FuelCell Energy

Advances in SOFC Development at FuelCell Energy:

SOFC Systems with Improved Reliability and Endurance

15th Annual SECA Workshop
Pittsburgh, PA
July 22-23, 2014

Hossein Ghezel-Ayagh

Ultra-Clean, Efficient, Reliable Power

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Presentation Outline

- **Introduction**
  - FCE Background
  - 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**

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FuelCell Energy Operations

Danbury – Corporate, Engineering and R&D

- Research Labs
- Design Center
- Operations and Service Support
- Product Conditioning

Torrington - Technology Manufacturing

- MCFC Stack Production
- Module Assembly
- 65,000 ft^2 facility / Opened in 2001

Global Technology and Manufacturing footprint

CO, USA/Calgary, Canada
SOFC Research

Ottobrun, Germany
Capacity for European market

Pohang, South Korea
Capacity being built for Asian market

World's Largest Fuel Cell Park

"The scale of this installation is contributing to the power and heating needs of an urban population and generating the electricity in a ***highly efficient and ultra-low emission*** *profile that supports our National renewable portfolio standard,"*
Tae-Ho Lee
Chief Executive Officer
Gyeonggi Green Energy

- **Scalable consisting of 21 DFC3000® power plants**
  - Only ~ 5.2 acres for 59 MW
- **Supplying electric grid and district heating system**
- **Constructed in only 14 months**
- **Adequate to power ~ 140,000 S. Korean homes**

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Utility Application

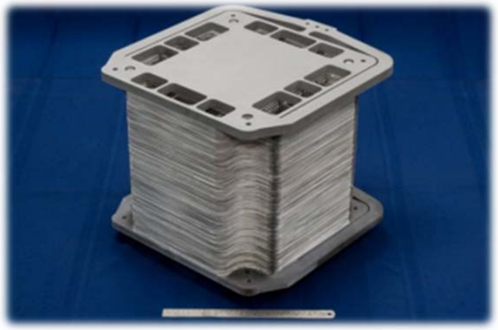
Type:	***14.9 MW fuel cell park***
Owner:	***Utility owned***
DOC:	***Dec-2013***

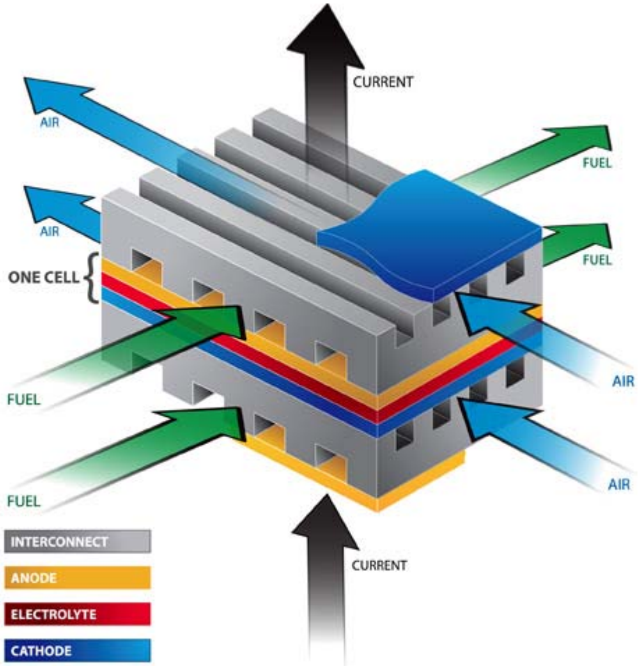
- **Baseload power**
- **Power sold to grid**
- **Enhances grid resiliency**
- **Easy to site**
  - 14.9 MW on only 1.5 acres
  - Clean, quiet & vibration free
  - Urban brownfield now a revenue generator

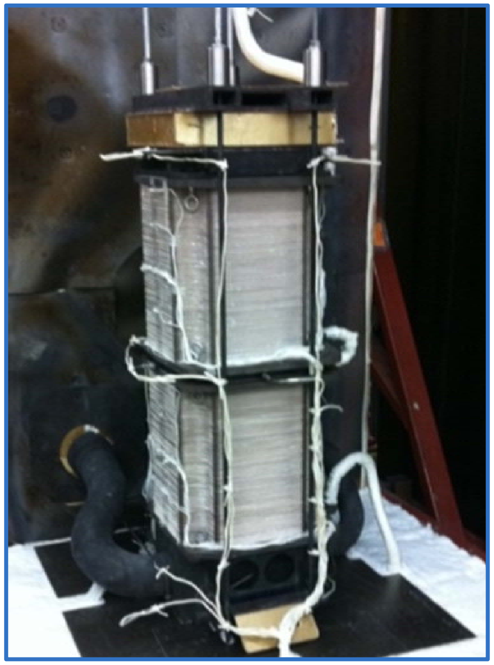
*"The Dominion Bridgeport Fuel Cell Park is another important step in our efforts to identify and develop opportunities to produce clean energy that is **reliable and cost effective**"*
Thomas F. Farrell II, Chairman
President and CEO
Dominion

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







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FCE/VPS SOFC Development Facilities

- Pilot Manufacturing & 36 Test Stations in Calgary
  - 10 - 121cm^2 stack
  - 4 - 550 cm^2 stack (to 3 kW)
  - 3 – 550 cm^2 stack (to 25 kW)
  - 4 – DARPA stack
  - 15 – single cell
- DARPA Stack/System Testing in Denver
- Laboratory and Bench Scale Fabrication and Testing in Danbury
  - 2 to 400kW test facilities

CALGARY, CANADA

DENVER, CO

DANBURY, CT

DE-FE0011691
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 a 50 kW Proof-of-Concept (PCM) system 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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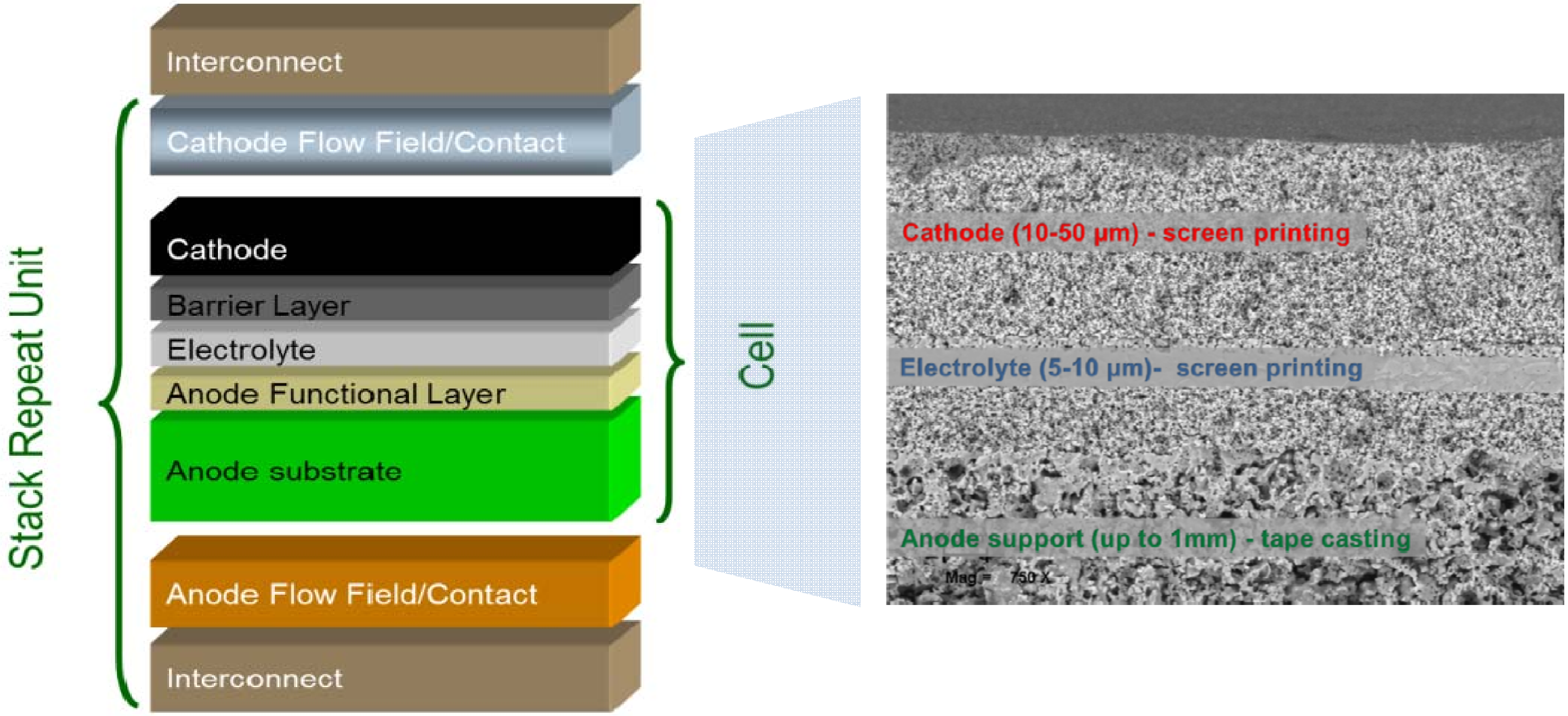
Cell Technology Overview



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

Scale Up & Manufacturing Development

- 121 cm^2 → 550cm^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

Cathode Development

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

Anode Development

- Reduce Cell Thickness (1mm → 0.6 mm)
- Enhance Performance at Higher Fuel Utilization
- Improve Performance at Lower Temperature
- Enhance Cell Mechanical Properties and Robustness

Cr Mitigation Strategies

- Cr tolerant cathode materials development
- Coating on metallic components to reduce Cr concentration
- High temperature Cr getters development

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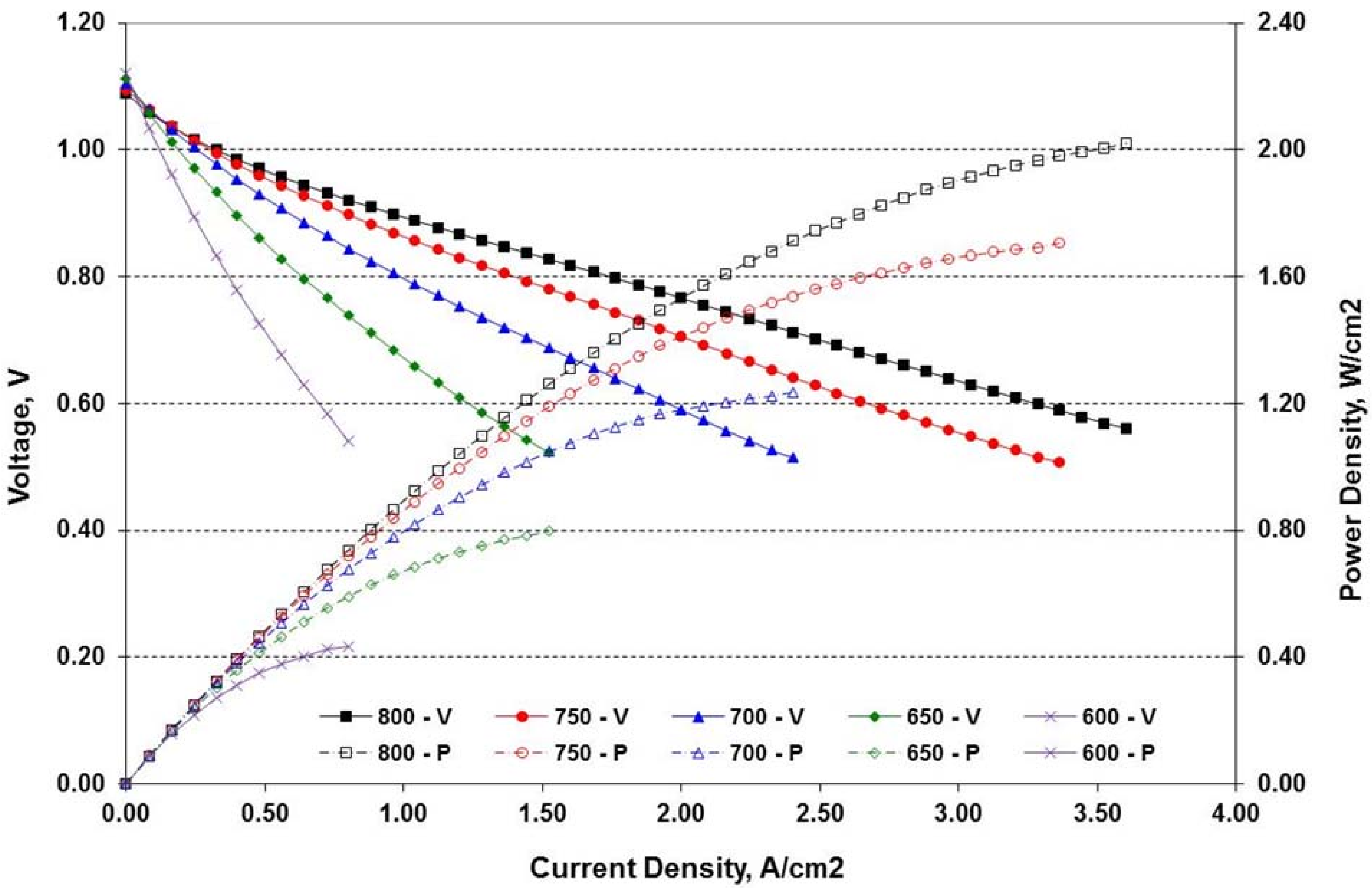
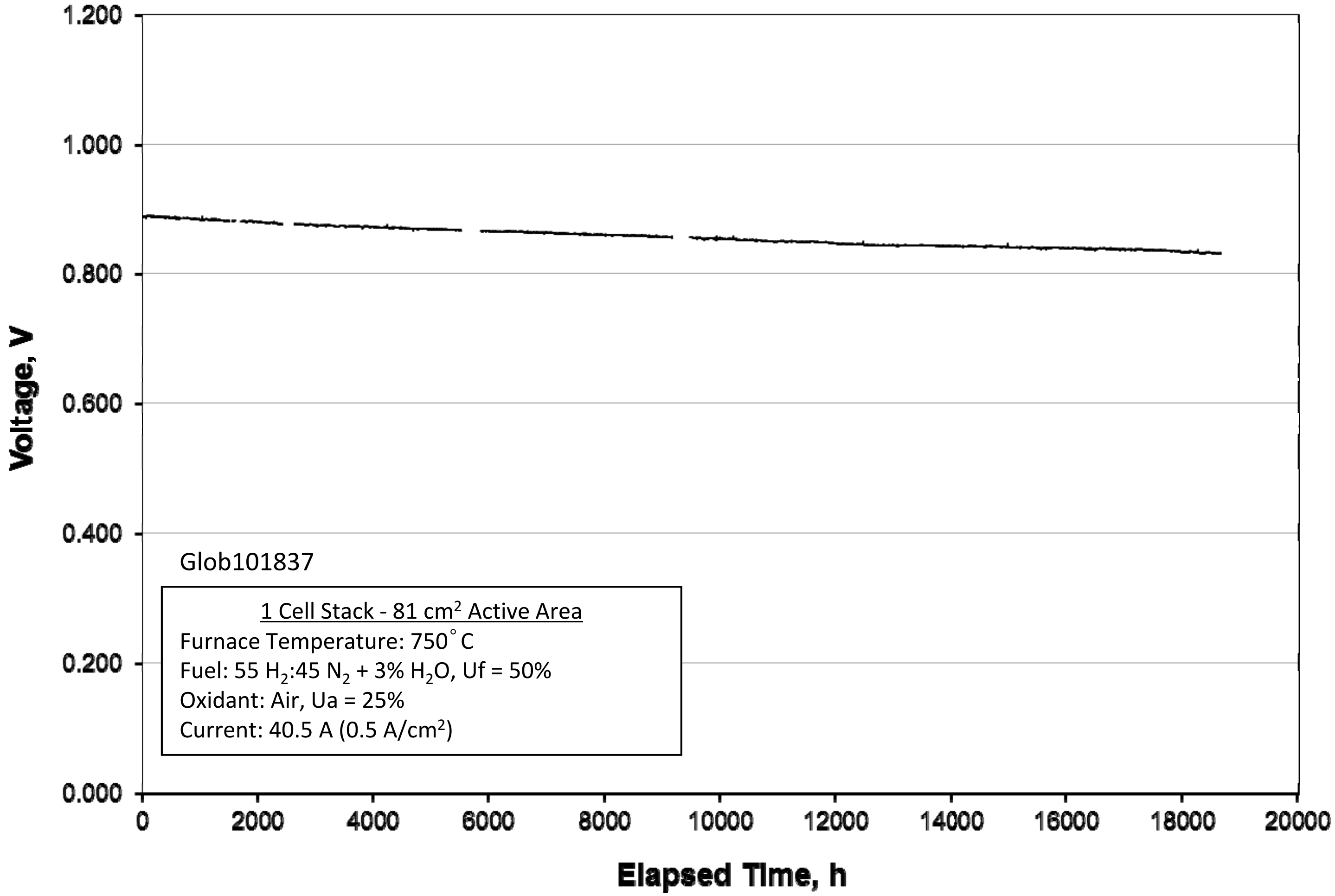
Recent Cell Performance Achievements



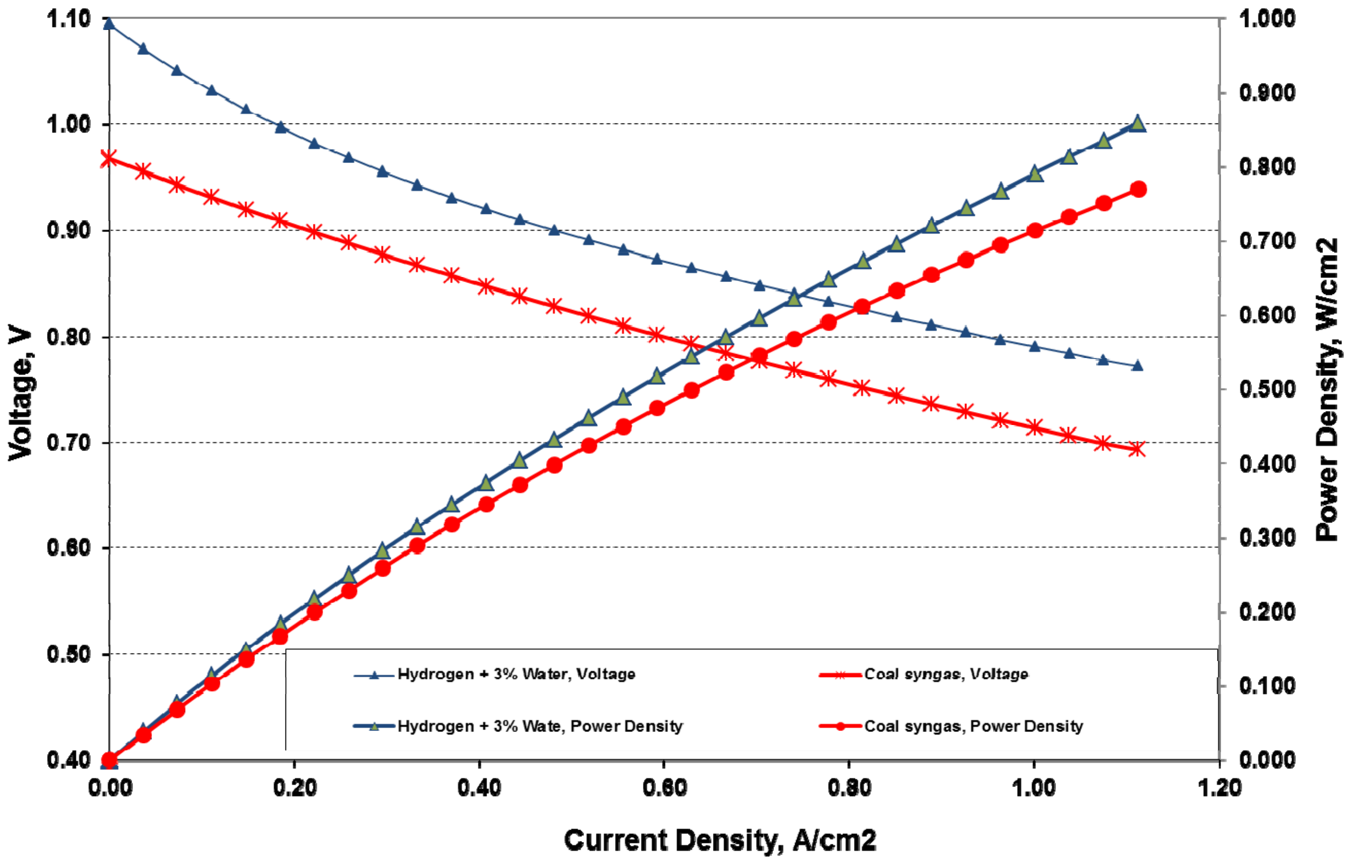
- Cell technology has excellent performance in a wide temperature window, achieving 2W/cm^2 at 800ºC

TSC3 Long-term Performance



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

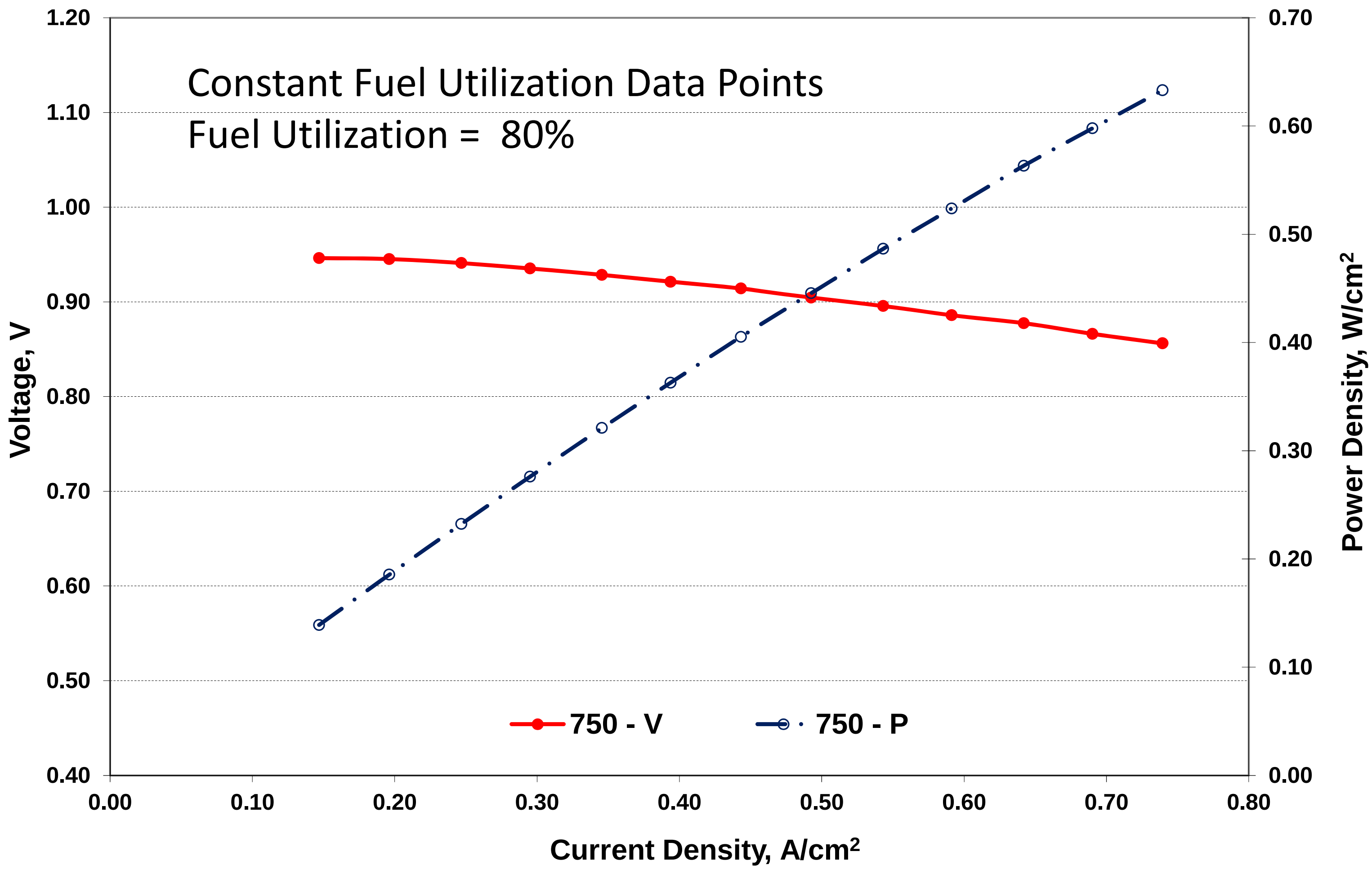
TSC3 Performance under Syngas



Coal Syngas Components	Molar Ratio (%)
Hydrogen	11.37
Methane	8.99
Carbon Monoxide	11.18
Carbon Dioxide	26.48
Water	40.35
Nitrogen (incl Ar)	1.62

➡ High output under syngas compositions were verified with minimal loss compared to pure hydrogen

TSC3 Performance at High Utilization



- High performance of TSC3 cell technology was verified at elevated utilization of 80%

Gen 1.0 Cr Tolerant Technology

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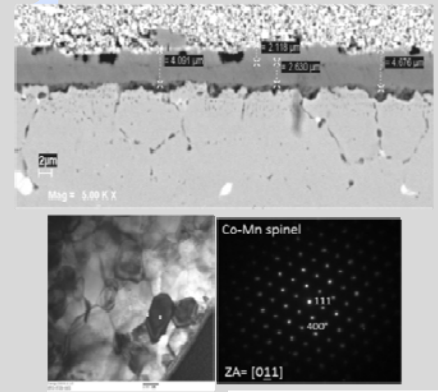
Cobalt Coated Interconnect

Sheet Metal
- PVD Cobalt coating

Co-coated Sheet Metal
- Interconnect (IC) cutting & forming

Co-coated IC
- Stack assembly

MCO Coated IC
- In-situ MCO Formed during Stack Operation



Chromium Getter Materials

Cr Getter Material Development
- Screened over 20 materials for interaction with Cr vapor
- Downselected three candidates (Ga, Gb & Gc)
- Evaluated candidate materials' compatibility, performance and stability

Cell Design and Development with Cr Getters

Modified cell design and fabrication process to incorporate Cr Getters within the cell

Single Cell and Stack Testing Validation
- Investigated Cr getters through accelerated cathode humidity tests
- Studied combined effects of Cr getters with IC coatings

Optimizing Cr Getter Design
- Analyzed Cr getters through post test analysis
- Developed blending of Cr getter materials for better microscopic and chemical stability
- Validated optimized design through cell and stack tests

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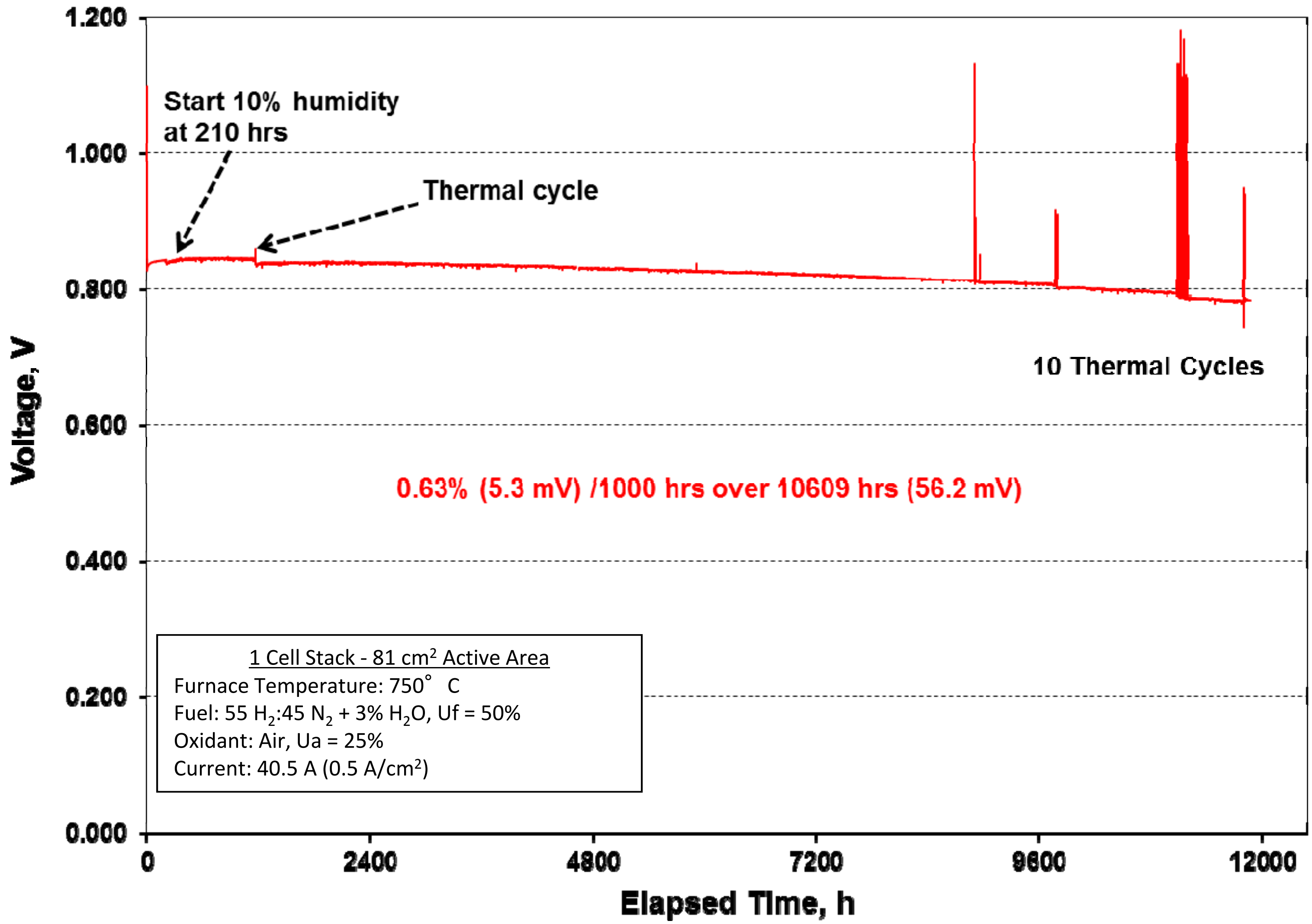
Single Cell Test of Gen 1.0 Cr Tolerant Technology



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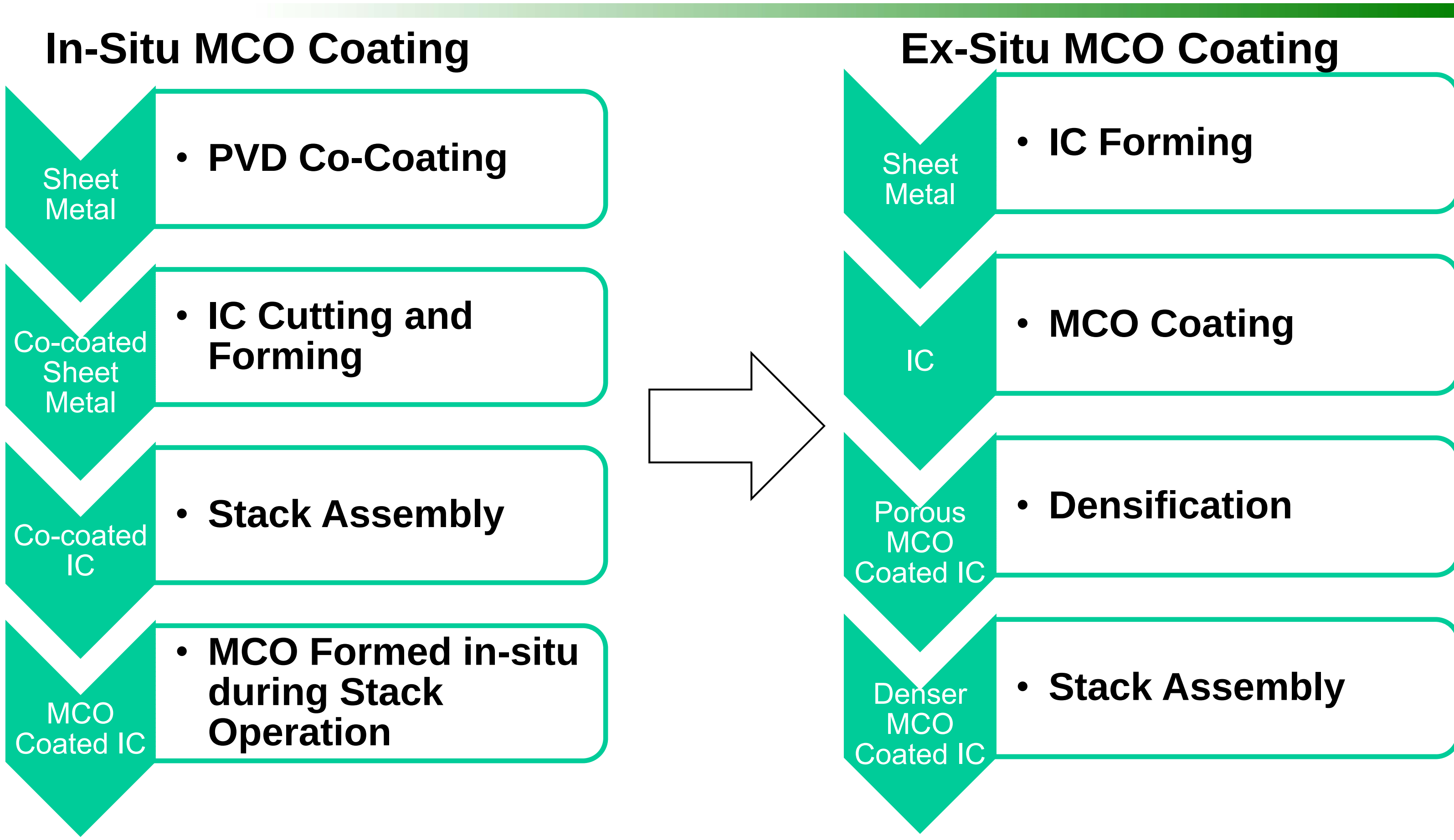
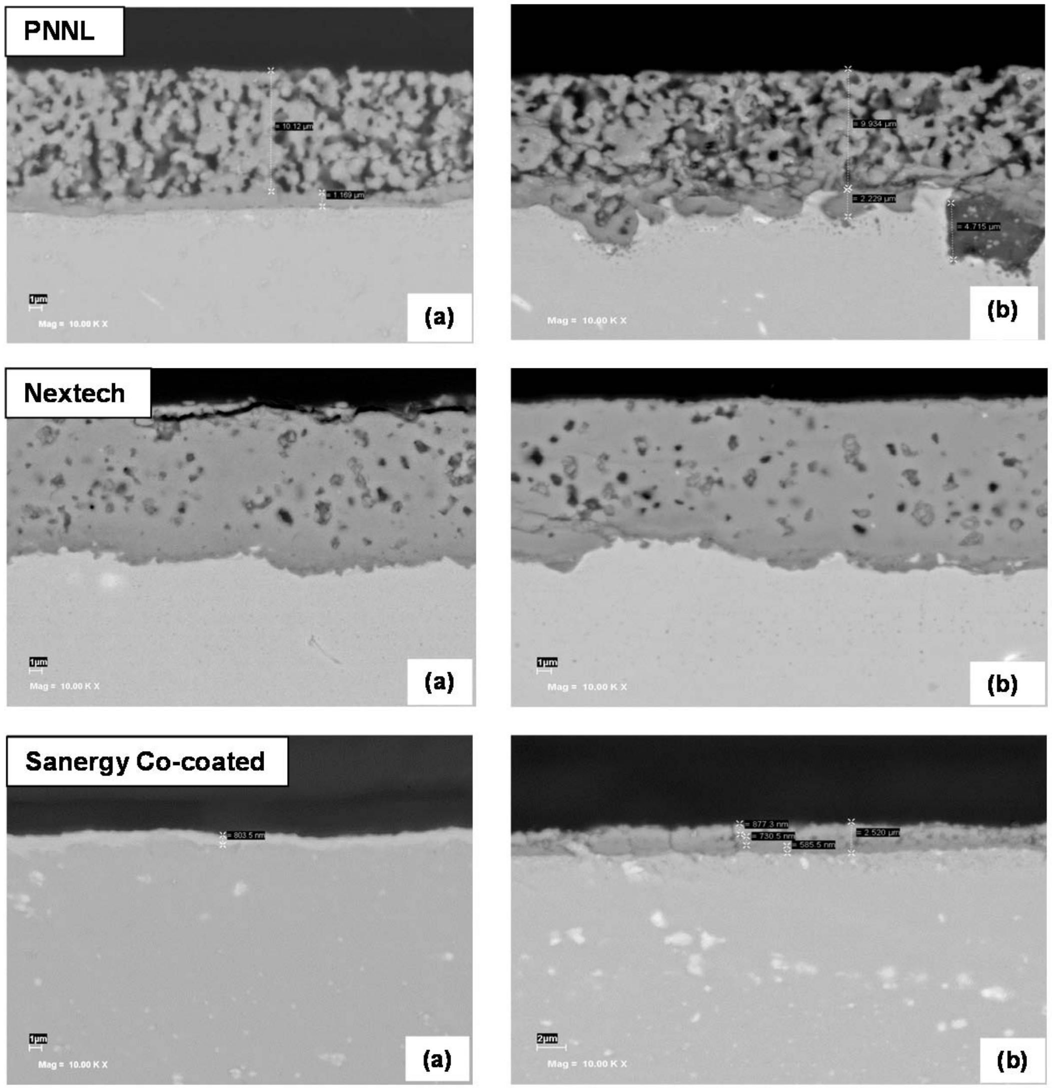
Comparison of MCO Spinel Coatings



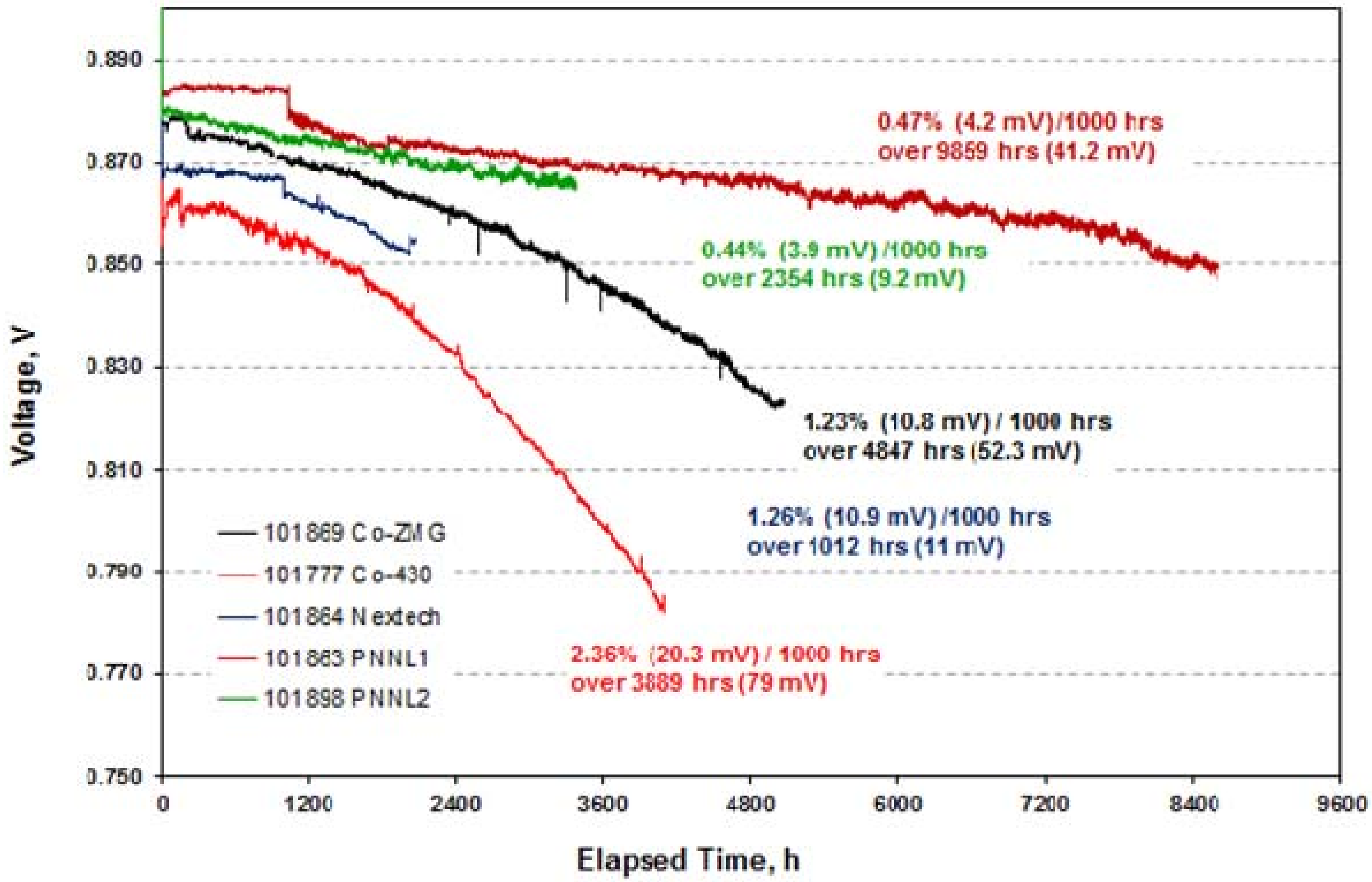
- Thick (> 10 micron) MCO deposits on pre-formed interconnect (flow media) were studied
- Ex-Situ Deposited MCO usually requires a high temperature densification process
- Both PNNL and Nextech MCO coatings were implemented on single cell test jigs

Interconnect Coating Evaluation



- MCO coated 441 with a thickness of 0.540 mm, provided by PNNL
- MCO coated Crofer with a thickness of 0.264 mm, provided by Nextech
- Cobalt coated Sanergy with a thickness of 0.150 mm, provided by Sandvik

Comparison of IC Coatings in High Humidity Air Tests (10% H_2O)



- Long-term single cell tests under very high humidity showed cells with MCO spinel coated IC have significantly lower degradation as compared to the cells with Co coated IC

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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 15 kW

Performance Improvement

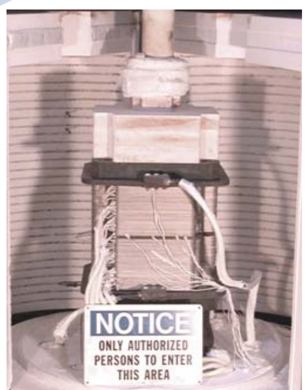
- Higher power density
- Higher fuel utilization
- Higher direct internal reforming

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

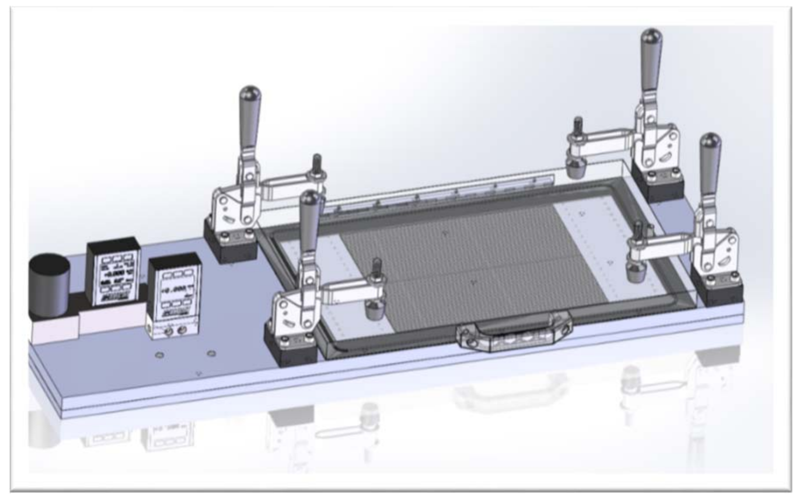

92-cell stack block


120-cell stack block


96-cell stack block

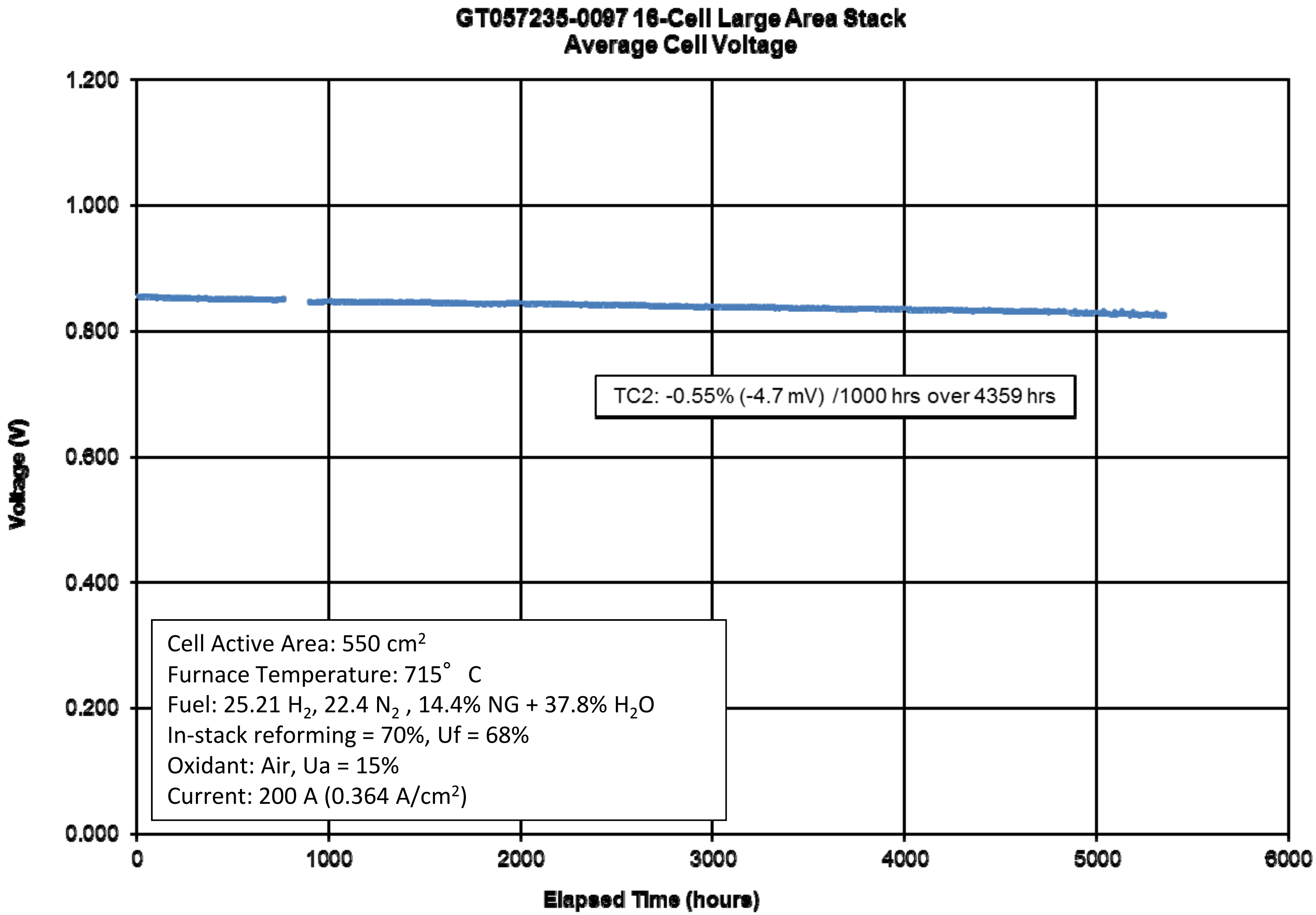
Stack Reliability Improvements

- Utilized DMAIC (Define Measure Analyze Improve Control) statistical tools, such as Gage R&R, to improve cell yield, decrease process time, and reduce defects through improved process control
- Implemented flow field quality and design improvements:
  - Reduced flow bypass along cell edges
  - Implemented detailed dimensional tracking
  - Improved flow field uniformity
  - Optimized anode flow field pressure drop
- Implemented cell contact improvements:
  - Optimized cathode contact layer thickness for large-area stacks
  - Improved cell to cell-holder dimensional fit
  - Improved flatness of anode contact layer
- Implemented Gen 1.0 Cr tolerant technology within stacks

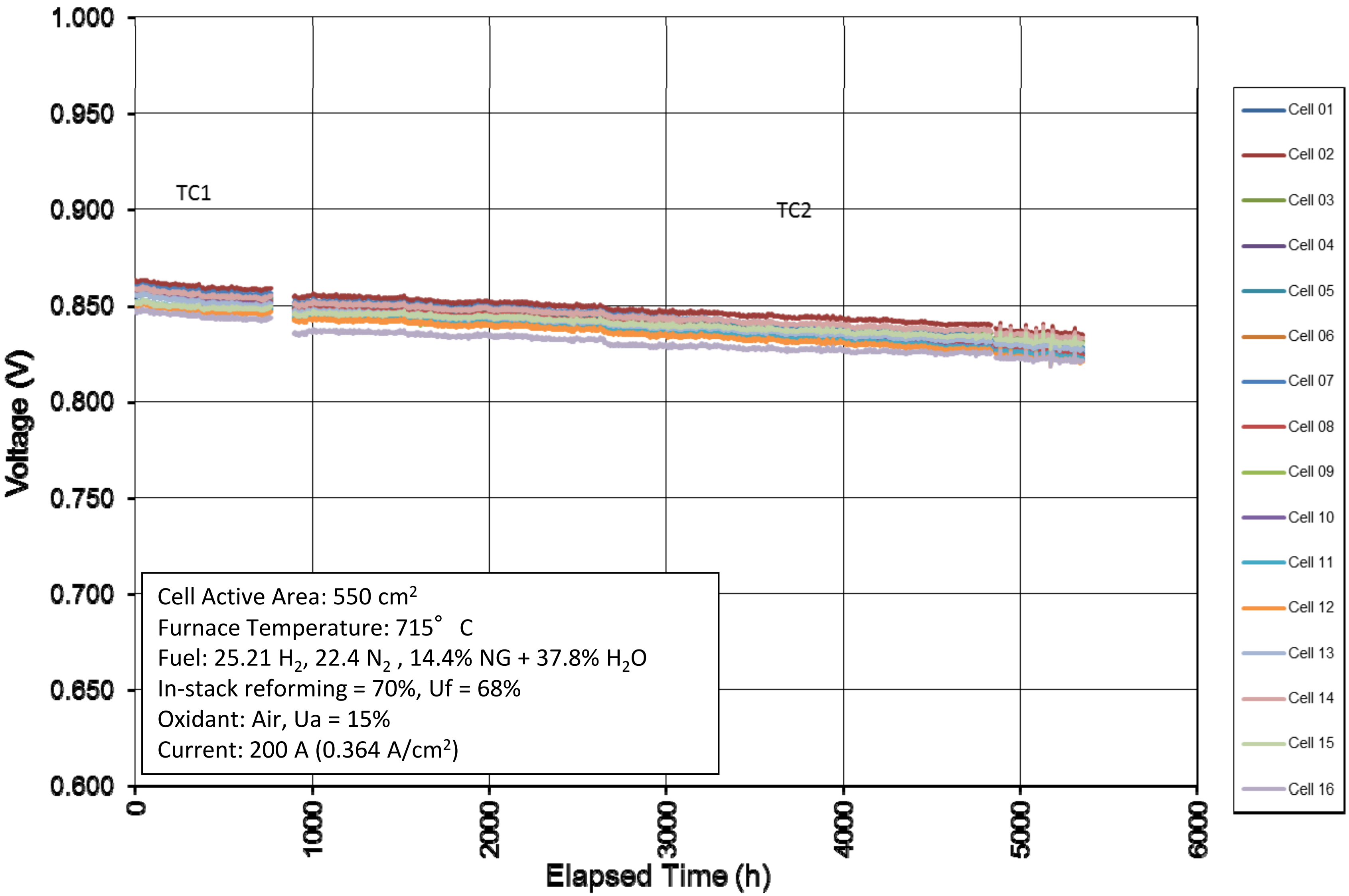


Flow Field Test Fixture to Quantify Part-to-Part Variation

Stack #97 with Improved Reliability



Cell Voltage Distribution in Stack #97



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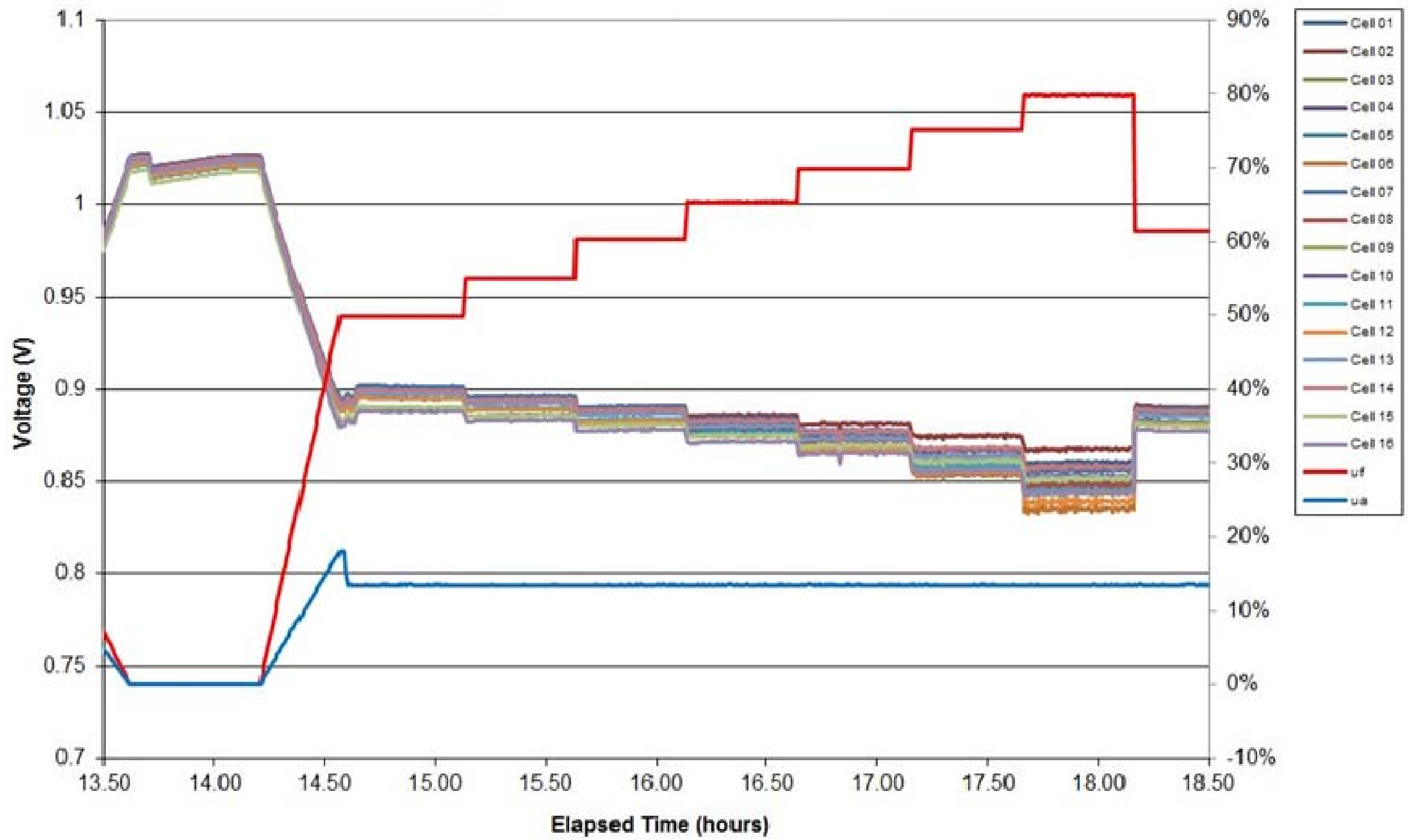
Stack Performance at High Utilization



➡ At 80% fuel utilization and 0.388 mA/cm^2, the16-cell stack resulted in 850 mV average cell voltage and excellent voltage uniformity

Test Stands Upgrades with Cathode Humidifiers

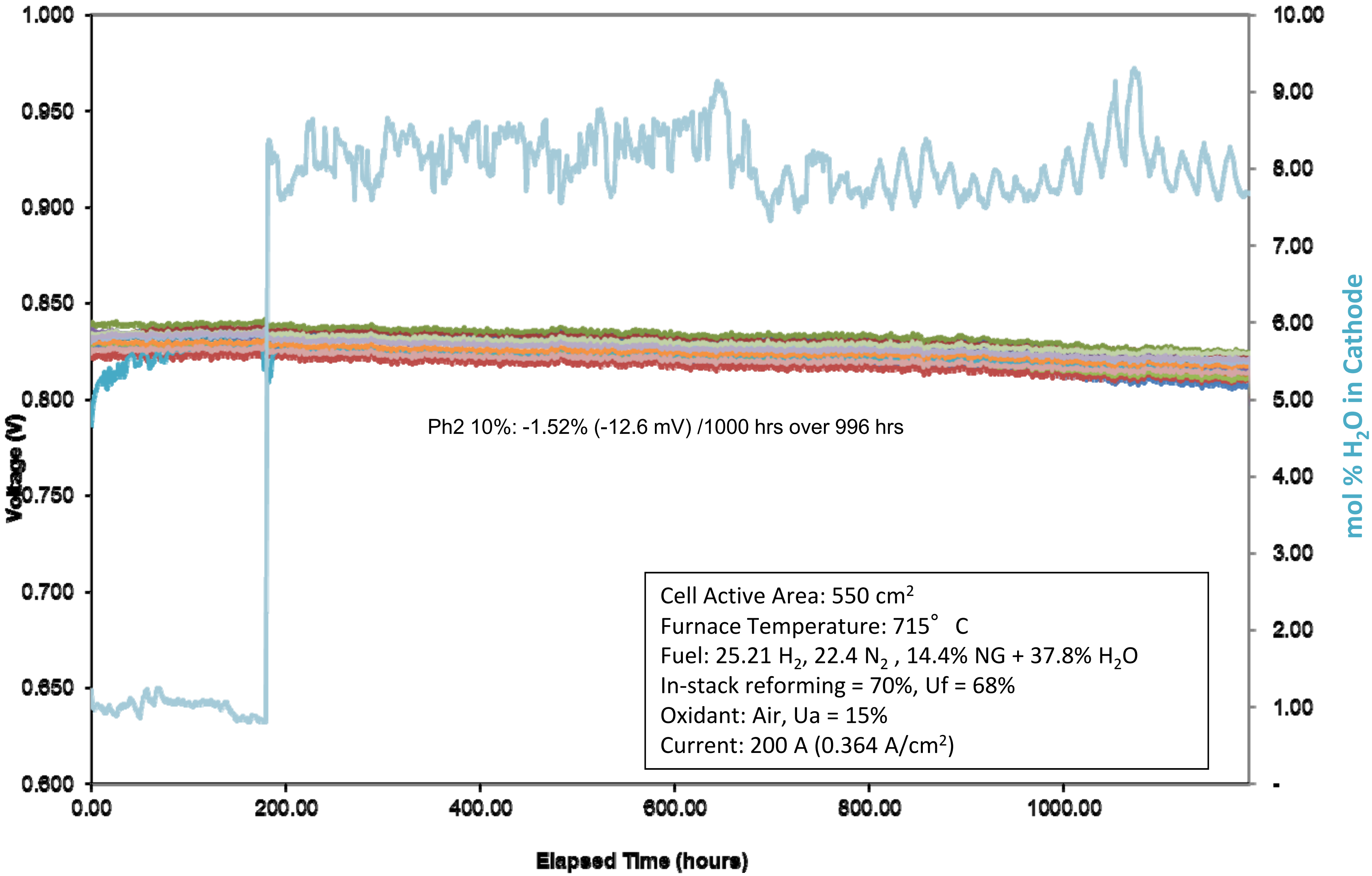
Objective

- Provide capability of short stack testing (16-cell) using controlled humidified cathode air in the range of 0 to 10 mol% humidity.

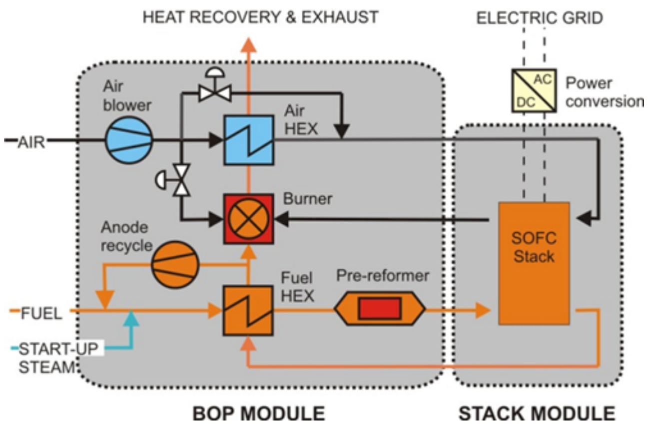
Approach

- Install 10 kW Humidifier inline with cathode inlet stream on 2 test stands (#25, #26)
- Develop software driver and additional programming to fully integrate humidifier into existing automated test stands.
- System features a dew point control type humidifier with secondary air dilution for humidity below 3 mol%

Large Area Stack Test of Cr Tolerant Technology Gen 1.0 Operating with High Cathode Humidity



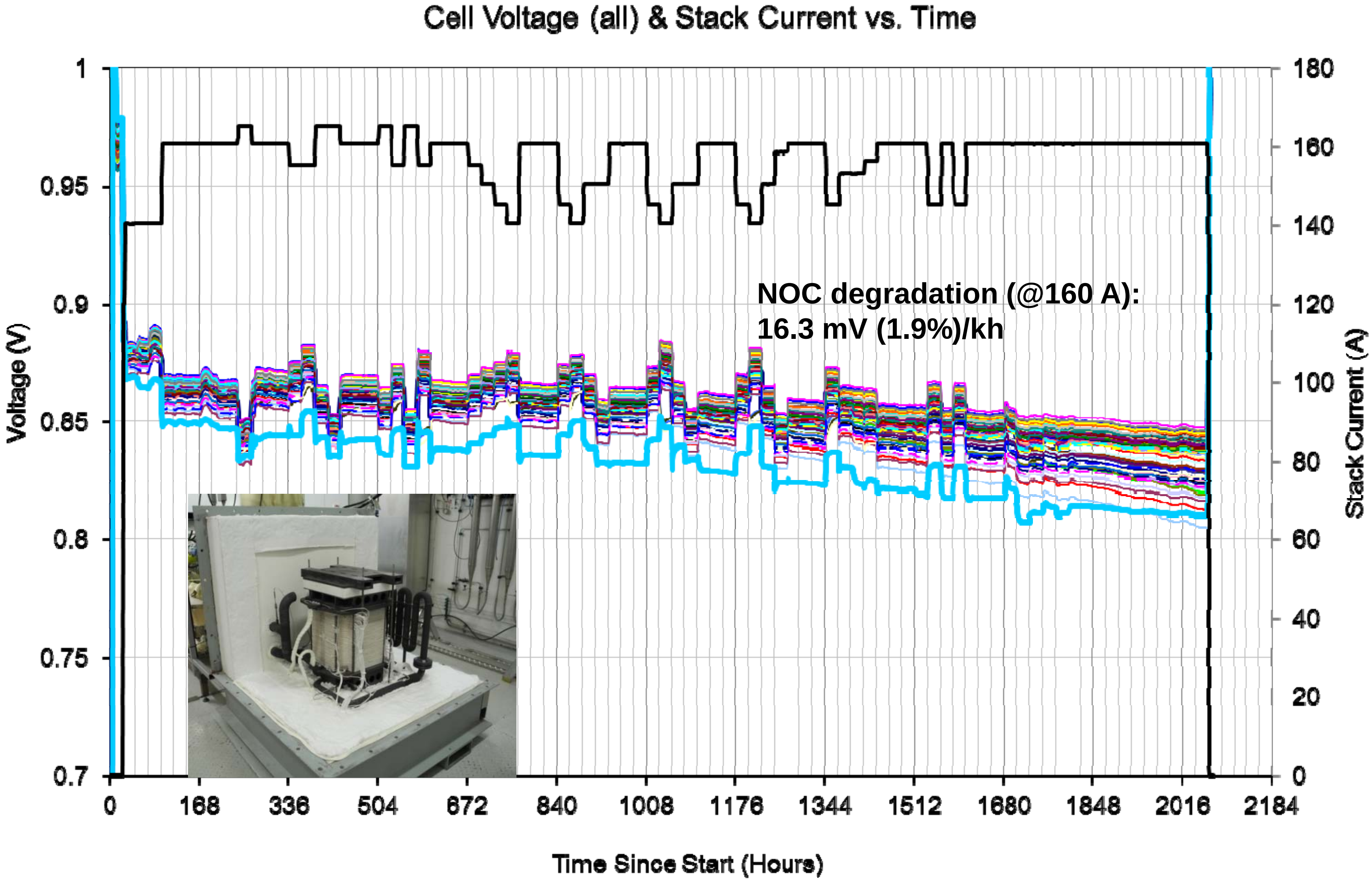
Stack Performance in Module
10 kW SOFC Demo Unit at VTT



- VPS has collaborated with VTT Technical Research Centre of Finland since 2010 to produce a 10 kW fully integrated SOFC system
    - Thermally self-sustained single stack module design
    - Natural gas fuelled with warm anode recycle loop
- A recent built 80-cell PCI stack Integrated with VTT balance of system in Finland

	100 h Average - TSC2 cells -	100 h Average - TSC3 cells -	32 h Average- TSC3 cells -
Stack Cell Count	64	64	80
Cell Voltage	772 mV	843 mV	857 mV
Stack Voltage	49.43 V	53.92 V	68.57 V
Module Power	9.885 kW	10.785 kW	11.013 kW
Fuel Utilization - System	81%	80%	80.4%
Module Efficiency (LHV)	60%	65%	66%

10 kW Demo Unit at VTT (80-cell stack)



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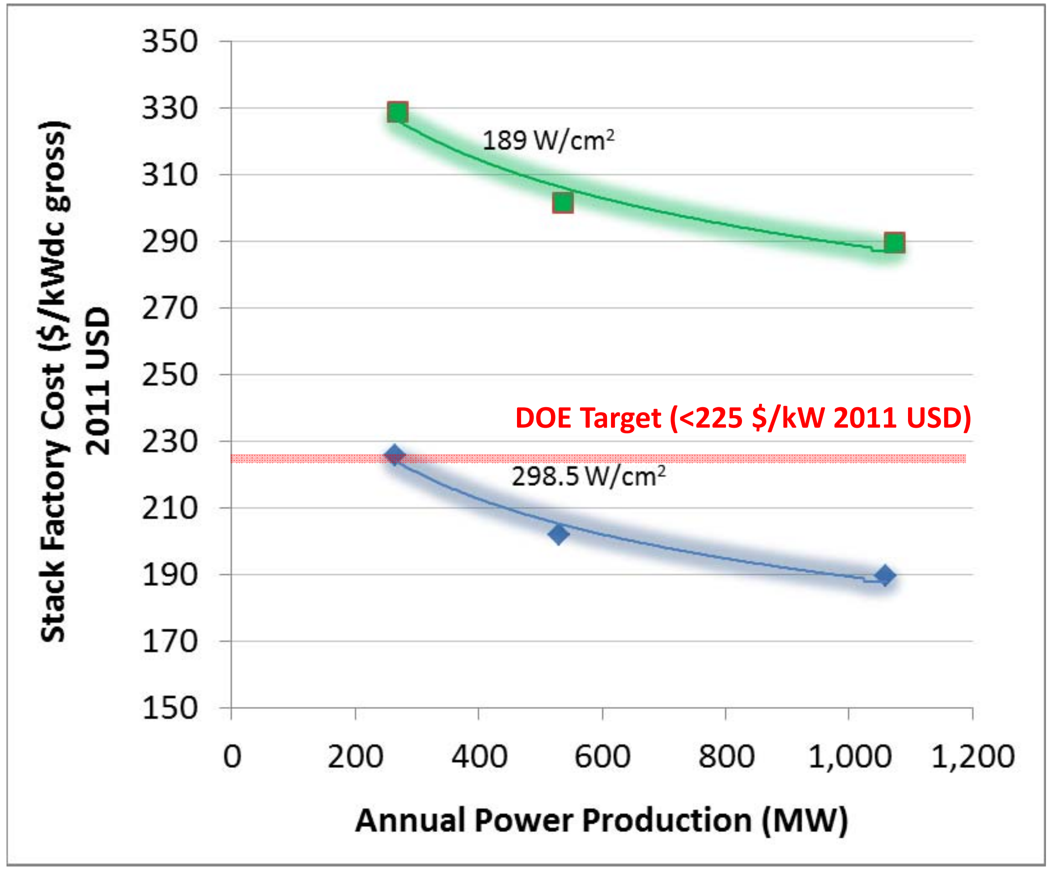
SOFC Stack Cost

Cost Reduction Focus Areas

1. **Stack Performance Increase**
    - Peak power 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
    - Elimination of process steps

SOFC Stack Block Cost Update in 2011 USD



The fuel cell stack cost has decreased substantially mainly due to the R&D activities in the SECA project.

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50 kW PCM System Design & Performance

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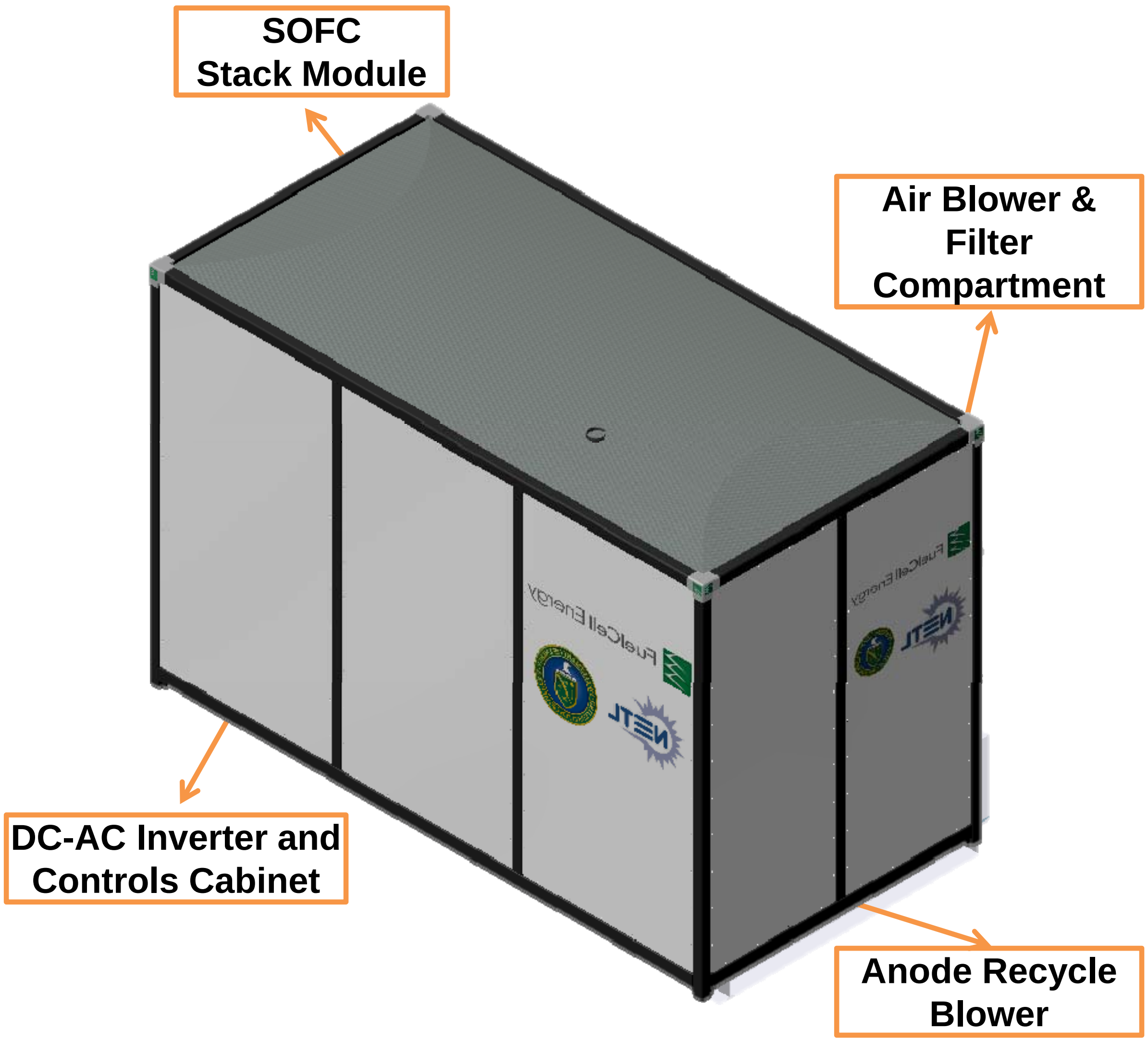
SOFC Gross Power	Normal Operating Conditions		Rated Power	
DC Power	**55.1**	**kW**	**60.3**	**kW**
Energy & Water Input				
Natural Gas Fuel Flow	4.9	scfm	5.4	scfm
Fuel Energy (LHV)	80.8	kW	88.9	kW
Water Consumption @ Full Power	0	gpm	0	gpm
Consumed Power				
AC Power Consumption	2.6	kW	2.7	kW
Inverter 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 Layout



- New compact plant design with 40% footprint reduction
- 14.5’ L x 7’ W x 10’ H
- Stack Module, MBoP, & EBoP factory assembled: shipped as a single skid
- Field-removable enclosure
  - Protects equipment from the elements
  - Enables field maintenance access without returning the entire unit to the factory

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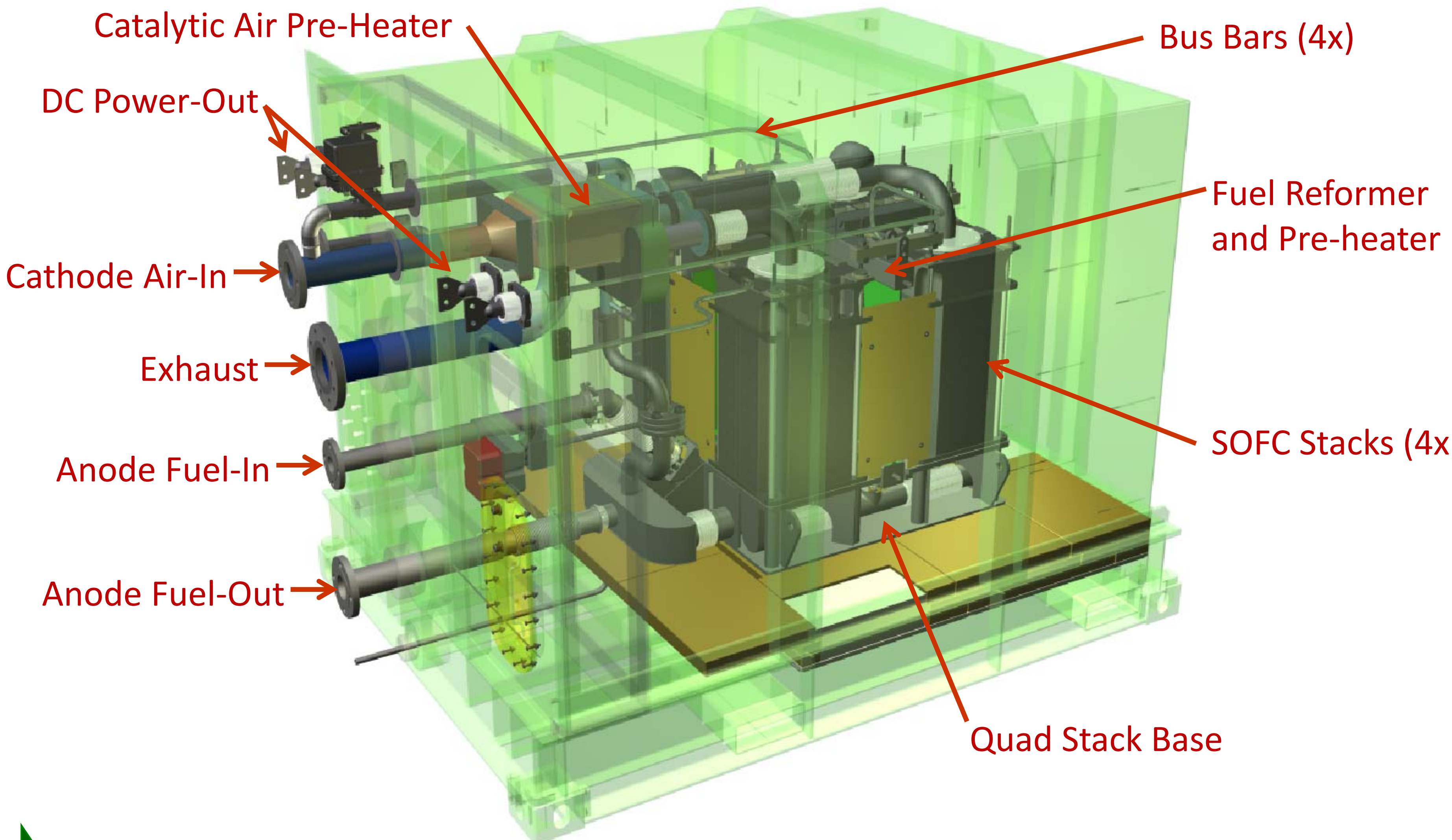
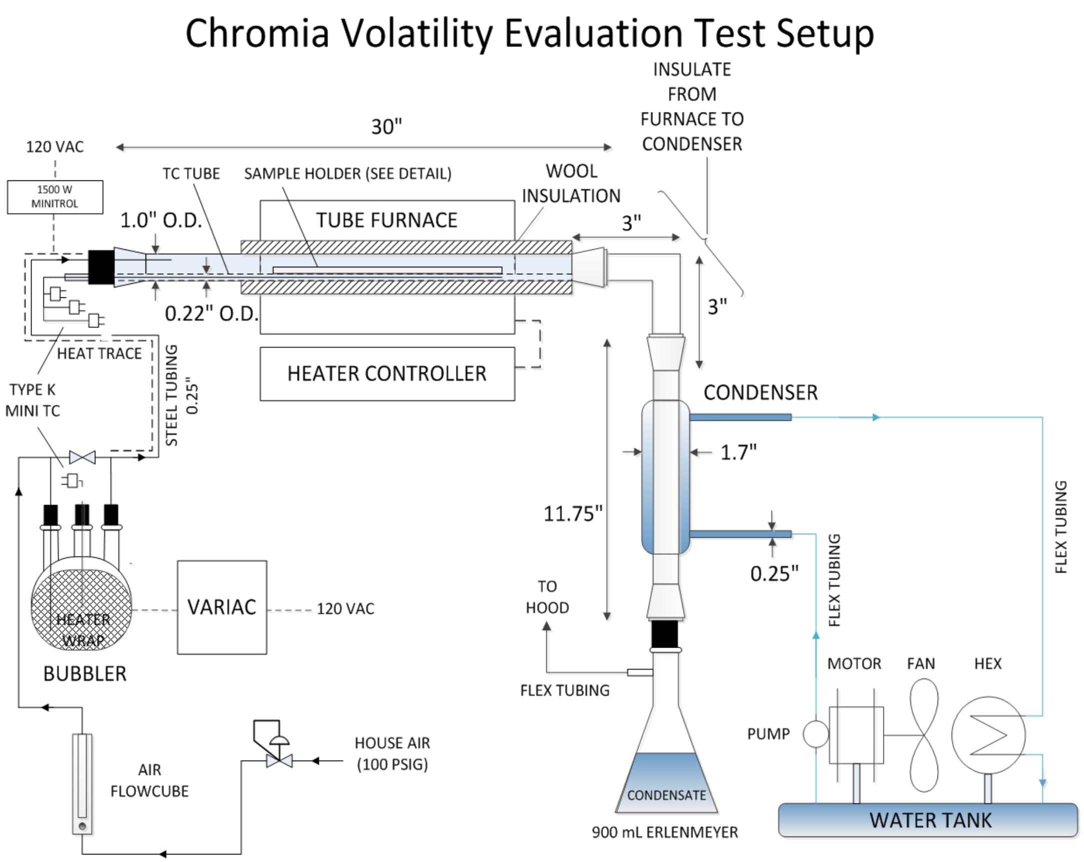
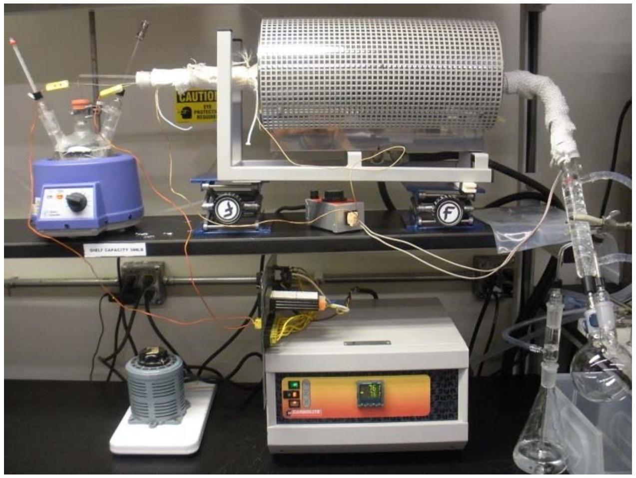
50kW SOFC Proof of Concept Module Design



- **50kW PCM combines SOFC stacks and hot BOP equipment into a compact enclosure. Fabrication is in progress for Q1-2015 testing.**

BOP Materials Development: Chromia Volatility Tests





Test Setup

Atomic Emission Spectrometer

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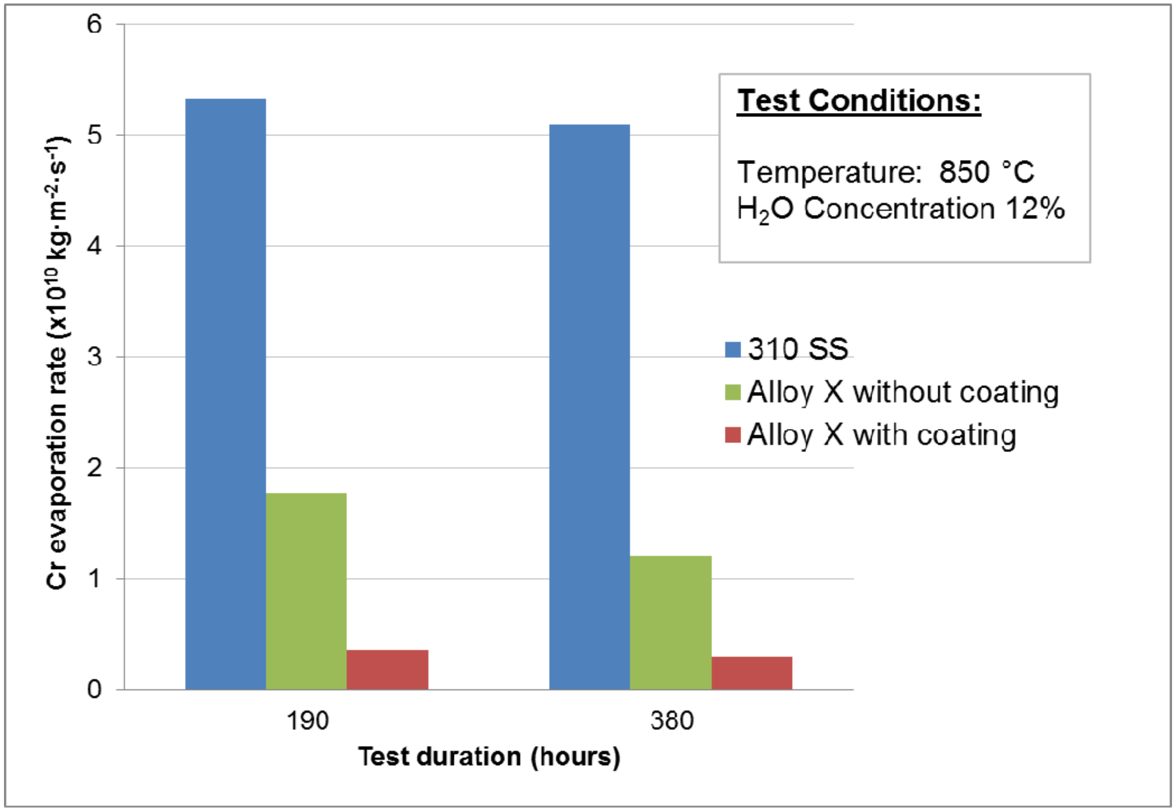
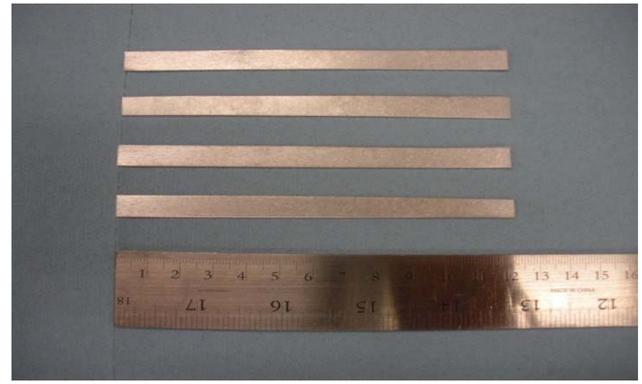
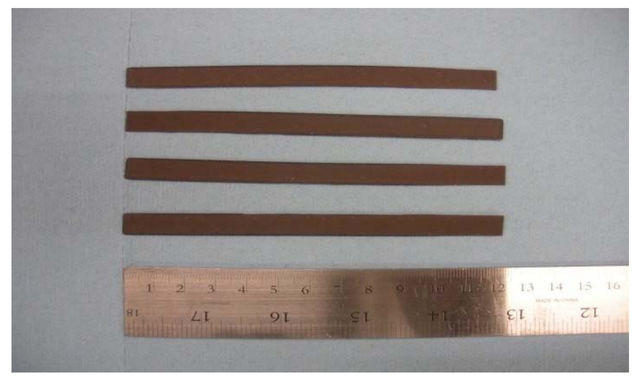
BOP Materials Development: Alloys with Reduced Cr Evaporation

Cr Evaporation Rate





Coated Alloy X



Coated Alloy X after oxidation at 850 ^{0}C and Humid Air (12% H_2O)

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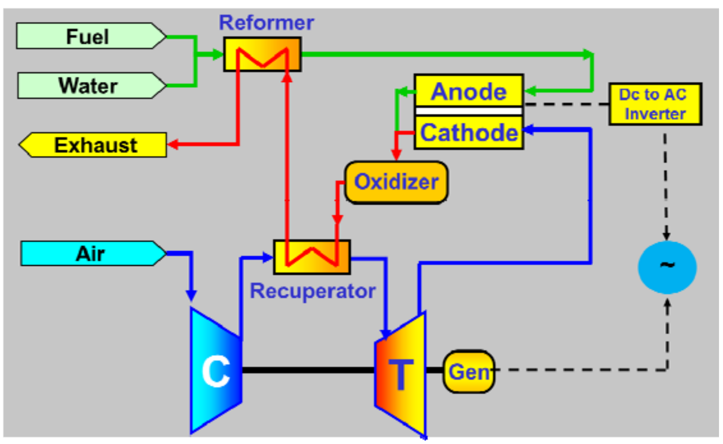
Application of SOFC in Small Unmanned Aerial System (SUAS)

Air Force System Requirements

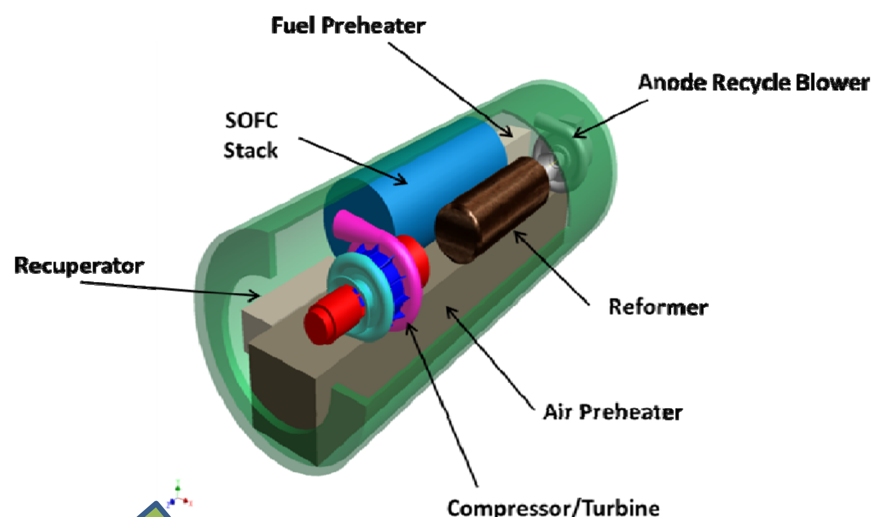
- Loiter = 55 mph (48 knots)
- Dash = 150 mph (130 knots)
- Altitude = 16,000 to 25,000 ft
- Endurance = 25 hrs
- GTOW = 30 lbs

Hybrid mTG/SOFC Advantages

	Piston Engine (1.5 HP)	mTG/SOFC (4 HP)	*% Change*
SFC (Specific Fuel Consumption) (kg/hr-kW)	0.32	0.24	-25%
Speed (mph)	48-70	48-130	+87.5%
Flight Endurance (hr)	20+	25+	+25%
Operating Ceiling (ft)	16,000	25,000	+56.3%



Patented FC/Turbine Hybrid System was Adapted to JP-8 Fueled Power Plant



- Increased peak power capabilities (3kW)
- High efficiency (>68%)

3 KW SOFC System

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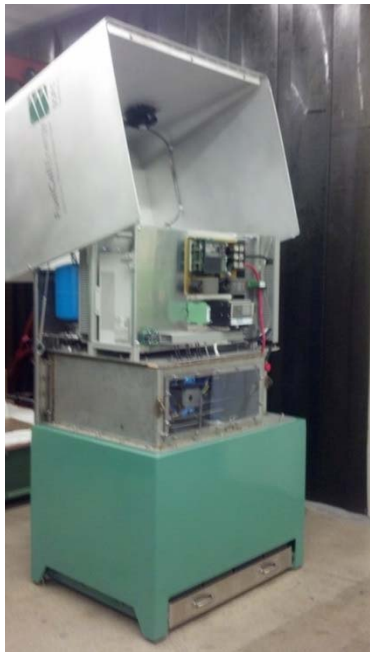

- SOFC Application Using Renewable Fuel
- Highly Compact
- Fuel Flexible and Water Neutral
- Unattended Operation with Remote Monitoring
- Grid Connected and Islanding Modes

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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- **SOFC Technology Applications**
- **Summary**

Recent Achievements

Developed Gen 1.0 Cr-mitigation strategies (interconnect coatings and Cr-getter materials) and validated the optimized materials sets over 10,000 hours of single-cell tests

Accumulated stack build and testing experience by manufacturing over 750 stacks including >130 of the stacks based on large area (625 cm^2) cells

Instituted a rigorous quality control program for improving cell and stack manufacturing processes to enhance SOFC reliability and endurance

Completed highly integrated 2nd-generation 50kW PCM design for testing of large-area full height stacks in system environment, resulting in 47% less volume (compared to 1st-gen module) while also incorporating hot BOP equipment within the stack module

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Guidance from NETL Management team: Travis Shultz, Shailesh Vora, and Heather Quedenfeld