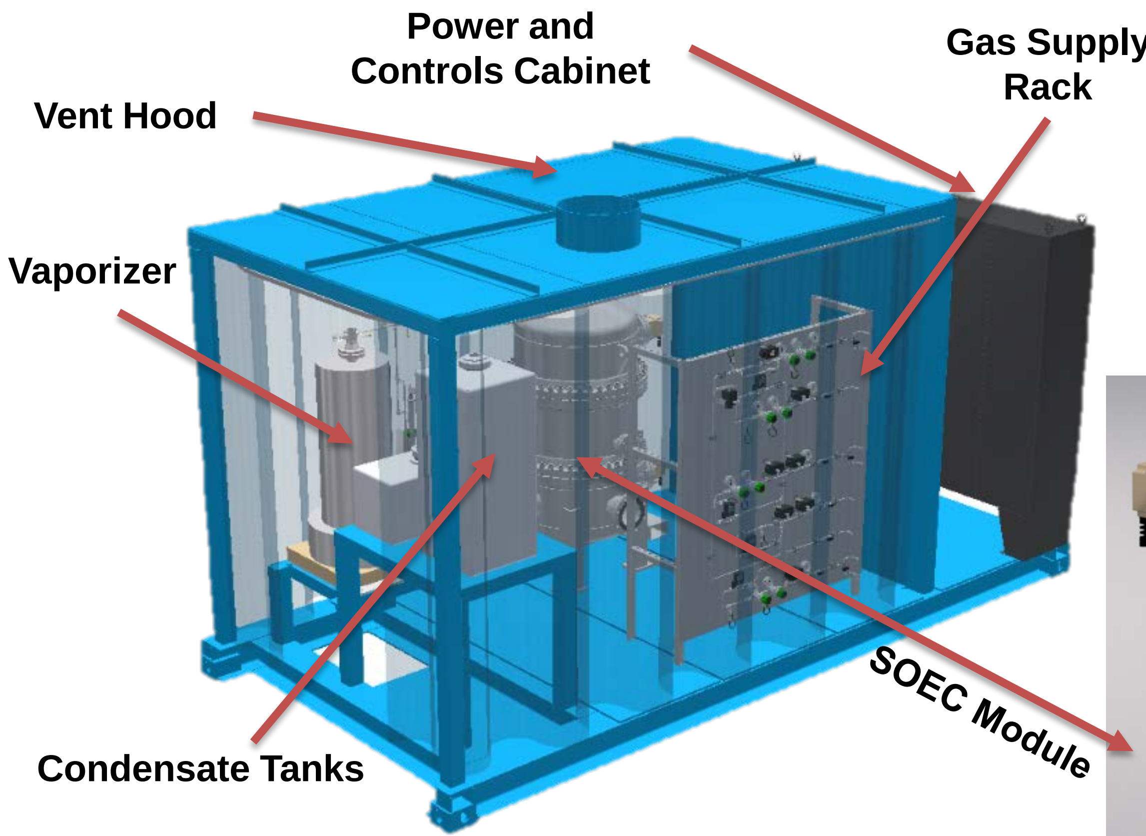
Forecourt Modular Electrolysis System Process Flow Diagram



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

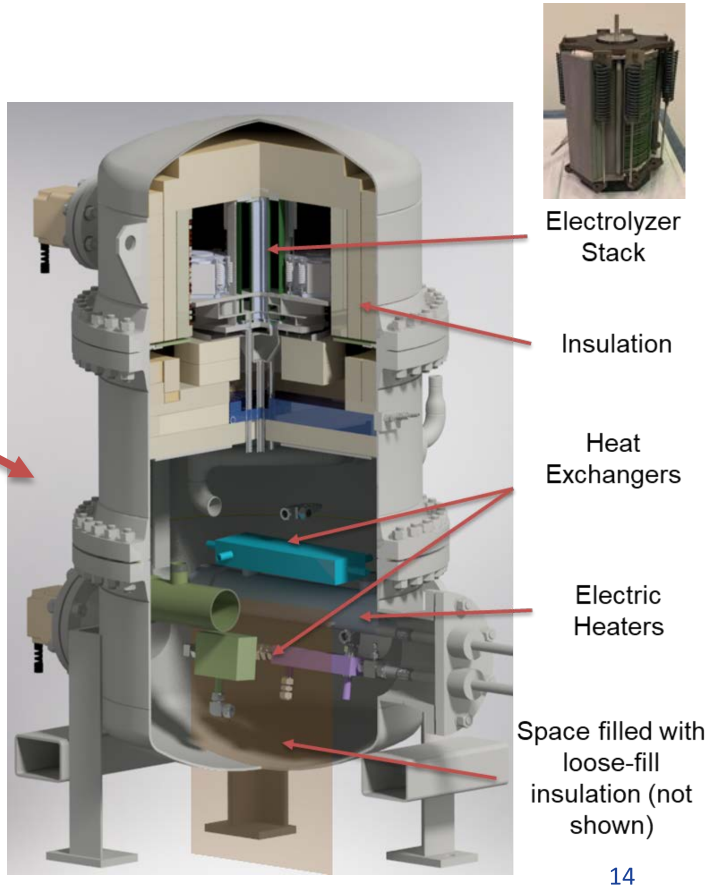
System Parameter	Performance
Stack Electrical Eff (LHV)	97.5%
System Electrical Eff (LHV)	90. 9%
System Total Eff (LHV)	78.0%
Electricity Consumption	36.8 kWh/kg
Thermal Consumption (kWh/kg)	5.9 kWh/kg
Total Energy Consumption	42.7 kWh/kg

Demonstration System



System Characteristics:

- 4-20 kg/day H_2 production
- 7-32 kWe
- Compressed Air Inlet
- Water Balance System



- 125 psig (8.6 barg) design pressure
- Accommodates 1x150-cell stack or 4x45-cell stacks with adapter
- 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.

Responses to Previous Year Reviewers' Comments

1) - The project does not have any partners other than a wholly owned subsidiary.

- The project would be strengthened by independent evaluation of the TEA results. Many questions from reviewers on the technical validity of the results in the areas of energy integration and overall process efficiency could be addressed by the addition of a partner to complete/validate the results independently.

- Having an independent team partner is not within the scope and budget of this project. However, FCE's SOEC system is currently being studied under a CRADA, with participants including: Exelon, Idaho National Laboratory, Sandia National Laboratory, Argonne National Laboratory, and National Renewable Energy Laboratory. The study includes independent verification of the TEA results for large commercial SOEC systems.

2) - Also, the researchers are not doing any statistics. This is especially important for the stack that was used for the go/no-go and showed interesting performance. The project team needs to figure out why the stack is performing as well as it is and replicate the performance.

- The team members should see if they can replicate the very interesting results obtained from their current stacks.

- The CSA stack that met the project go/no-go milestone ran for >4000 hours. Duplication of the stack is beyond the project period of performance and budget. The 4 kg H_2 /day demonstration will provide additional validation of a duplicate stack with three times more cells.

3) - Details on certain approaches (e.g., how to reduce performance degradation) are lacking.

- For the degradation mechanisms, it would have been interesting (1) to state where the Ni was going and (2) to explain what the reaction layer forming in the anode was.

- Ni loss in the electrochemical active region of the SOEC cathode is caused by conversion to a vapor phase. We have not seen formation of reaction layer such as strontium zirconate in the anode. However, we have seen Cr species in the SOEC anode. The mitigation approach to degradation is by using the appropriate operating conditions (e.g. steam concentration, current density) and implementation of Cr-getters in the SOEC anode.

Collaborations

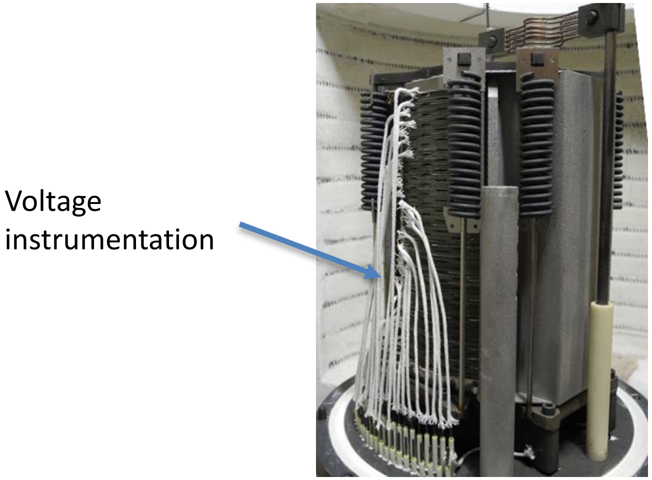
- **Versa Power Systems (VPS), <u>Operating as FuelCell Energy</u>**
  - VPS is a key sub-recipient providing the following expertise in the project:
    - SOFC materials & components R&D
    - Stack design
    - Cell/stack pilot manufacturing and QC
    - Cell/stack testing

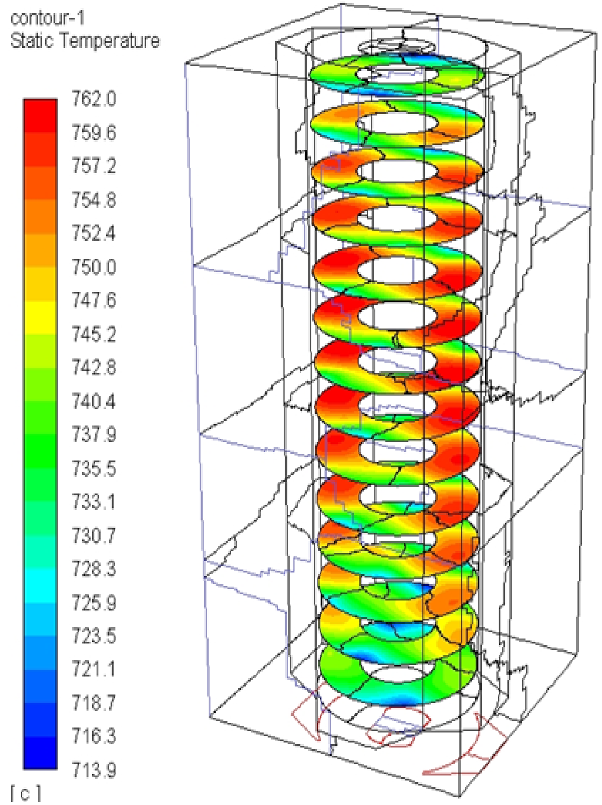
Cell Pilot Manufacturing Processes at VPS: (Tape Casting, Screen Printing, and Co-sintering)

- **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

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
  - Design, fabricate and test >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

Proposed Future Work

Future Work

- Cell and Stack
  - Fabricate ≥ 150-cells for use in the prototype for demonstration of 4 kg/day H_2 production
  - Assemble a150-cell stack for tests of 4 kg/day H_2 system demonstrator
- System and Demonstration
  - Complete fabrication of balance of plant components and equipment for 4 kg/day H_2 prototype system
  - 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

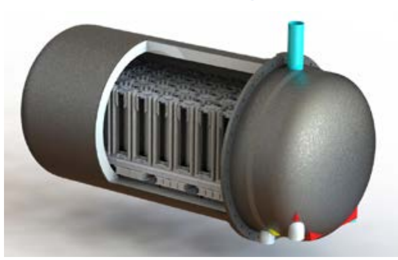
Technology Transfer Activities

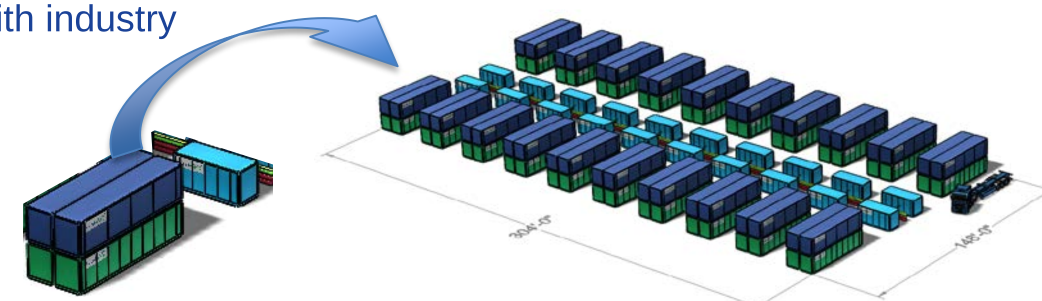
Collaboration and Coordination

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

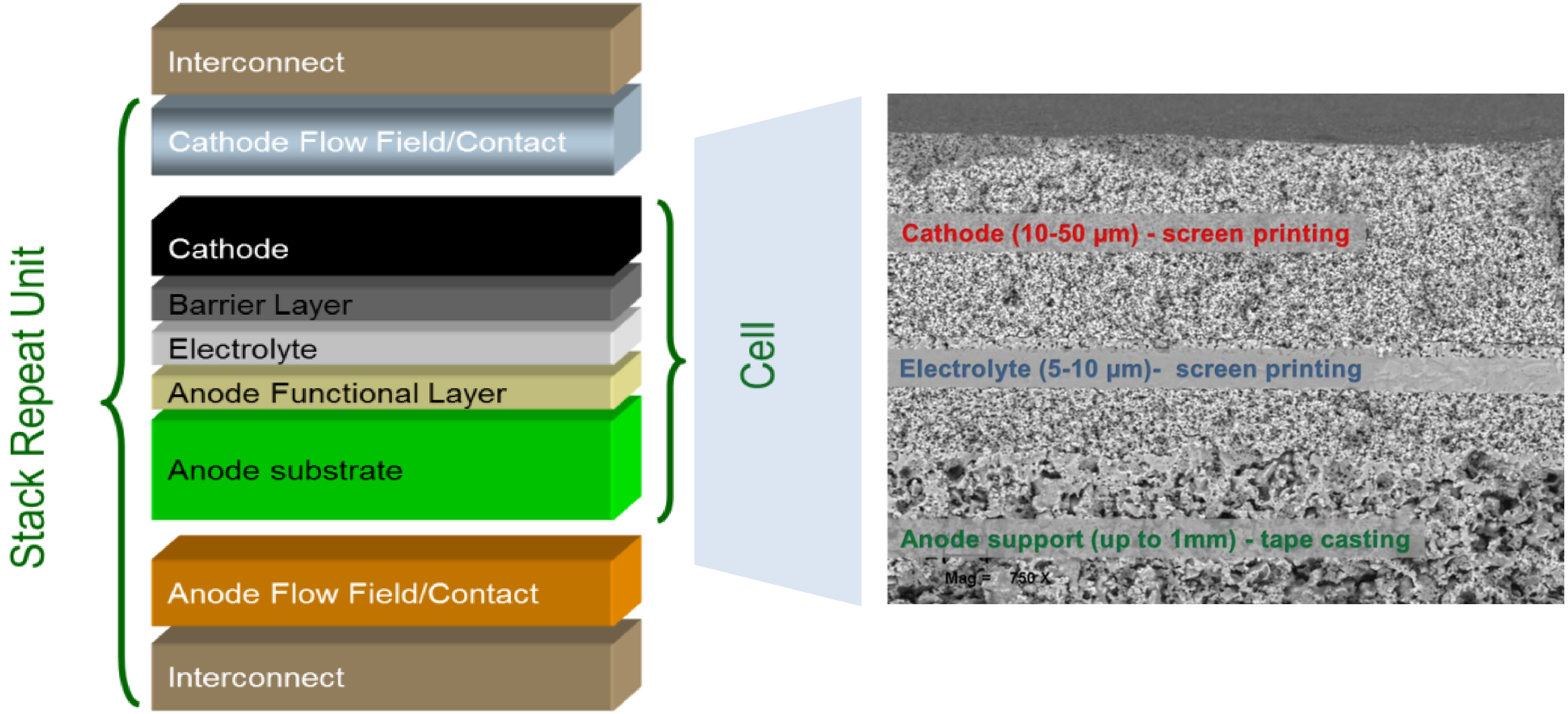
Summary

- 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 was initiated

Summary

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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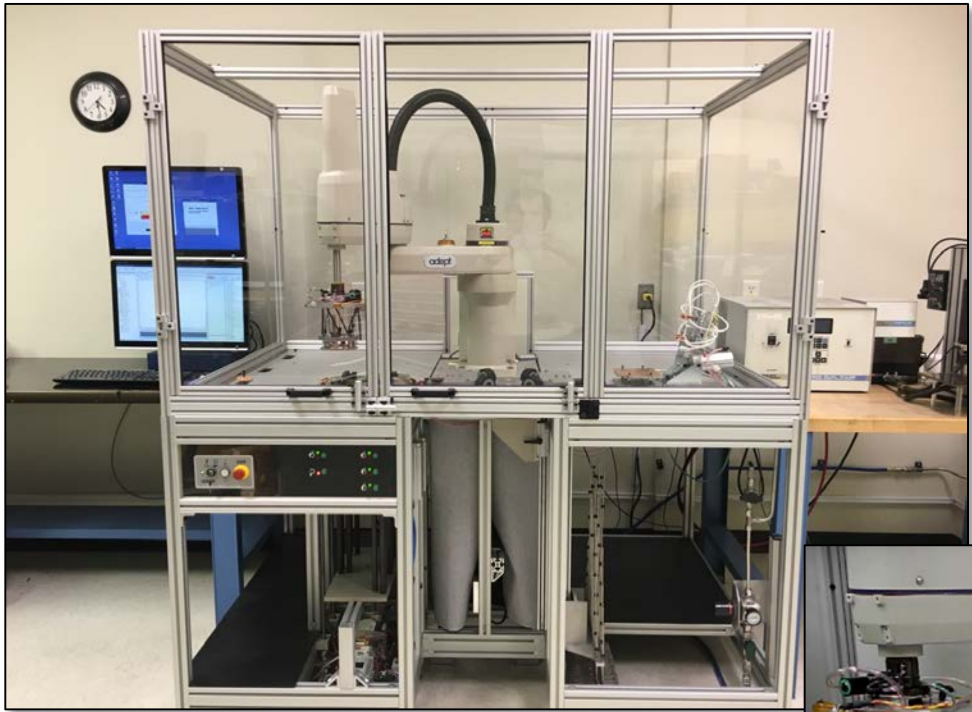
Automated Work Cell

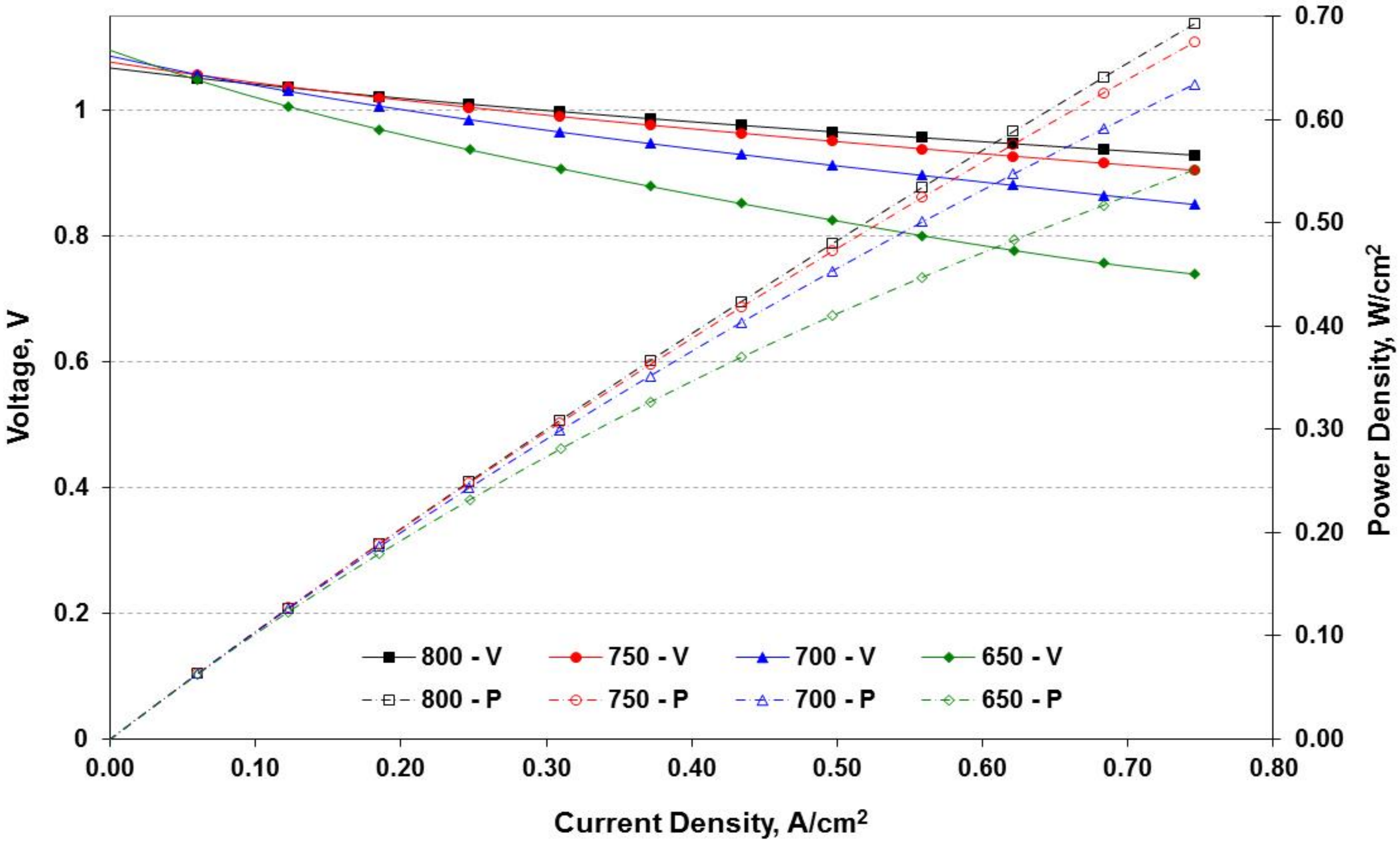


Automated work cell commissioned and performs:

- Stack builds
- Cell and interconnect QC

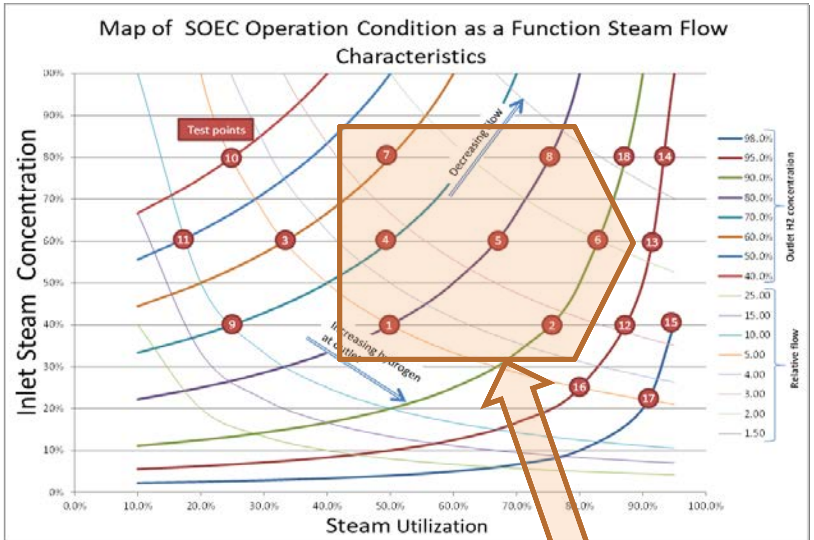
Demonstrated production rate of up to 4 stacks per 8-hour work shift

HiPoD Fuel Cell Performance

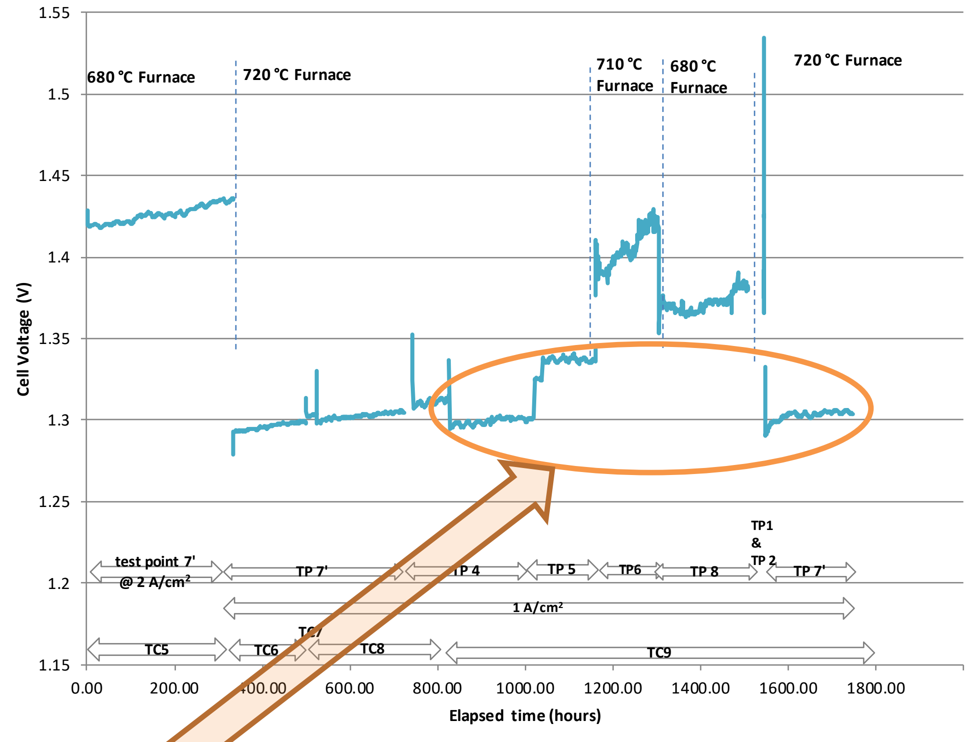


- **Baseline HiPoD Cell Performance Characteristics in Fuel Cell Mode**

Milestone 1.4.1: Parametric stack testing



Test conditions explored



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

20 cell stack:

Milestone targets

- >500 hours parametric testing
- System relevant conditions
- At least 5 operating points

Results

- >1700 hours parametric testing ✓
- System relevant conditions ✓
- 8 operating points ✓

Accelerated Cycling (6,080 Cycles)