FuelCell Energy

Ultra-Clean, Efficient, Reliable Power

Reliable SOFC Systems

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16th Annual SECA Workshop

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Ultra-Clean | Efficient | Reliable Power

Presentation Outline

- **Introduction**
  - FCE SECA Program Team Members
  - SOFC Technology Program Overview
- **Progress in SOFC Technology**
  - Cell Development and Manufacturing
- **Stack Development**
  - Scale-up and Test Results
- **Proof-of-Concept Module (PCM) Development**
  - 50 kW PCM System
  - Stack Module
- **SOFC Technology Applications**
- **Summary**

Integrated Fuel Cell Company

Research & Development

Design megawatt–class distributed power generation solutions

- *Global fuel cell technology platform*
- *Robust intellectual property portfolio*
- *Leveraging core technology for opportunities in new markets*

Manufacturing, Sales, & Project Execution

Project development – Direct Sales

Global manufacturing profile (200+ MW capacity)

Engineering, Procurement and Construction

Services

Operate & Maintain power plants

- *Over 100 DFC® plants operating at more than 50 sites in 9 countries*
- *>3.6 billion kWh ultra-clean power produced*
- *> 300 MW installed/backlog*

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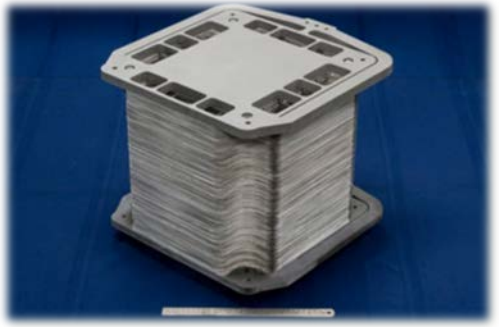
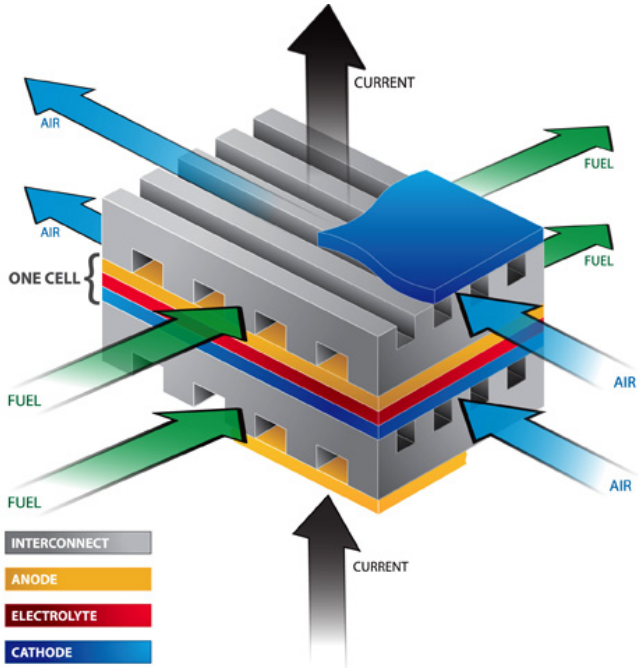
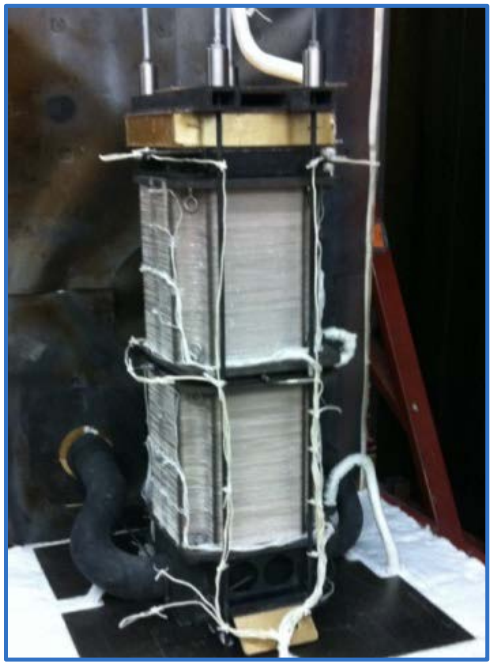
SOFC Cell and Stack Technology Background

- Planar anode supported cells (up to 1000 cm^2)
- Wide window of operating temperature, from 650ºC to 800ºC
- Stacks with integrated manifolds and cross-flow gas delivery
- Ferritic stainless steel sheet metal interconnect
- Compressible ceramic gasket seals
- Capable of in-stack Direct Internal Reforming (DIR) of methane to hydrogen
- Standardized stack blocks configurable into stack towers for various power applications







FCE/VPS
SOFC Development Facilities

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Materials Laboratory and Bench Scale Fabrication

Facilities for up to 400 kW Stack Tests

Outdoor Pads for 400 kW Grid Connected System Tests

Versa Power Systems

SOFC Materials & Components R&D

Pilot Manufacturing & QC

36 Test Stations: Single Cell to 25 kW Stack Testing

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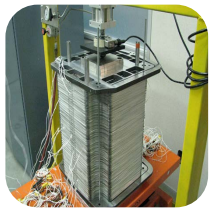
Project Objectives

Development of SOFC technology suitable for ultra-efficient central power generation systems (coal and natural gas fuels) featuring >90% carbon dioxide capture

Conduct cell & stack R&D focusing on performance, reliability, cost and manufacturing enhancements



Fabricate and test fuel cells & stacks including endurance testing (≥1000 hours) under system-relevant operating conditions

Design, build and operate 50-200 kW demonstration systems using natural gas fuel to validate stack operation in system environment

Develop concept system design and stack module for a MW-class power plant

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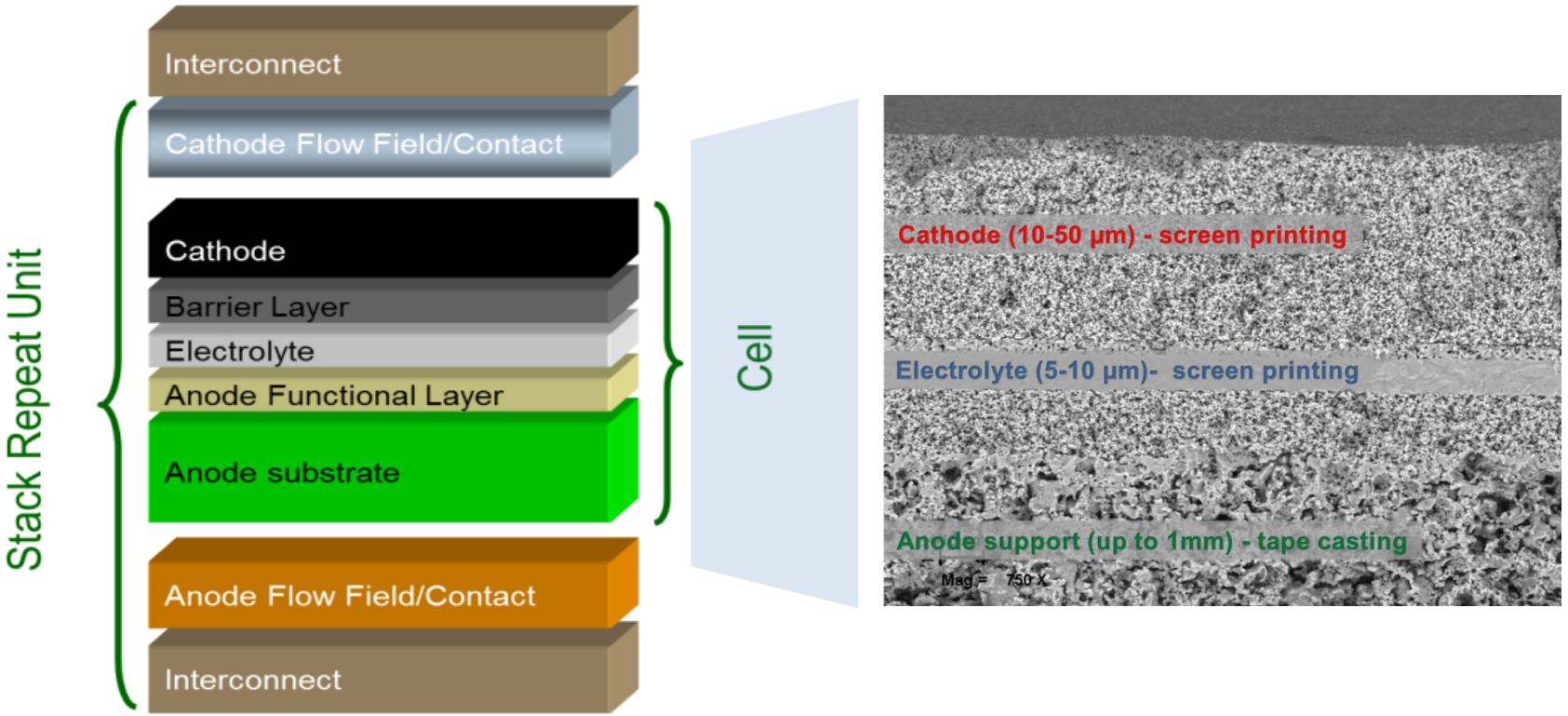
Cell Technology Overview



Component	Materials	Thickness	Porosity	Process
Anode	Ni/YSZ	0.3 - 1 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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Cell Development Path

"TSC" Manufacturing Process

Anode Development

- Reduce Cell Thickness
- Enhance Performance at Higher Fuel Utilization
- Improve Performance at Lower Temperature
- Enhance Cell Mechanical Properties and Robustness

Cathode Development

- Enhance Performance and Endurance
- Lower Operating Temperature
- Increase Operating Window

Scale Up & Manufacturing Development

- 121 cm^2 → 1000 cm^2
- Established Cell Baseline at 550 cm^2
- > 6000 Cells (25 x 25 cm^2) Fabricated
- Production Volume of 500 kW (annual) & >95% Fabrication Yield Demonstrated

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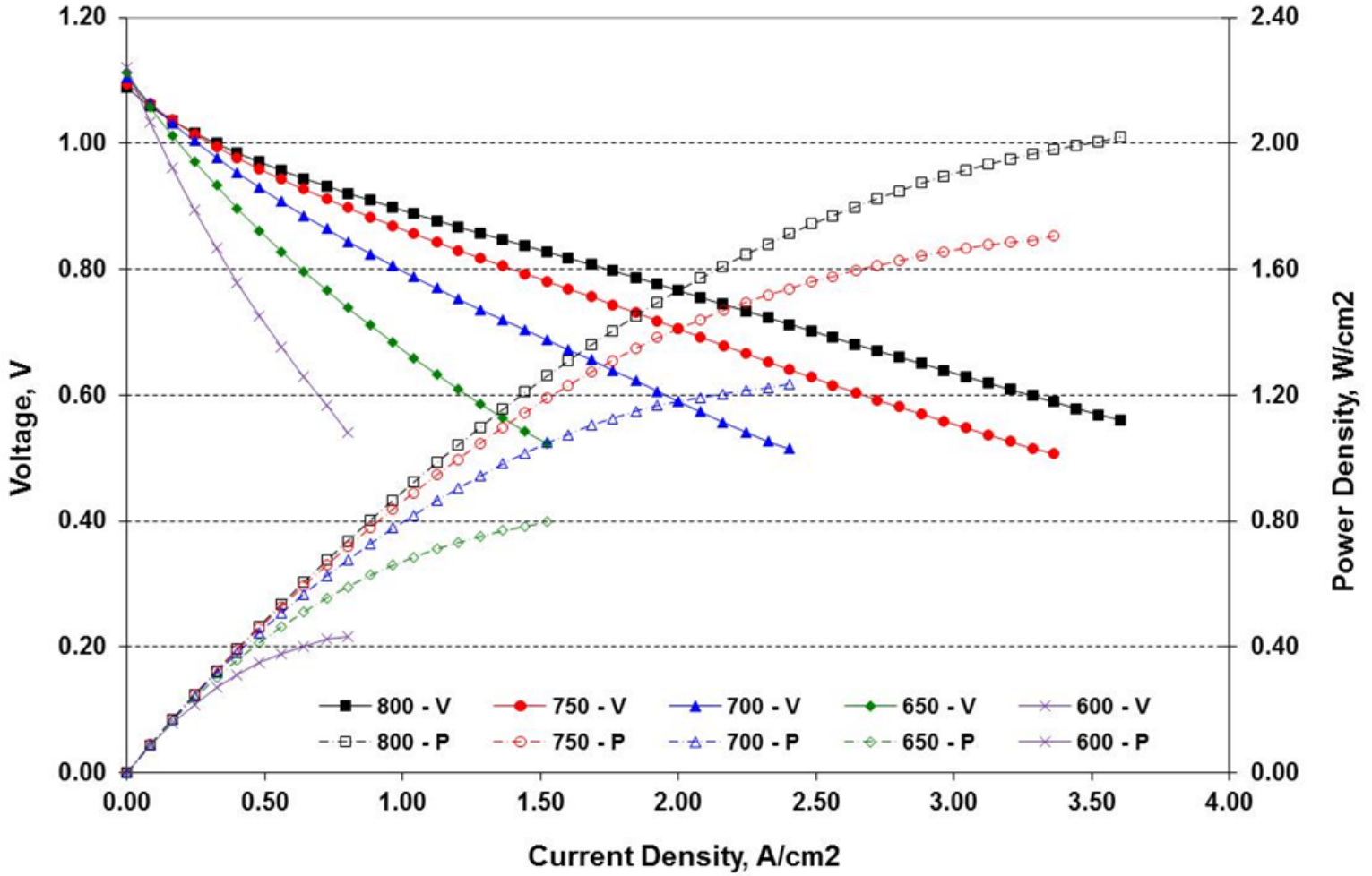
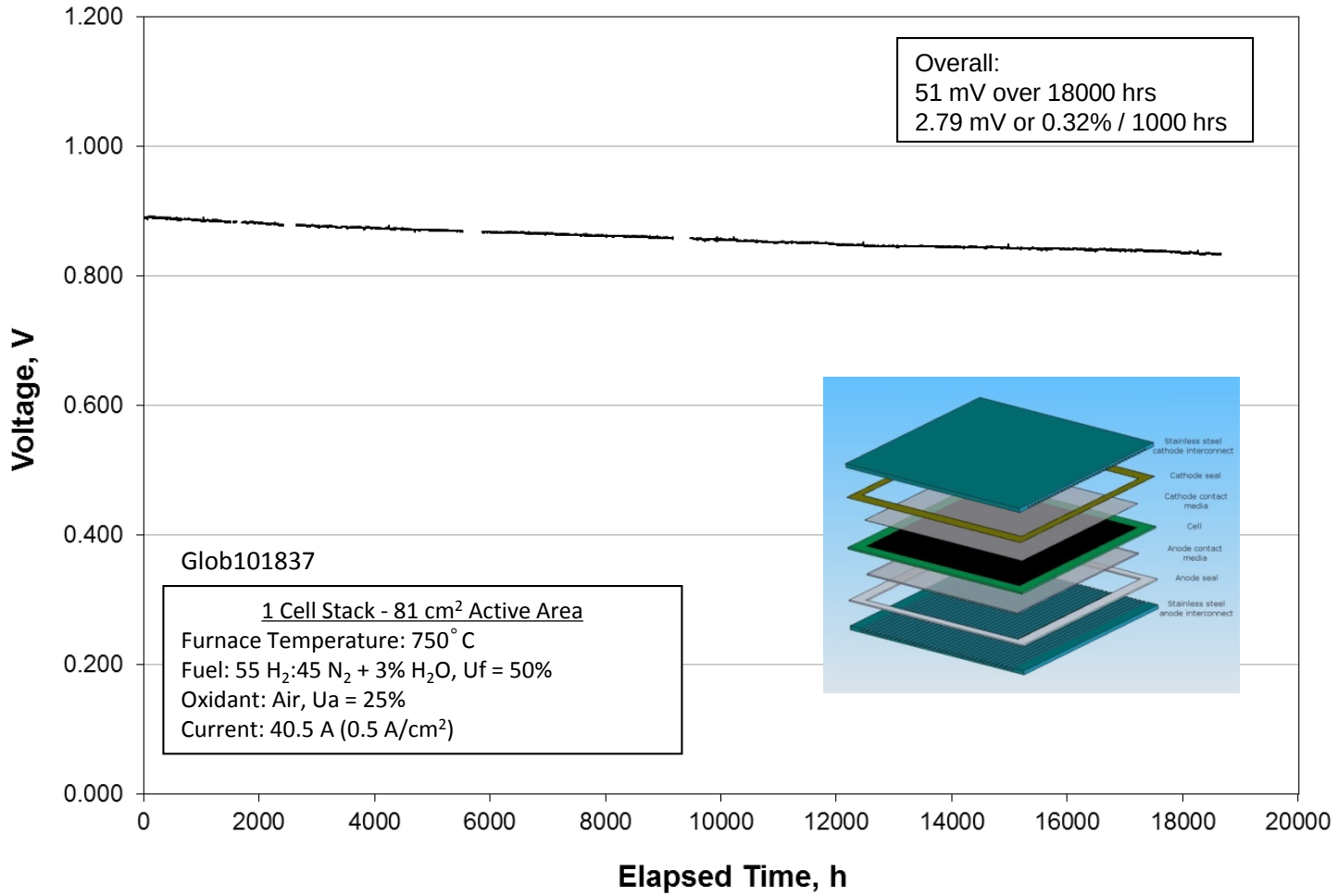
Recent Cell Performance Achievements



- Cell technology has excellent performance in a wide temperature window, achieving 2W/cm^2 at 800ºC

TSC3 Long-term Performance



→ Long-term cell endurance was verified in >2 years of operation with a 0.32%/1000h performance degradation

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Cell Manufacturing QC Improvements

Previous Hand Held Cell Thickness Measurement Device

New Cell Thickness QC Station

- Improvements in the quality of the manufactured cell components and assembly were implemented
- New cell thickness measurement station was designed & implemented, simulating thickness when compressed in stack
- Qualification results:
  - Total Gage Reproducibility and Repeatability (Gage R&R) of 6% was archived (Desired target < 30%) with 0.04 mm total tolerance

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Gen 1.0 Cr Tolerant Technology

Cobalt Coated Interconnect

- PVD Cobalt coating

Sheet Metal

Co-coated Sheet Metal

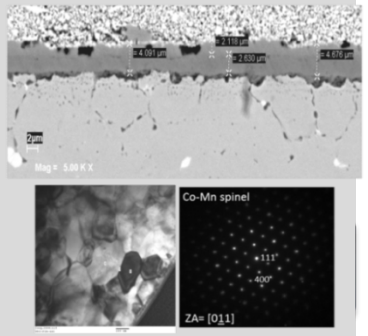
- Interconnect (IC) cutting & forming

- Stack assembly

Co-coated IC

MCO Coated Interconnect

- In-situ MCO Formed during Stack Operation



Chromium Getter Materials

Cr Getter Material Development

Cell Design and Development with Cr Getters

Single Cell and Stack Testing Validation

Optimizing Cr Getter Design

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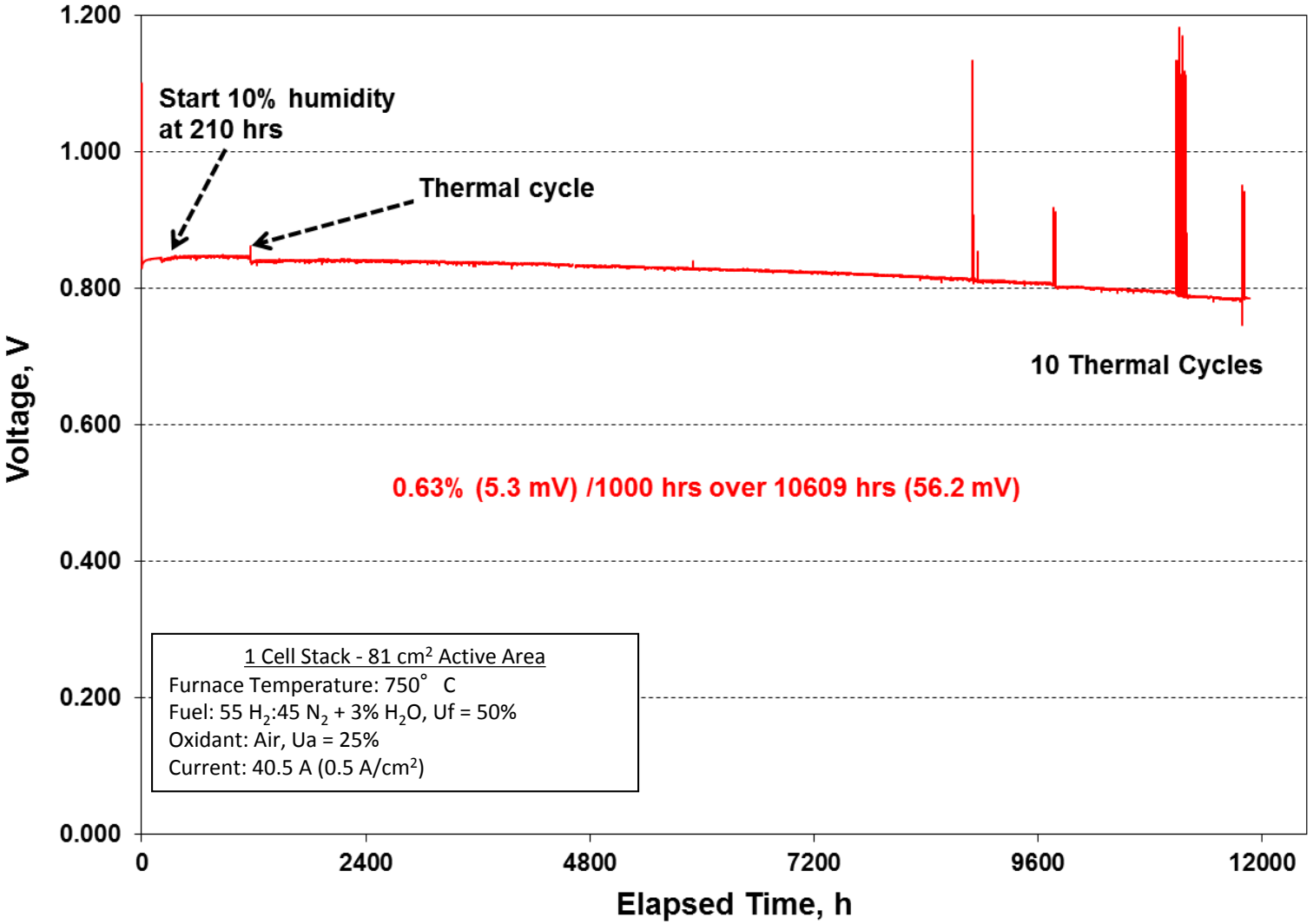
Single Cell Test of Gen 1.0 Cr Tolerant Technology



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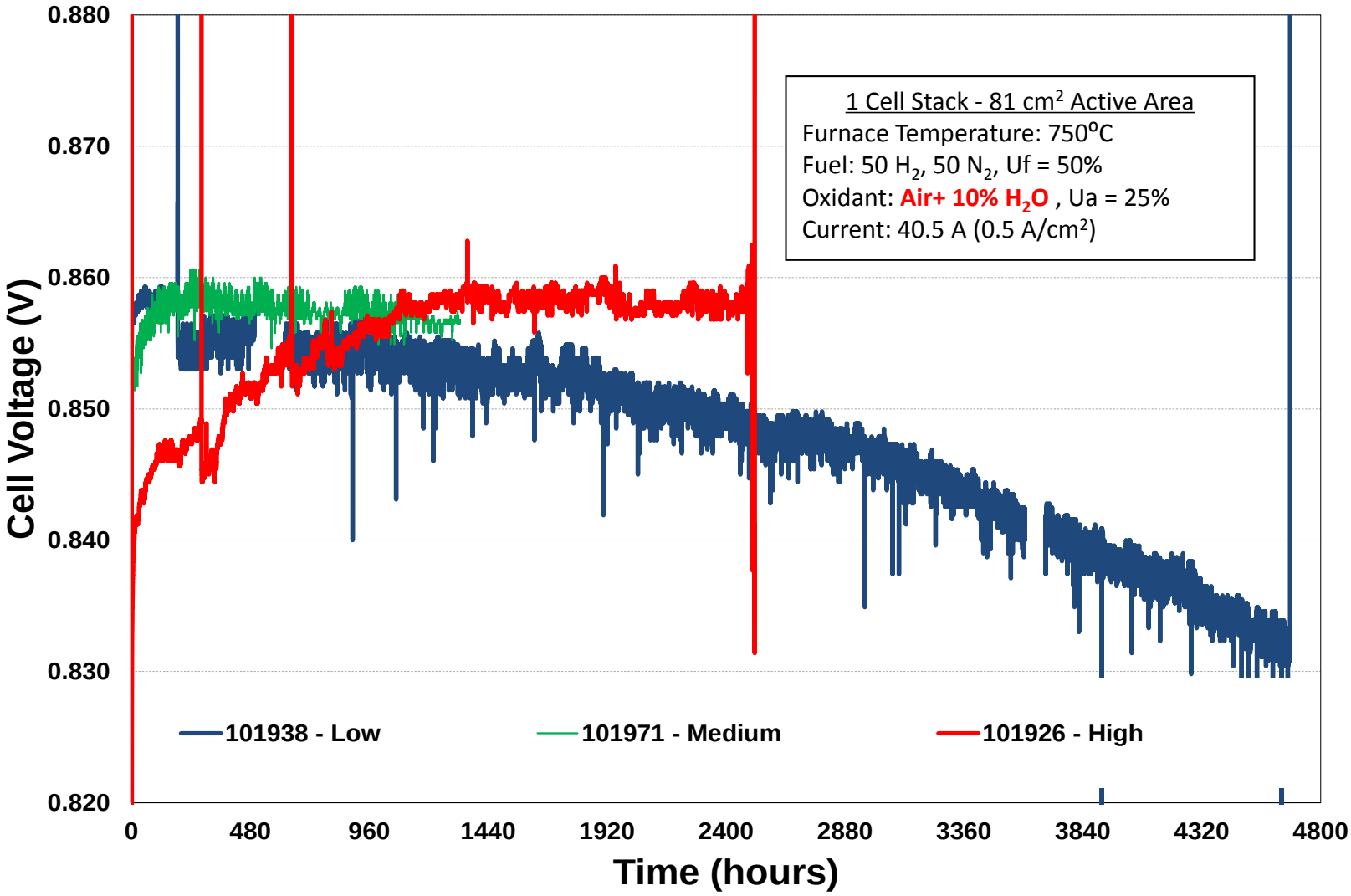
Optimization of Gen2 Cr Mitigation Technology



- **Higher Cr getter loading leads to 2% lower initial performance, but better tolerance to Cr poisoning**

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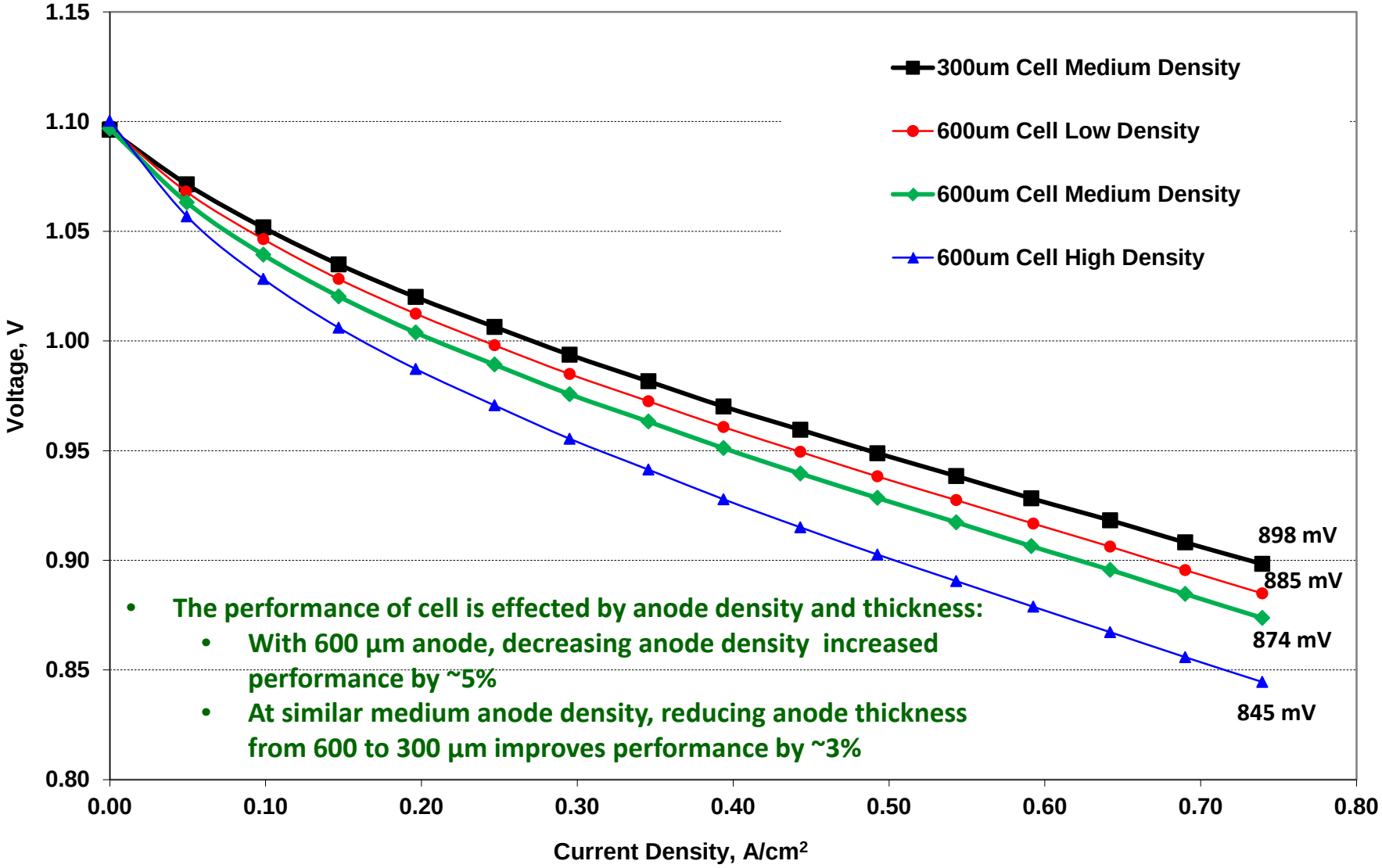
Effect of Anode Support Thickness and Density



- The performance of cell is effected by anode density and thickness:
  - With 600 µm anode, decreasing anode density increased performance by ~5%
  - At similar medium anode density, reducing anode thickness from 600 to 300 µm improves performance by ~3%

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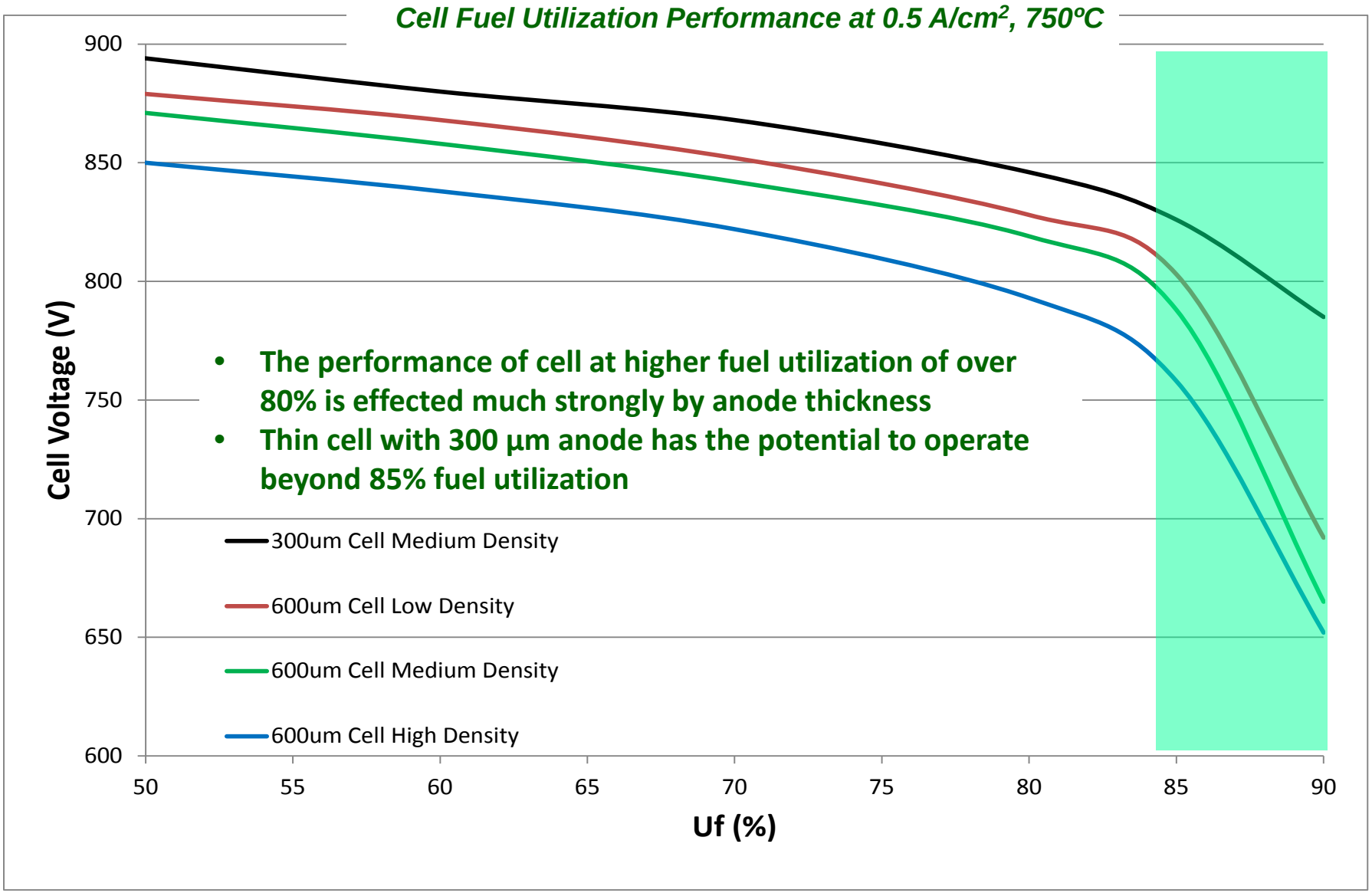
Effect of Anode Thickness and Density on Fuel Utilization



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Stack Development Path

6-cell short stack

16-cell short stack

Scale Up

- Scaled up cell active area from 121 to 550 cm^2
- Scaled up from 28 cells up to 120 cells
- Stack power from 1 kW to 16 kW

Performance Improvement

- Higher power density
- Higher fuel utilization
- Higher direct internal reforming

Cost Reduction

- Simplified stack design/part reduction

Endurance Enhancement

- Improved stack thermal and flow management
- Incorporated new cell materials
- Incorporated advanced flow media

64-cell stack block

92-cell stack block

96-cell stack block

120-cell stack block

Baseline Stack Building Block

Operating Conditions	
Fuel Utilization	68%
Air Utilization	15 – 40%
In-Stack Reforming	25 – 70%
Stack Current	160 A (291 mA/cm^2)
Gross DC Electrical Power	~16 kW

Cell Size	25 x 25 cm^2
Active Area	550 cm^2
Number of Cells	120

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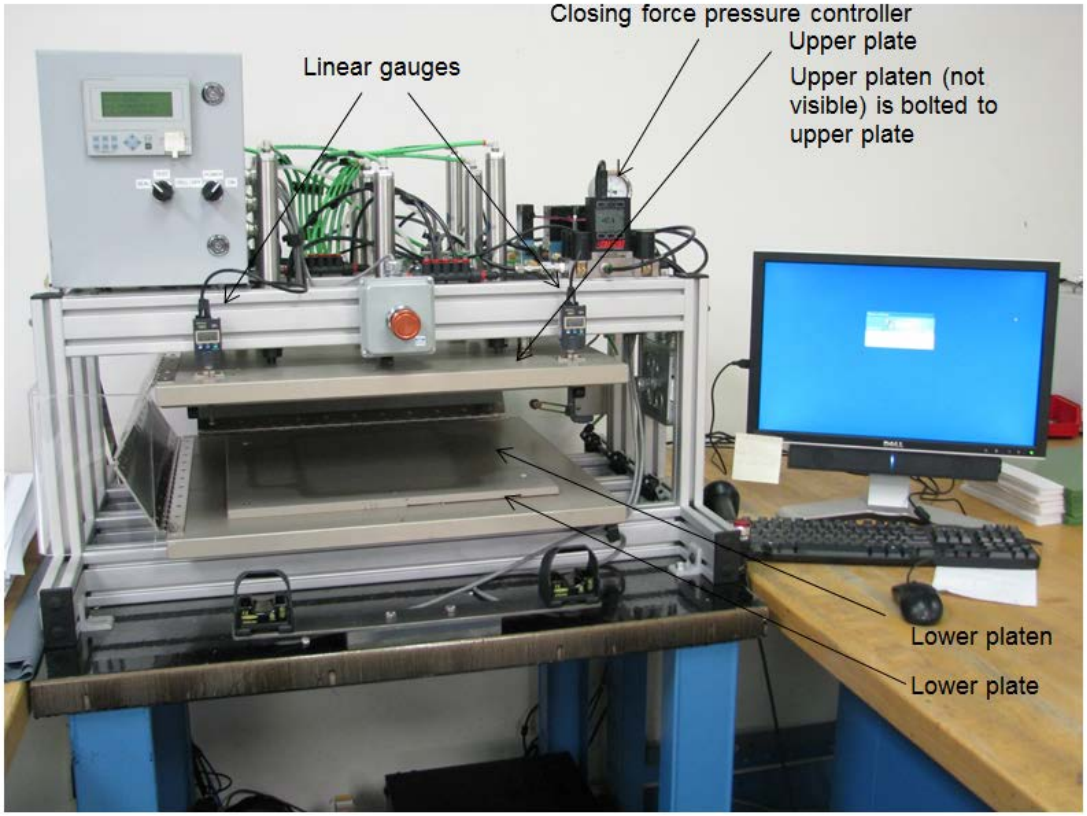
Stack Manufacturing QC: Thickness Measurement



- Completed design, procurement and assembly of 2 new double-hinge QC stations
- Purpose: measure thickness for:
  1. Anode Tape and Seals
  2. Stack Metallics
- Qualification Results: Total Gage R&R <20% for all components implemented thus far as compared to 80% with prior measurement system
- Tools have been released to production and are being evaluated for thicknesses measurement for other repeat components and assemblies

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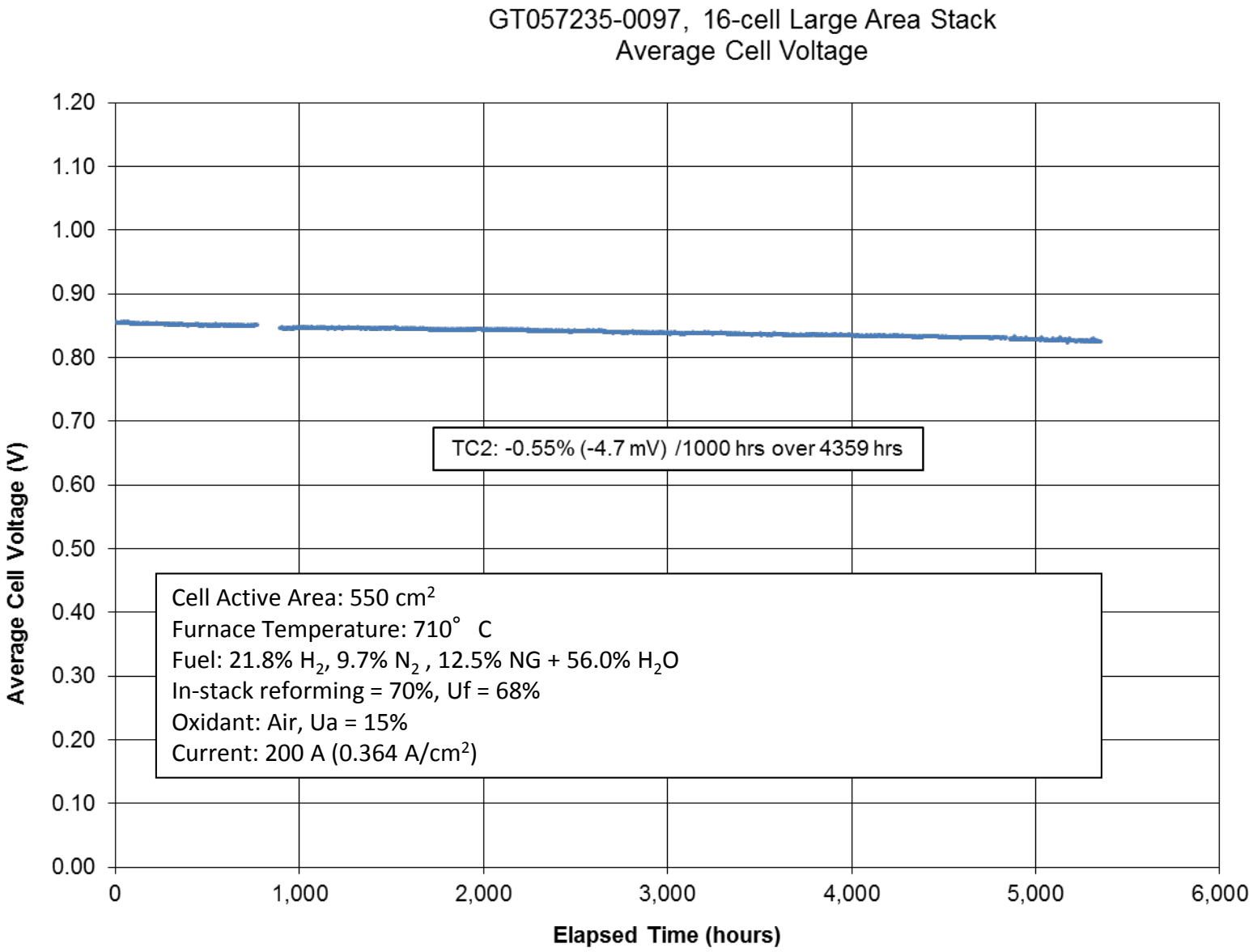
Stack #97 with Improved Reliability



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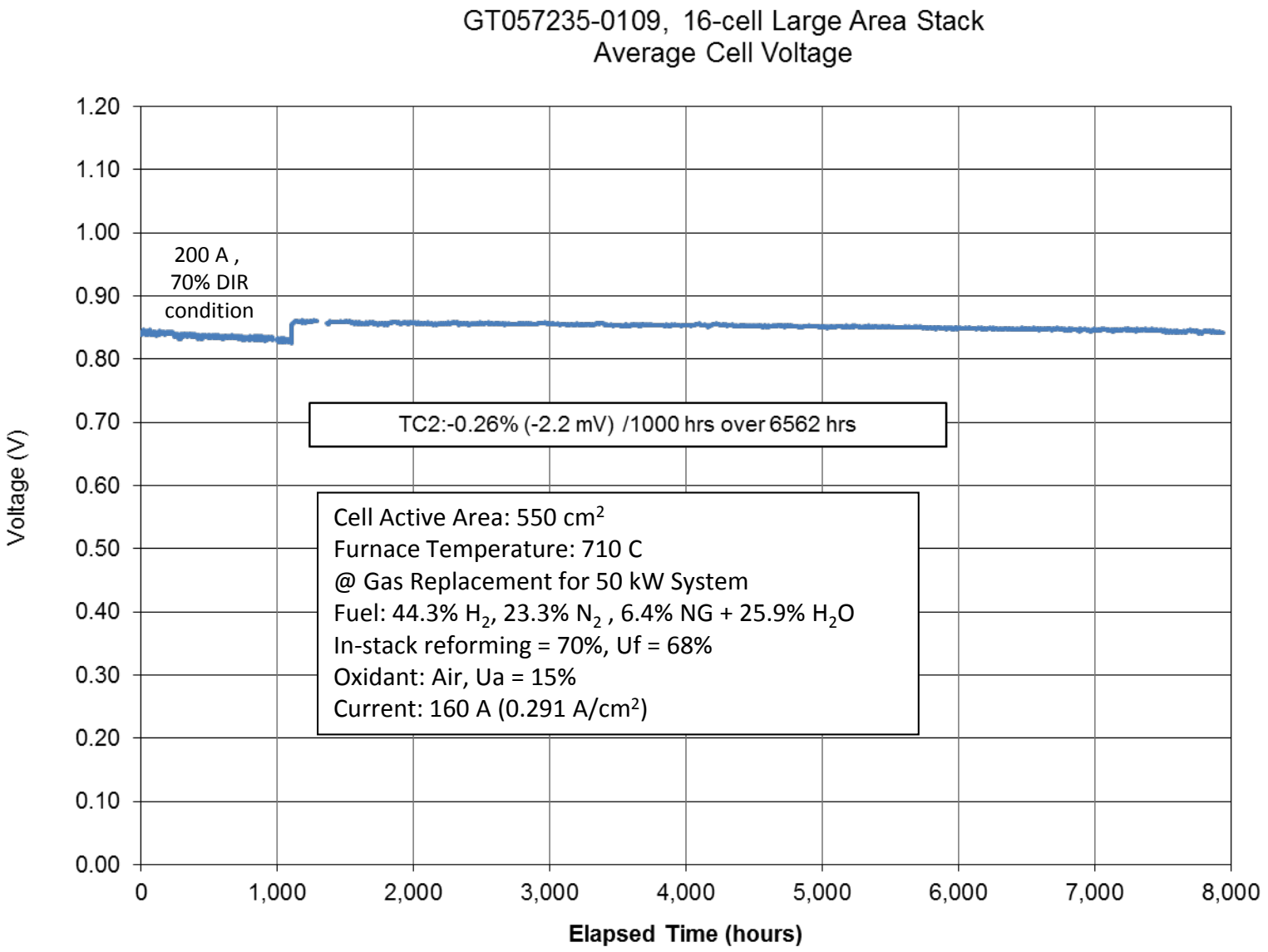
Stack #109 with Improved Reliability & Gen 1.0 Cr Tolerant Cell



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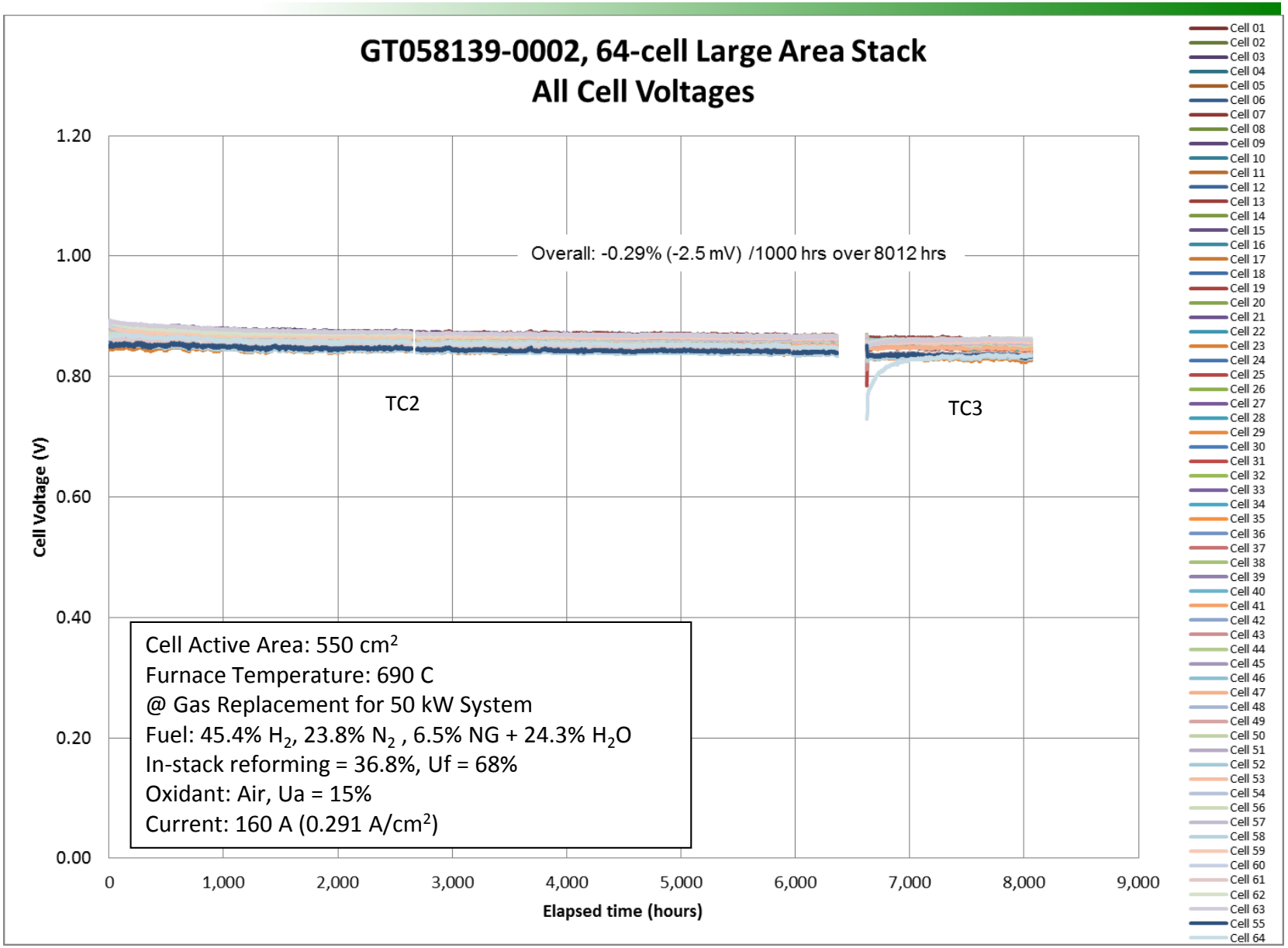
Tall Stack with Improved Reliability & Gen 1.0 Cr Tolerant Cell



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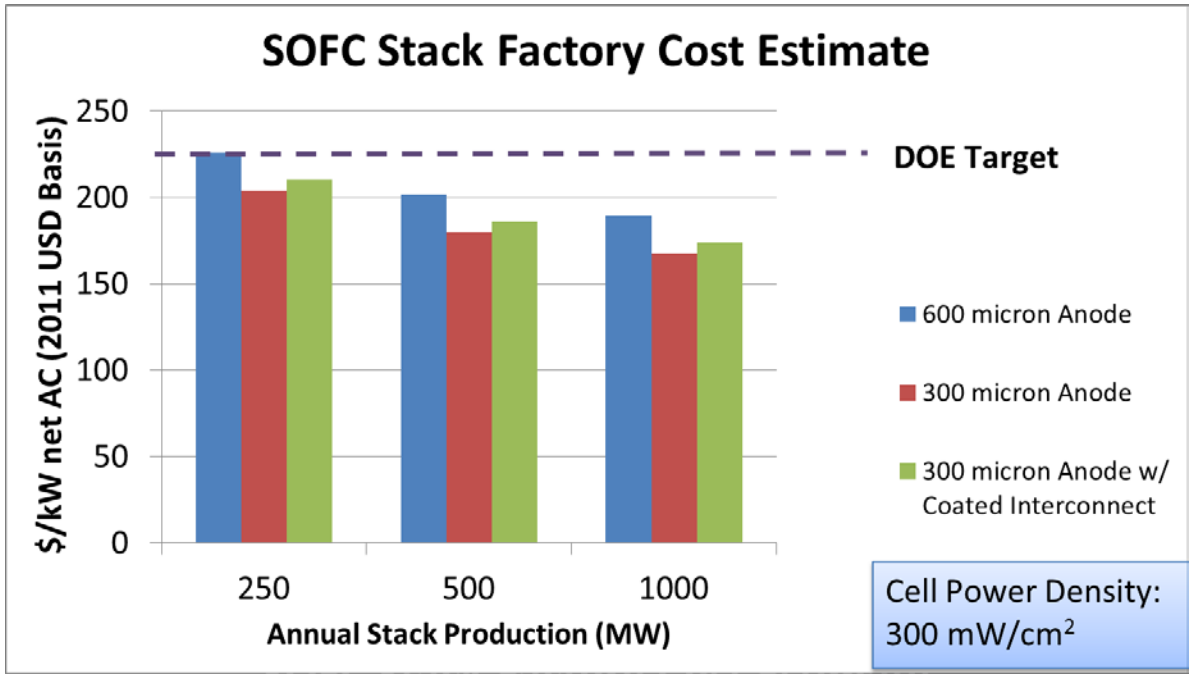
SOFC Stack Cost Update



Cost Reduction Focus Areas

1. **Stack Performance Increase**
   - Power Density increase
   - Improved thermal management
2. **Material Reduction:**
   - Thinner cells and stack components
   - Interconnect material reduction
   - Eliminated intermediate plates
3. **Manufacturing Process Changes & Optimization**
   - Interconnect manufacturing development
   - Improved material utilization
   - Automation

Future R&D activities are focused on manufacturing cost reduction, production yield increase, and lowering cell and stack materials cost

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Tested Stacks Prior to Module Integration

Recently, four 120-cell stacks were built and conditioned to be utilized in a 50 kW Proof-of-Concept System Tests

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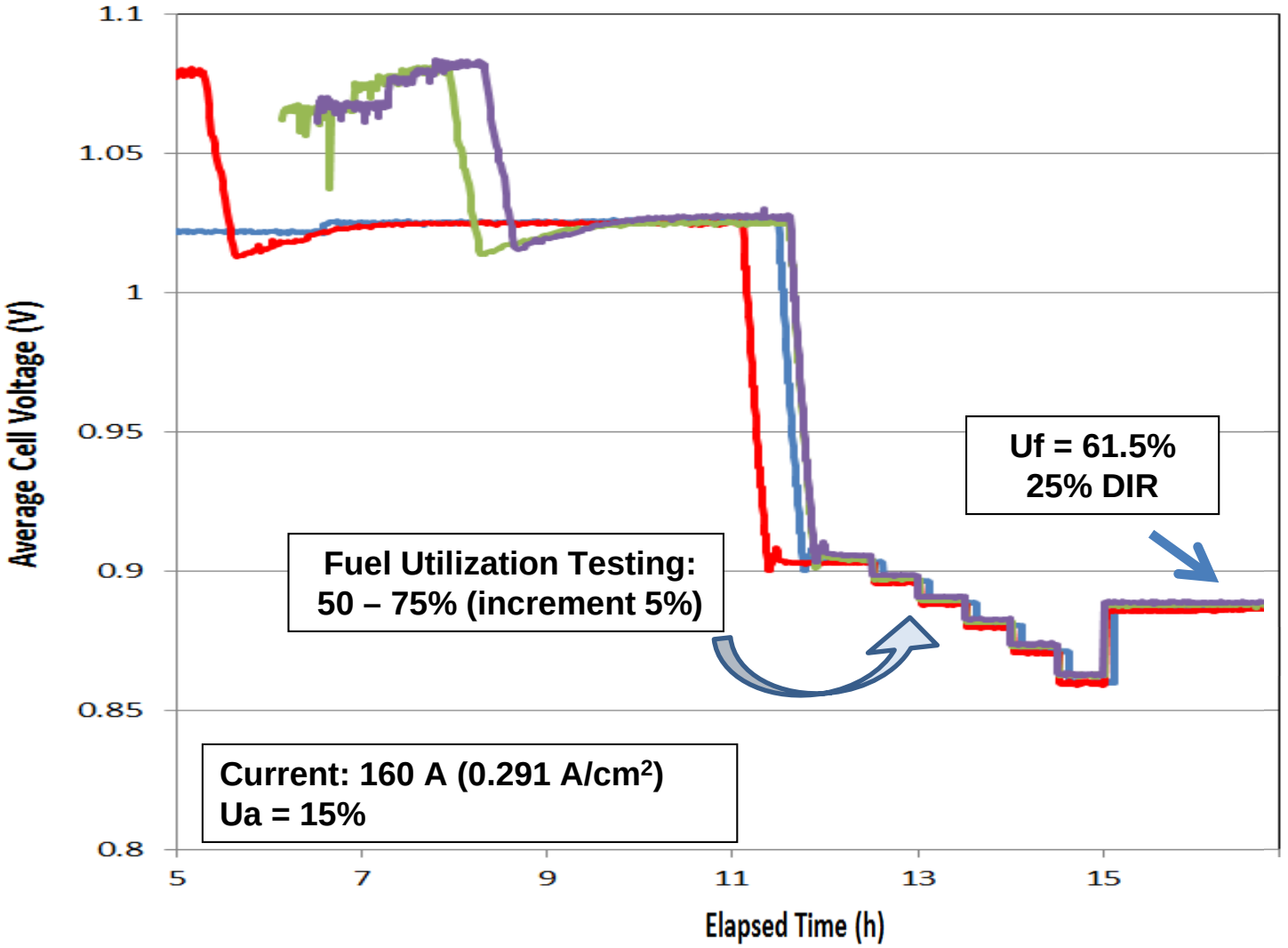
Reproducibility of Four Stacks
TC1 Utilization Testing



All four stacks showed similar performance during the Factory Acceptance Tests

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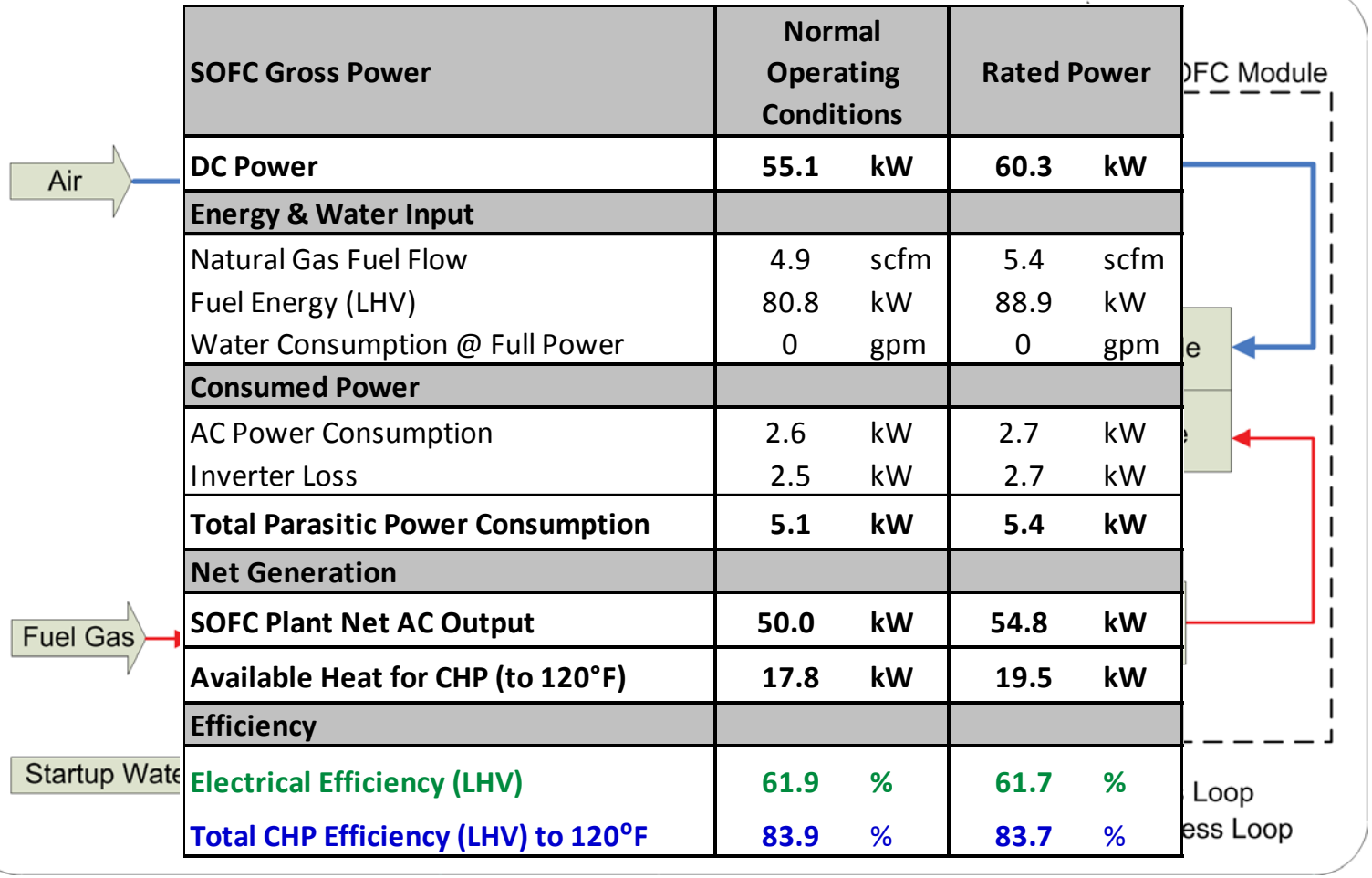
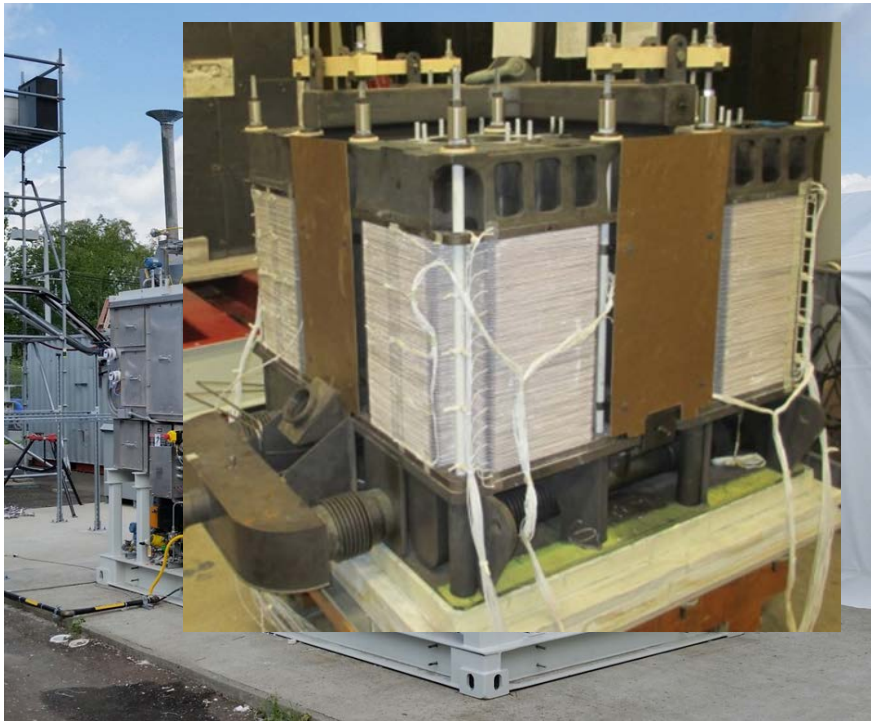
50 kW PCM System Design & Performance

SOFC Gross Power	Normal Operating Conditions		Rated Power	
DC Power	**55.1**	**kW**	**60.3**	**kW**
Energy & Water Input				
Natural Gas Fuel Flow	4.9	scfm	5.4	scfm
Fuel Energy (LHV)	80.8	kW	88.9	kW
Water Consumption @ Full Power	0	gpm	0	gpm
Consumed Power				
AC Power Consumption	2.6	kW	2.7	kW
Inverter Loss	2.5	kW	2.7	kW
Total Parasitic Power Consumption	**5.1**	**kW**	**5.4**	**kW**
Net Generation				
SOFC Plant Net AC Output	**50.0**	**kW**	**54.8**	**kW**
Available Heat for CHP (to 120°F)	**17.8**	**kW**	**19.5**	**kW**
Efficiency				
Electrical Efficiency (LHV)	**61.9**	**%**	**61.7**	**%**
Total CHP Efficiency (LHV) to 120°F	**83.9**	**%**	**83.7**	**%**



- **50kW PCM system is designed to enable stack reliability testing under real-system conditions (Q1-2015).**

50kW PCM System



- Factory assembled stack module using four baseline 120 cell stacks
- System fabricated as a single 14.5’ L x 7’ W x 10’ H skid
- Field installable enclosure

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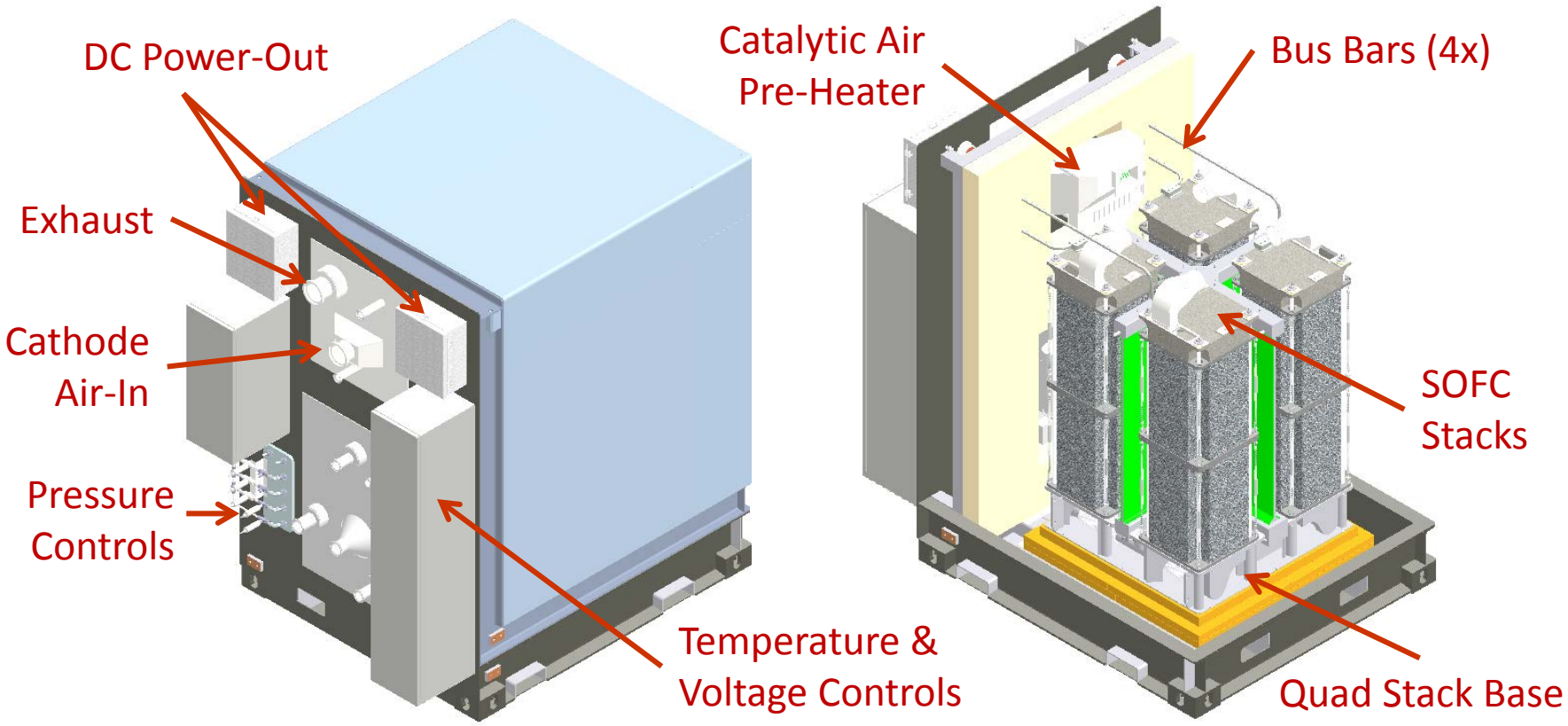
100kW SOFC Modular Power Block (MPB)



100kW MPB architecture:

- Fully integrated hot BOP equipment within the module
- Integrated module-specific instruments significantly decrease wiring
- Reduced Cr evaporation protective coatings by >80%

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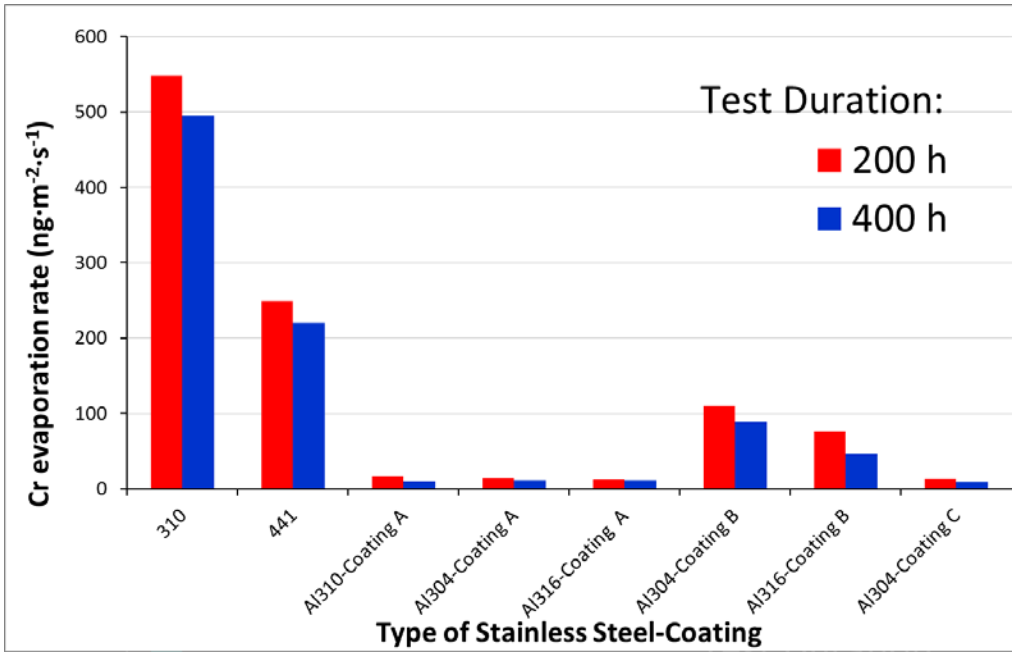
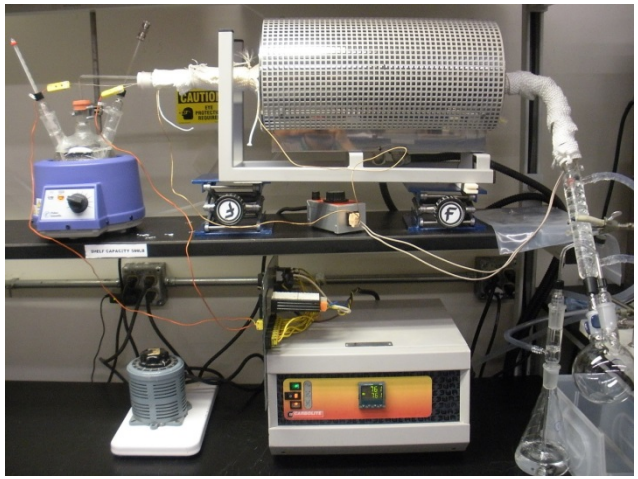
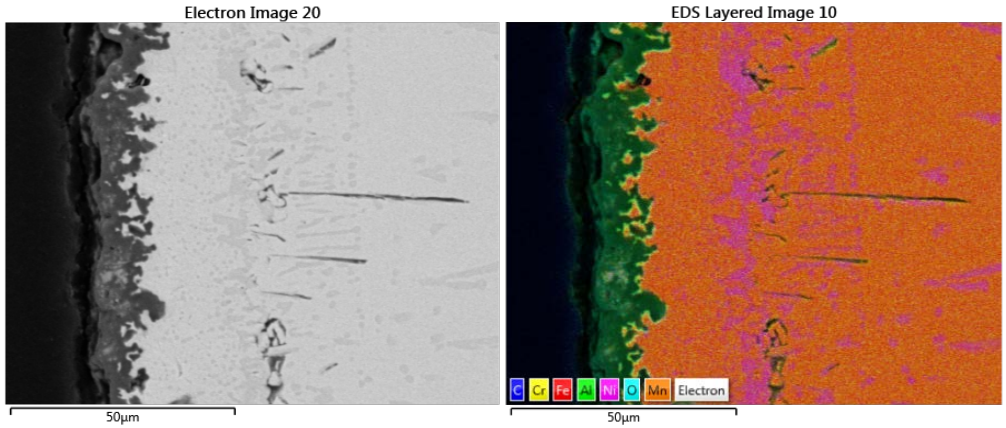
BOP Materials Development: Chromia Volatility Tests





Test Setup



Back-scattered Electron Image (left) and Elemental Map (right) of Coated (A Type) 316 Alloy

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Next Generation SubMW Class Power Plant

- System is designed with the capability to achieve 200 kW net ac
- It houses (2) 100kW SOFC Module Power Blocks (MPB)
- Skid sized as standard ISO 20’ x 8’ shipping container
- Thermally integrated modules enable compact system design
- 2.5X higher power density than 50kW Plant:
  - 50kW = 2.23 ft^2/kW
  - 200kW = 0.88 ft^2/kW
- Stack Module and BOP factory assembled & shipped as a single skid
- First demonstration at 100 kW with a single module

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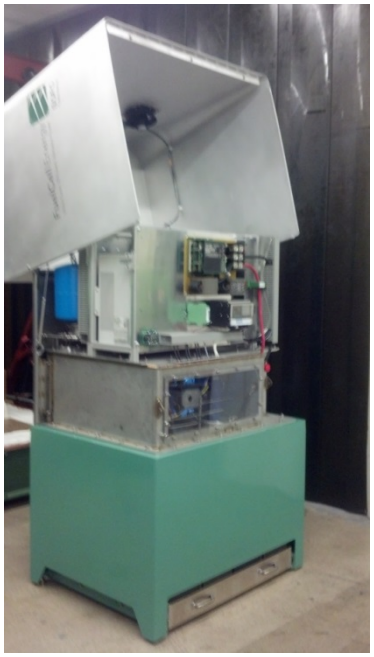
3 KW SOFC System

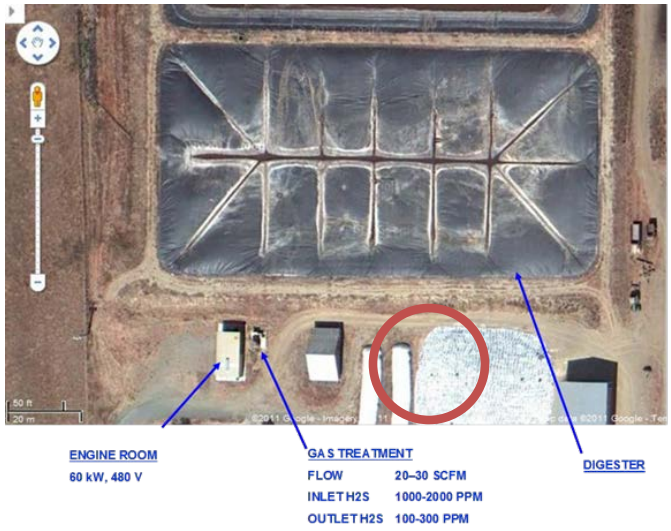


- SOFC Application Using Renewable Fuel
- Highly Compact
- Fuel Flexible and Water Neutral
- Unattended Operation with Remote Monitoring
- Grid Connected and Islanding Modes

System Characteristics

Dimensions, ft (lxwxh)	3.5x3x5
Fuel Type	Natural Gas, ADG
ADG Fuel Flow, scfm	0.56
Air flow, scfm	11
Efficiency, % (LHV)	58.4
Net Power Output, kW	3.2

Demonstration Site: Cal-Denier Dairy Farm



Project Partners

TDA Research

SMUD
SACRAMENTO MUNICIPAL UTILITY DISTRICT
The Power To Do More.℠

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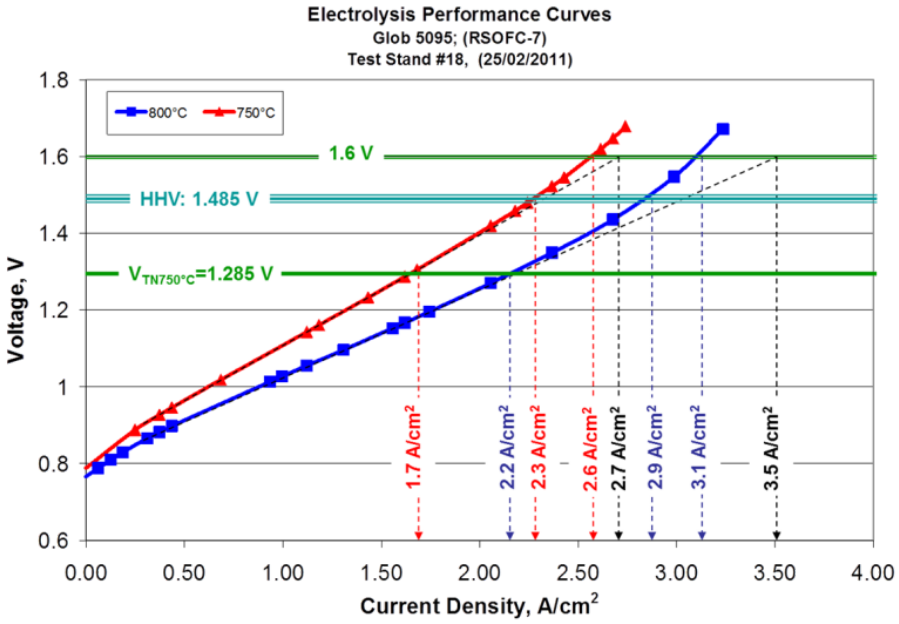
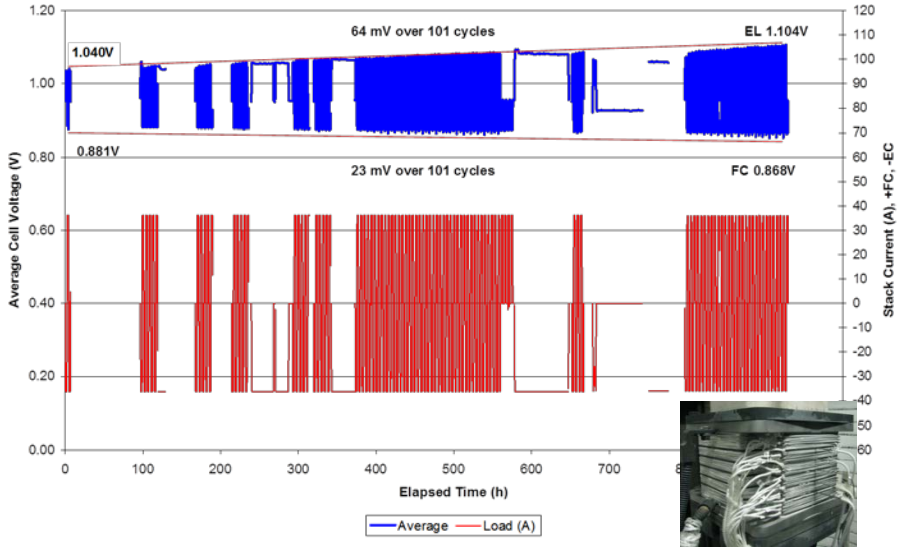
Solid Oxide Electrolysis Cell (SOEC) Development

- FCE/VPS was awarded a new contract DOE-EERE for development of SOE Stack Technology with Ultra-High Electrolysis Current Density and Efficiency
- Objective is to exceed DOE 2020 water electrolysis stack efficiency target of 78% via an ultra-high electrolysis current density of more than 3 A/cm^2 at an upper limit voltage of ~1.6 V
- Demonstrated cell operation with >6,000 accelerated cycles (equivalent to >15 years of daily cycling) with < 0.03 mV/cycle



Cell Performance at Ultra-High Current Density



kW-Class Stack Cyclic Test

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Achievements

- Developed Gen 1.0 Cr-mitigation strategies (interconnect coatings and Cr-tolerant materials) and validated the optimized materials sets over 10,000 hours of single-cell tests with 10% H_2O in cathode air
- Accumulated stack build and testing experience by manufacturing over 750 stacks including >130 of the stacks based on large area (625 cm2) cells
- Improved cell / stack manufacturing and enhanced Quality Control procedures to increase stack reliability and endurance. A 64-cell large area stack is validated at system operating conditions in test stand for 1 year
- Fabricated and factory tested 4 x 120 cell Large Area Stacks (LAS) for the 50 kW Proof-of-Concept (POC) System
- Fabricated a highly integrated 50kW module design for testing of large-area full height stacks in system environment
- Initiated the design of a 200 kW SOFC system for demonstration testing of the next generation SOFC stack towers

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Acknowledgements

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