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# Advances in SOFC Power System Development

**Hossein Ghezel-Ayagh**

**17th Annual Solid Oxide Fuel Cell (SOFC) Project Review Meeting**

**Pittsburgh, PA**

**July 19-21, 2016**

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# Presentation Outline

- **Introduction**
  - FCE Organization
  - SOFC Technology Overview
- **Progress in SOFC Technology**
  - Cell Development and Manufacturing
- **Stack Development**
  - Scale-up and Test Results
- **System Development**
  - 50 kW Proof-of-Concept Module (PCM) System
  - 200 kW System Development
- **Innovative Concepts**
- **Summary**

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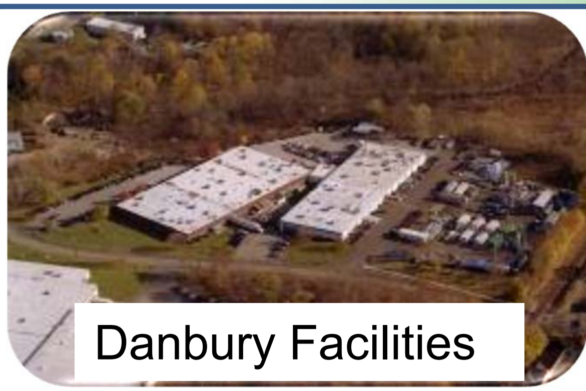
# *FuelCell Energy's SOFC Development Facilities*



Danbury Facilities

Materials Laboratory and Bench Scale Fabrication

Facilities for up to 400 kW Stack Tests

Outdoor Pads for 400 kW Grid Connected System Tests

Calgary Facilities

SOFC Materials & Components R&D

Cell & Stack Pilot Manufacturing & QC

33 Test Stations: Single Cell to 25 kW Stack Testing

# *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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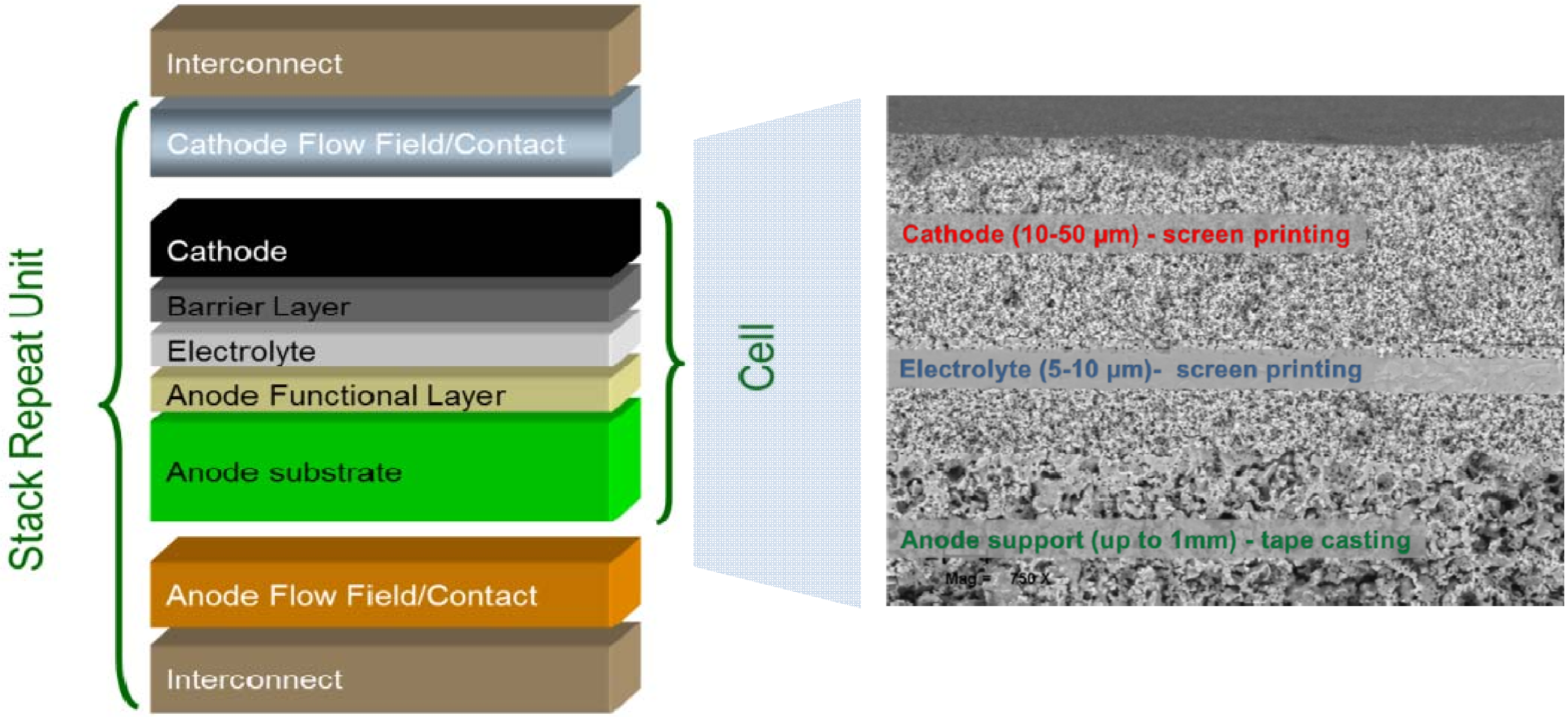
# Cell Technology Overview




| Component | Materials | Thickness | Porosity | Process |
|---|---|---|---|---|
| Anode | Ni/YSZ | 0.3 - 0.6 mm | ~ 40% | Tape casting |
| Electrolyte | YSZ | 5 - 10 $\mu$m | < 5% | Screen printing |
| Cathode | Conducting ceramic | 10 - 50 $\mu$m | ~ 30% | Screen printing |

# 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 $cm^2$
- > 8000 Cells (25 x 25 $cm^2$) Fabricated
- Production Volume of 500 kW (annual) & >95% Fabrication Yield Demonstrated

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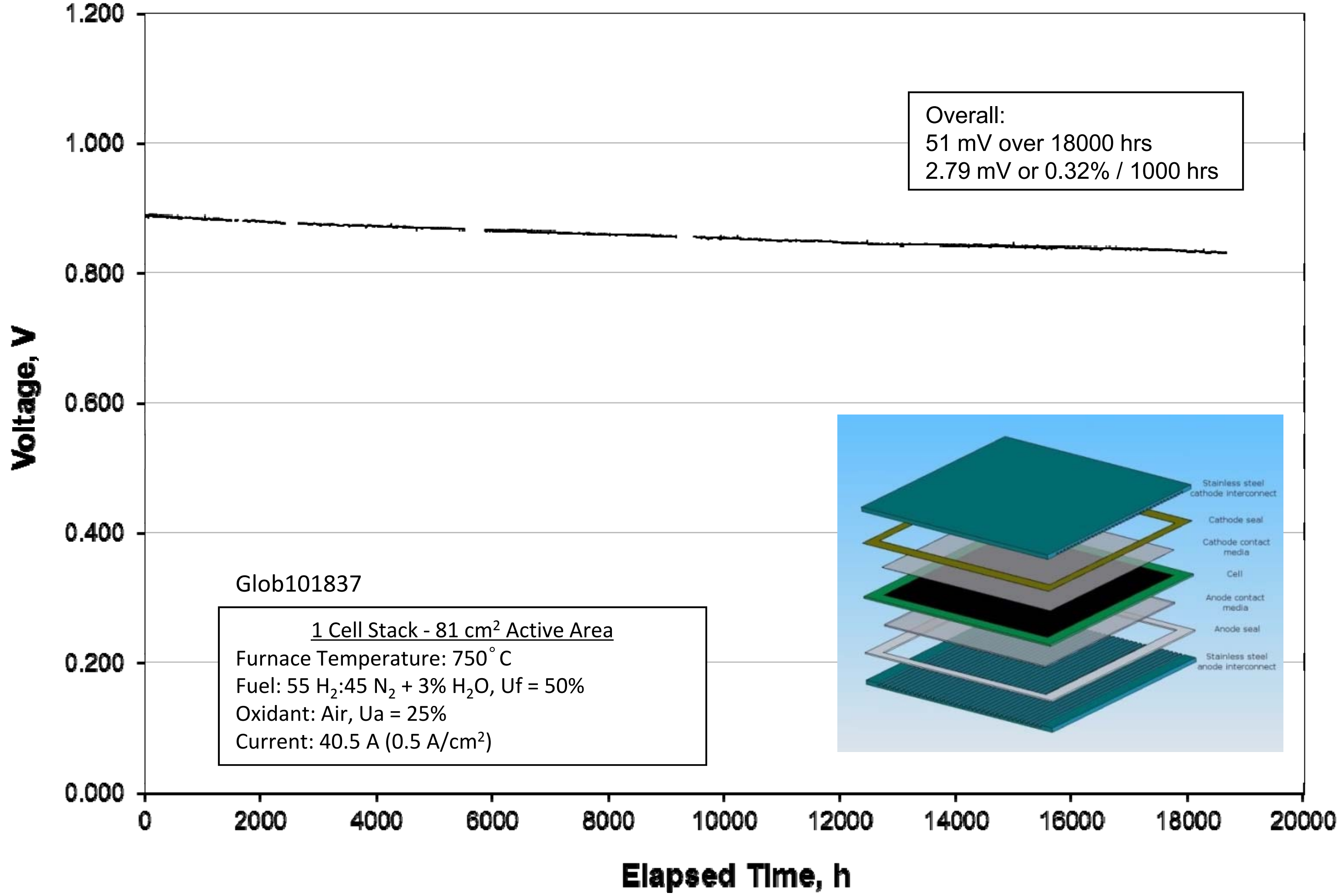
# *TSC3 Long-term Performance*




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

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# *Cr Tolerant Technology*

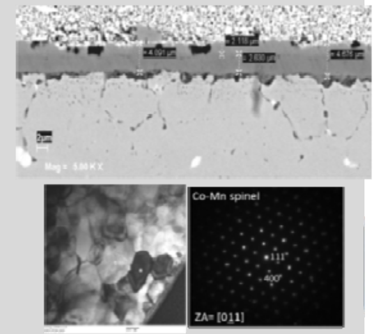
## Cobalt Coated Interconnect

**Sheet Metal**
- PVD Cobalt coating

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

**Co-coated IC**
- Stack assembly

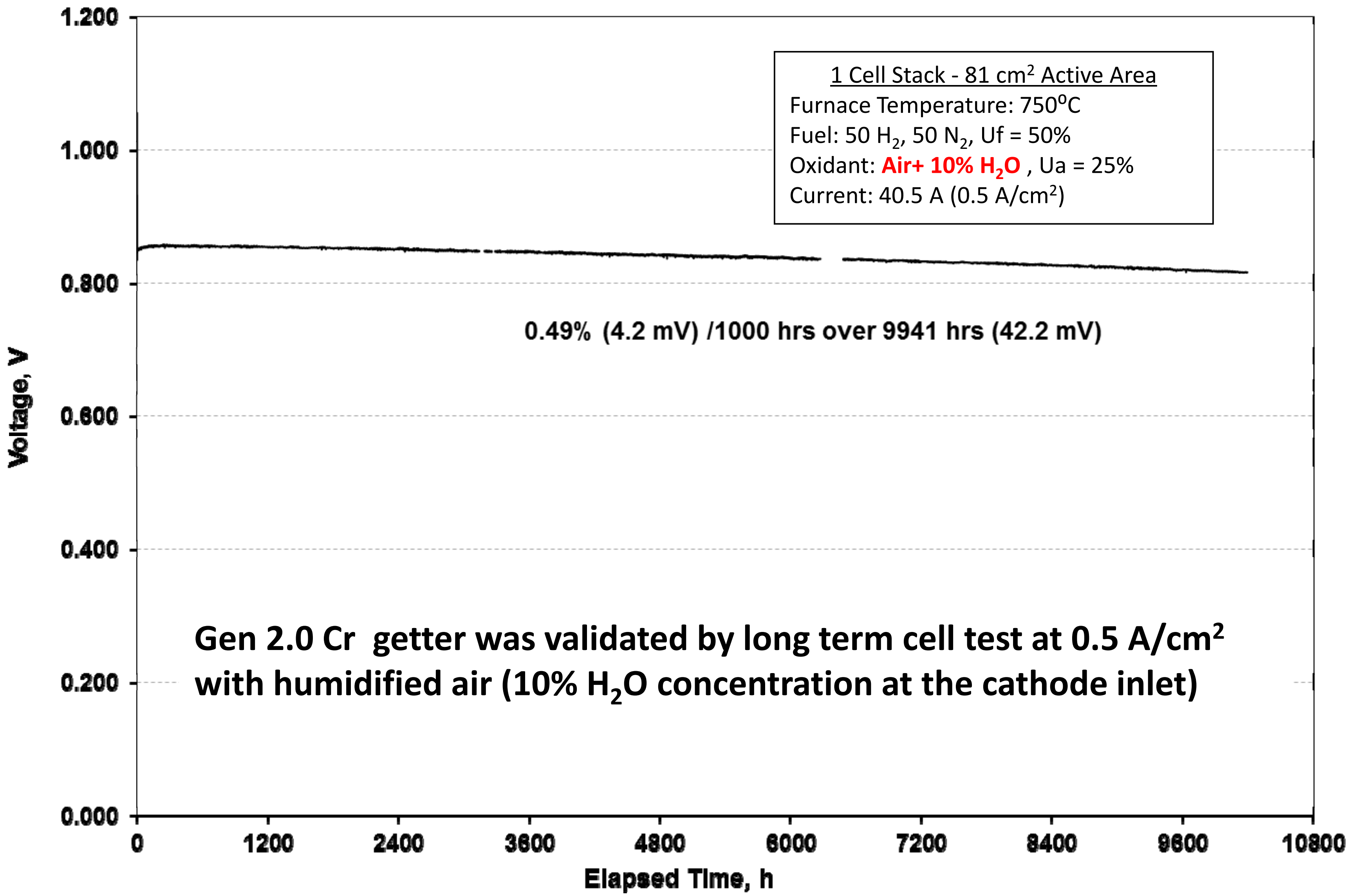
**MCO Coated Interconnect**
- In-situ MCO Formed during Stack Operation



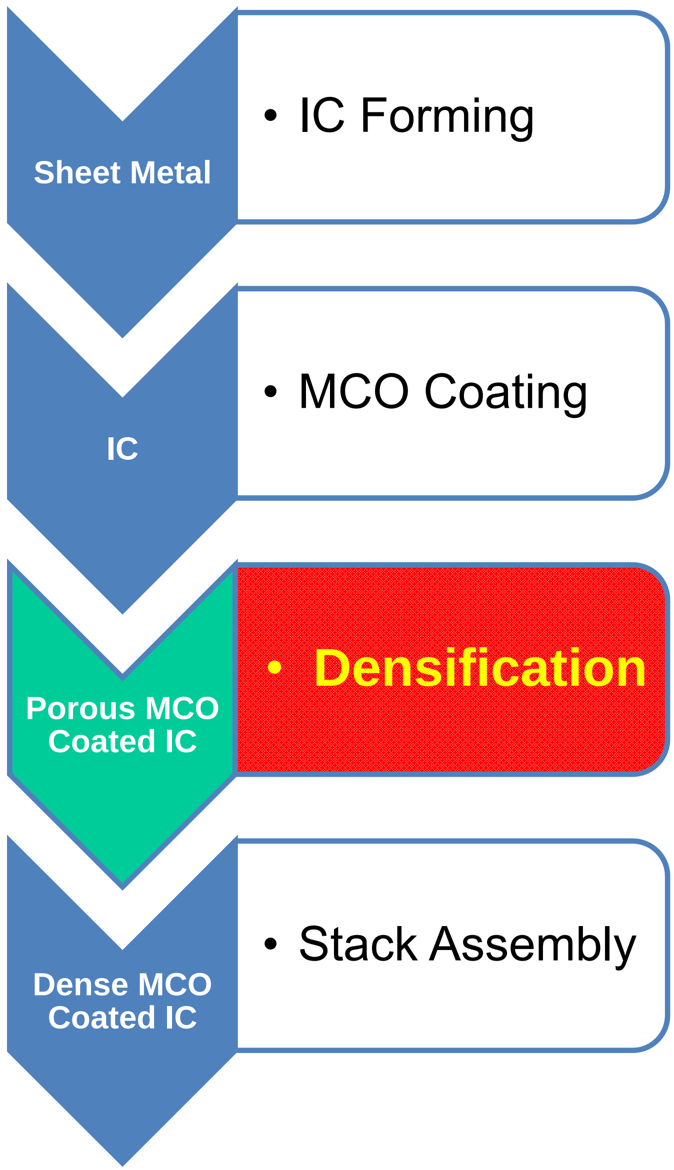

## Chromium Getter Materials

Cr Getter Material Development → Cell Design and Development with Cr Getters → Single Cell and Stack Testing Validation → Optimizing Cr Getter Design

# Gen 2.0 Cr Getter Development

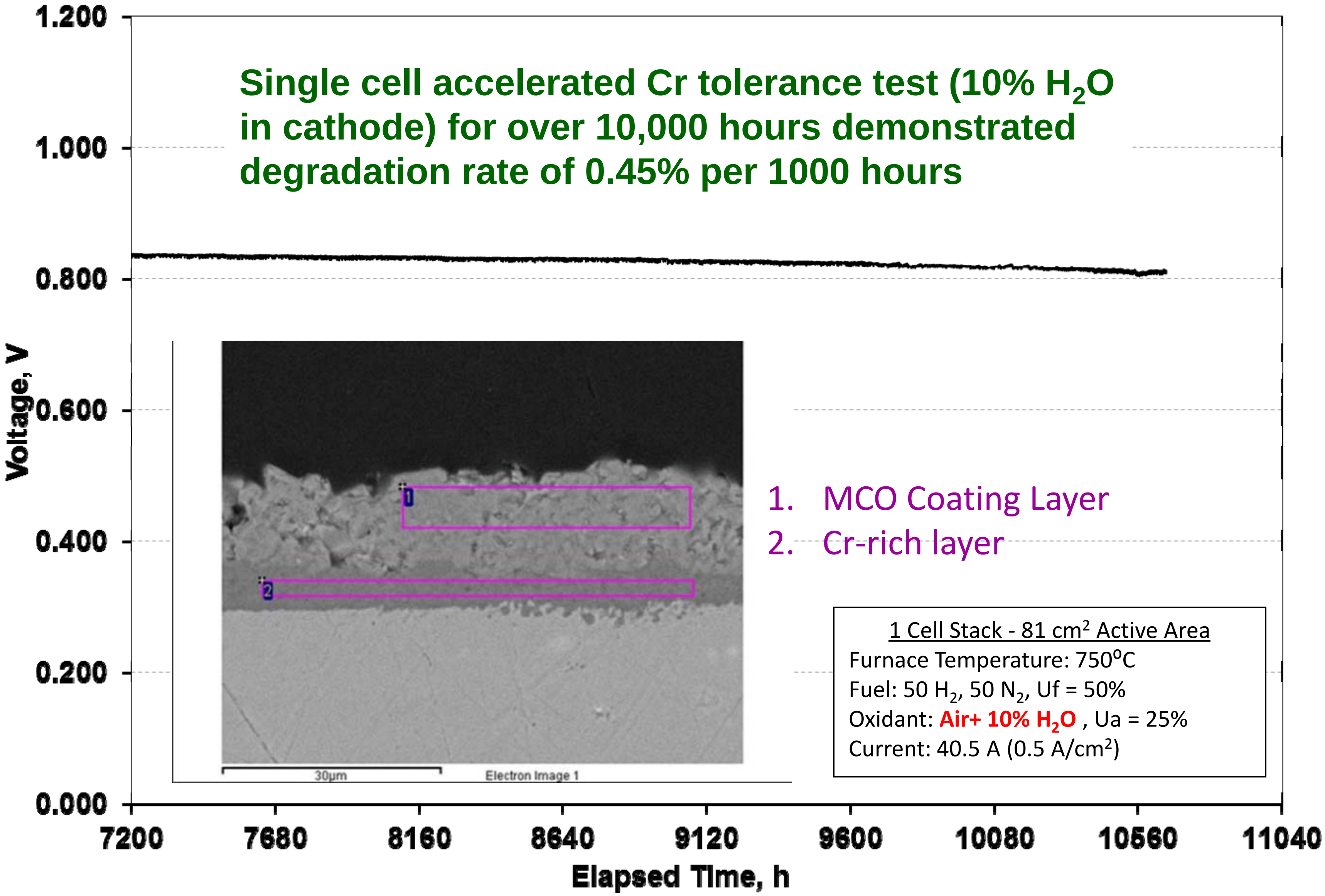


# *In-house MCO Coating*

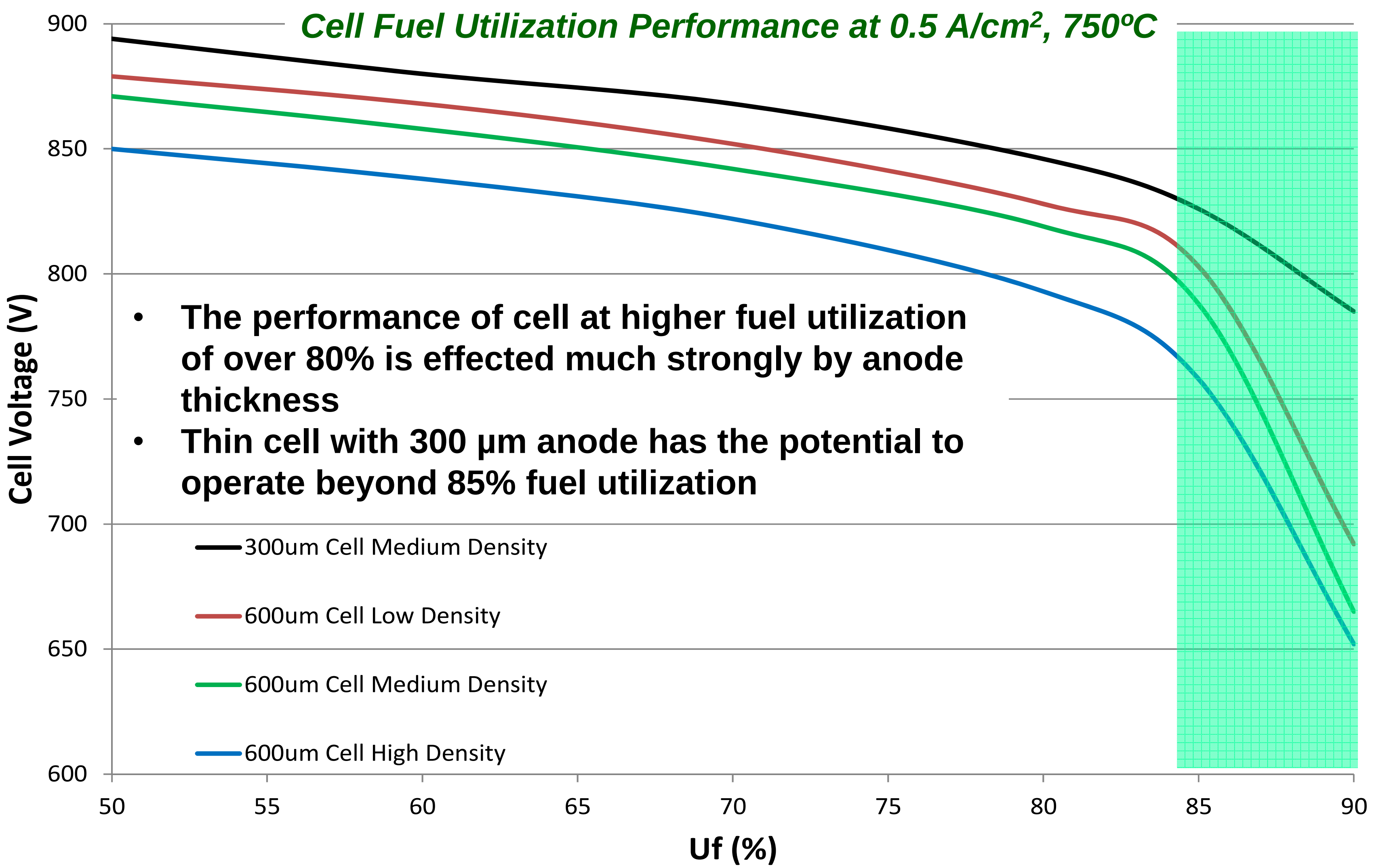



- Issues with ex-situ MCO coating
  - High-temperature reducing atmosphere densification process leads to high cost and oxides forming at anode side IC
- In-house MCO coating focused on simpler densification process
  - Eliminate the need for  >900ºC densification in reducing environment
- Arrived at coating approaches which demonstrated superior performance in accelerated Cr tolerance single cell tests
- One approach was tested for over 10,000 hours in high humidity cathode air (10% $H_2O$)

# *MCO Ex-Situ Coated Interconnect*

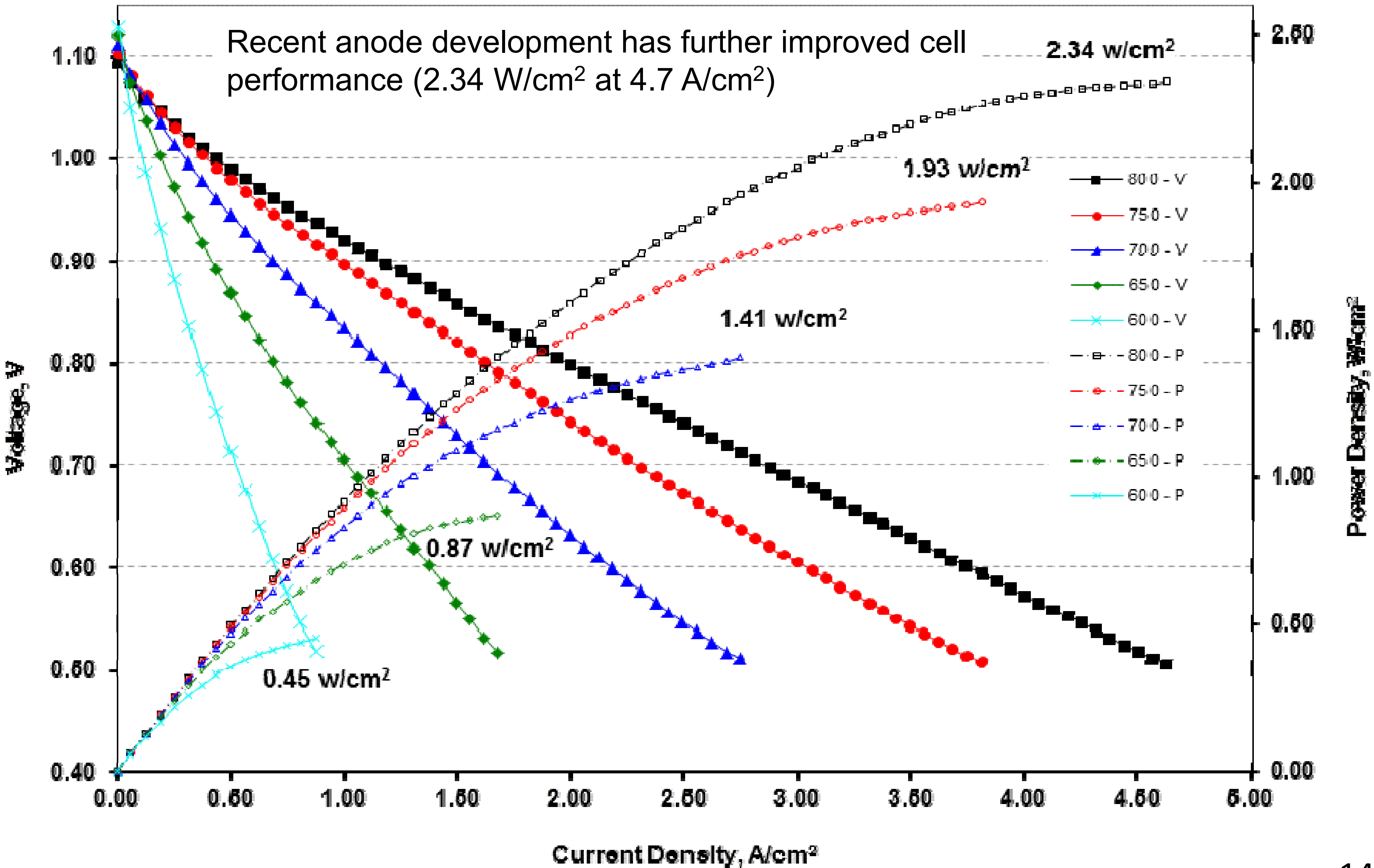


# Effect of Anode Thickness and Density on Fuel Utilization




- **The performance of cell at higher fuel utilization of over 80% is effected much strongly by anode thickness**
- **Thin cell with 300 μm anode has the potential to operate beyond 85% fuel utilization**

# Recent Thin Cell Performance



# Test of Thin Cells up to 95% Fuel Utilization

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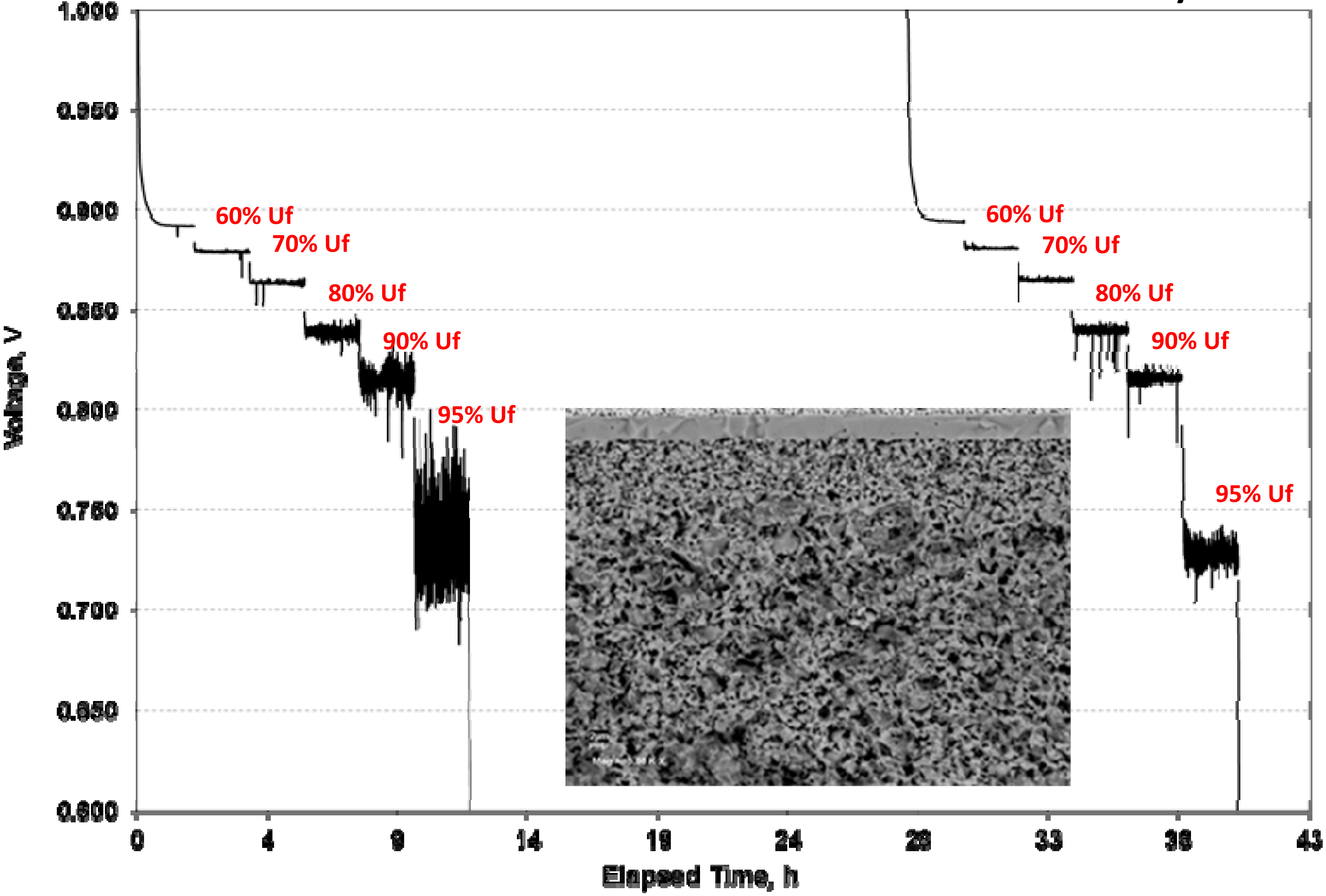
**Constant utilization tests for thin cell before and after thermal cycle.**




➡ **Stable fuel utilization (Uf) was demonstrated up to 95% at 0.5A/cm$^2$**

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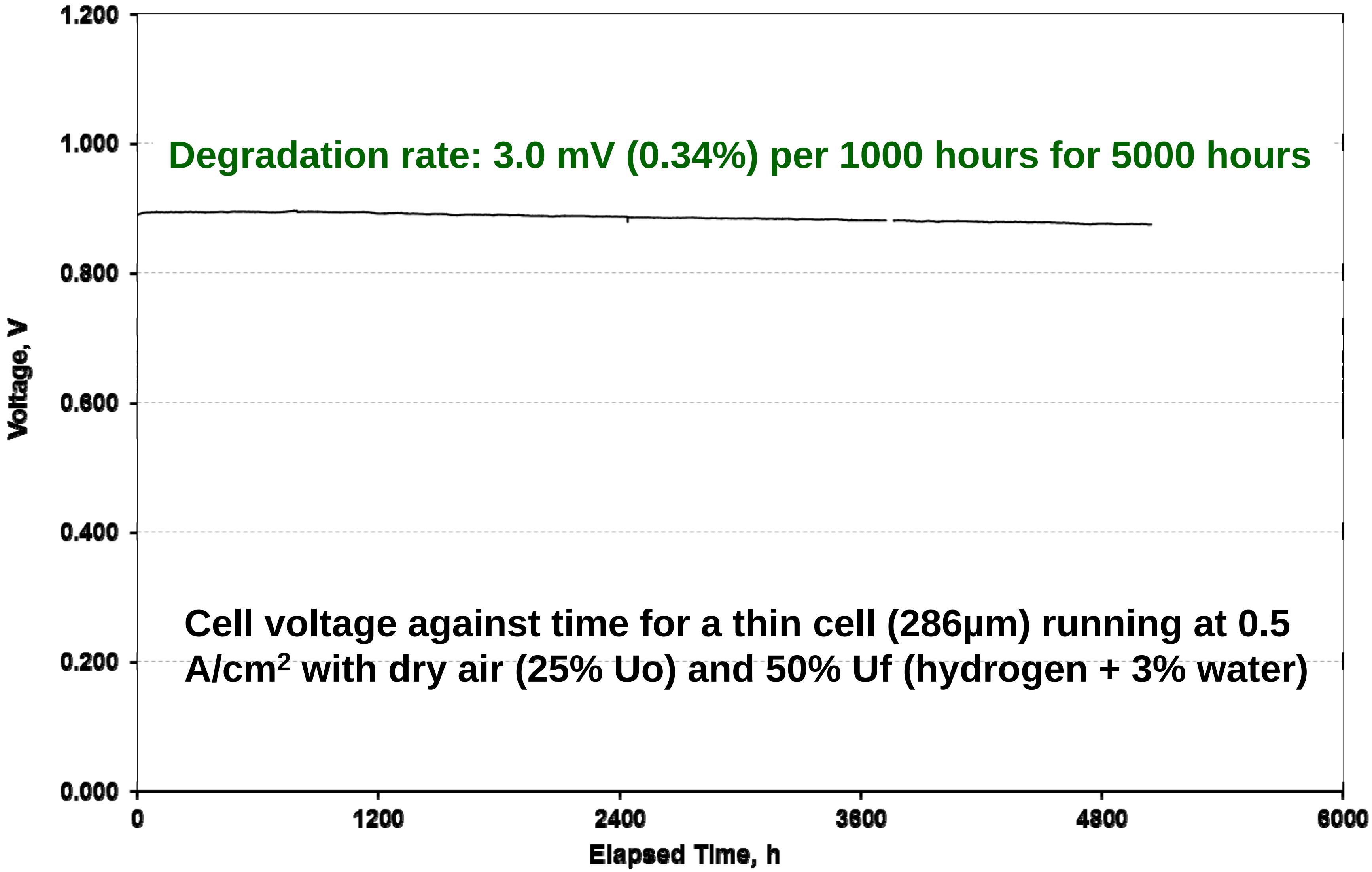
# *Steady-State Test of Thin Cell*



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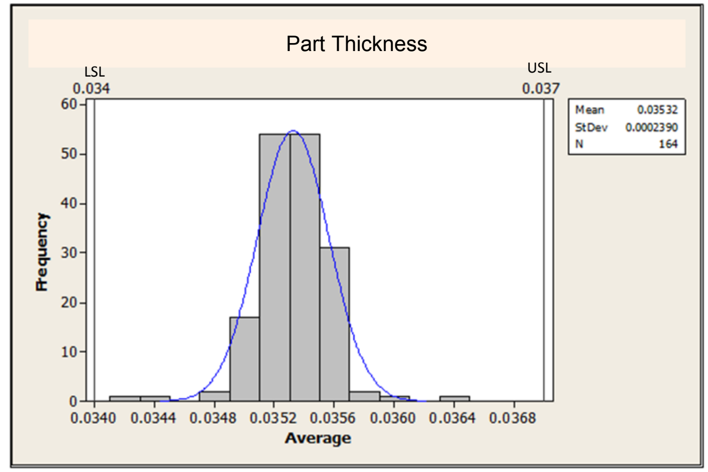
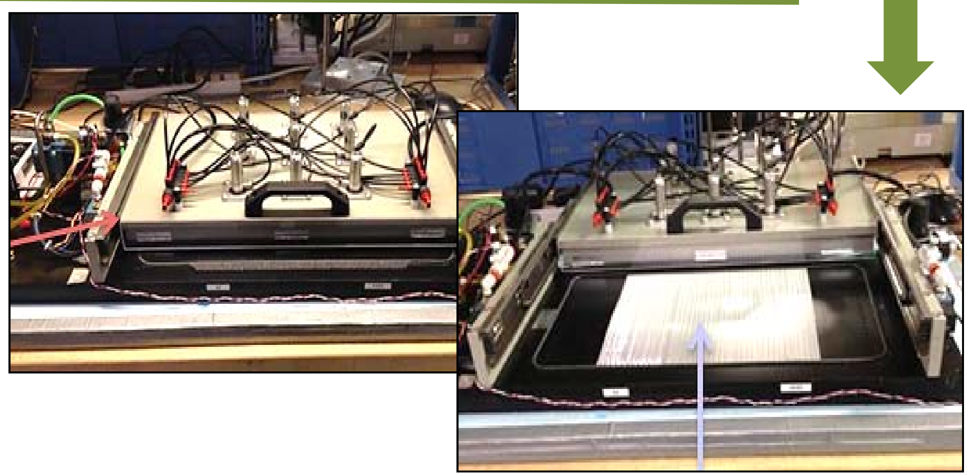
# *Improved Stack Metallics Fabrication Quality*

Finishing Equipment for
Stack Metallic Fabrication




Acceptance of Parts
Between LSL & USL

High Quality Built Stack
& Stack Modules



Advanced QC Station for Ensuring the
Quality of Stack Metallic Components

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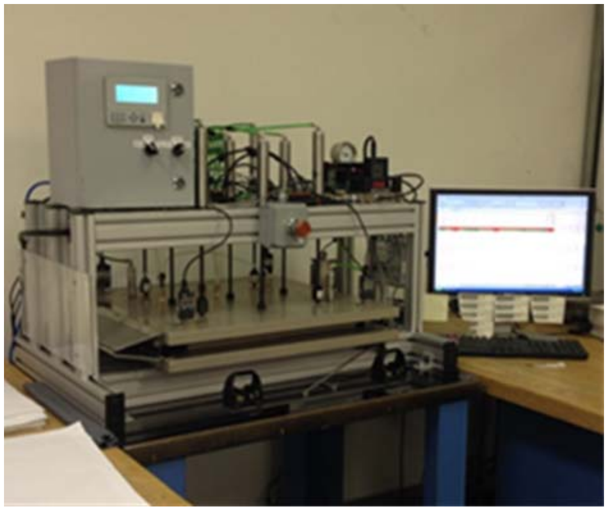
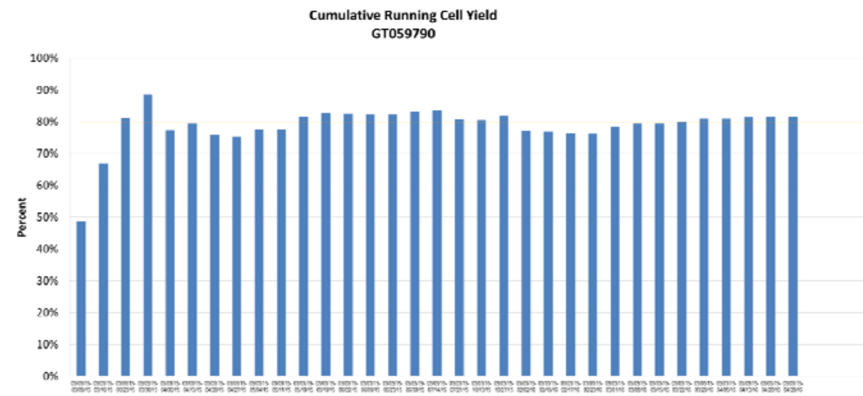
# *Improved Cell Fabrication Quality Control*



New High-Throughput & Multi-Functional QC Stations Ensure Quality Cell Components




Increased Stabilized Cell Production Yields via Tools & Corrective Action

- Increased Production Quality
- Reduced Inspection Labor Time
- Increased Stack Operational Reliability

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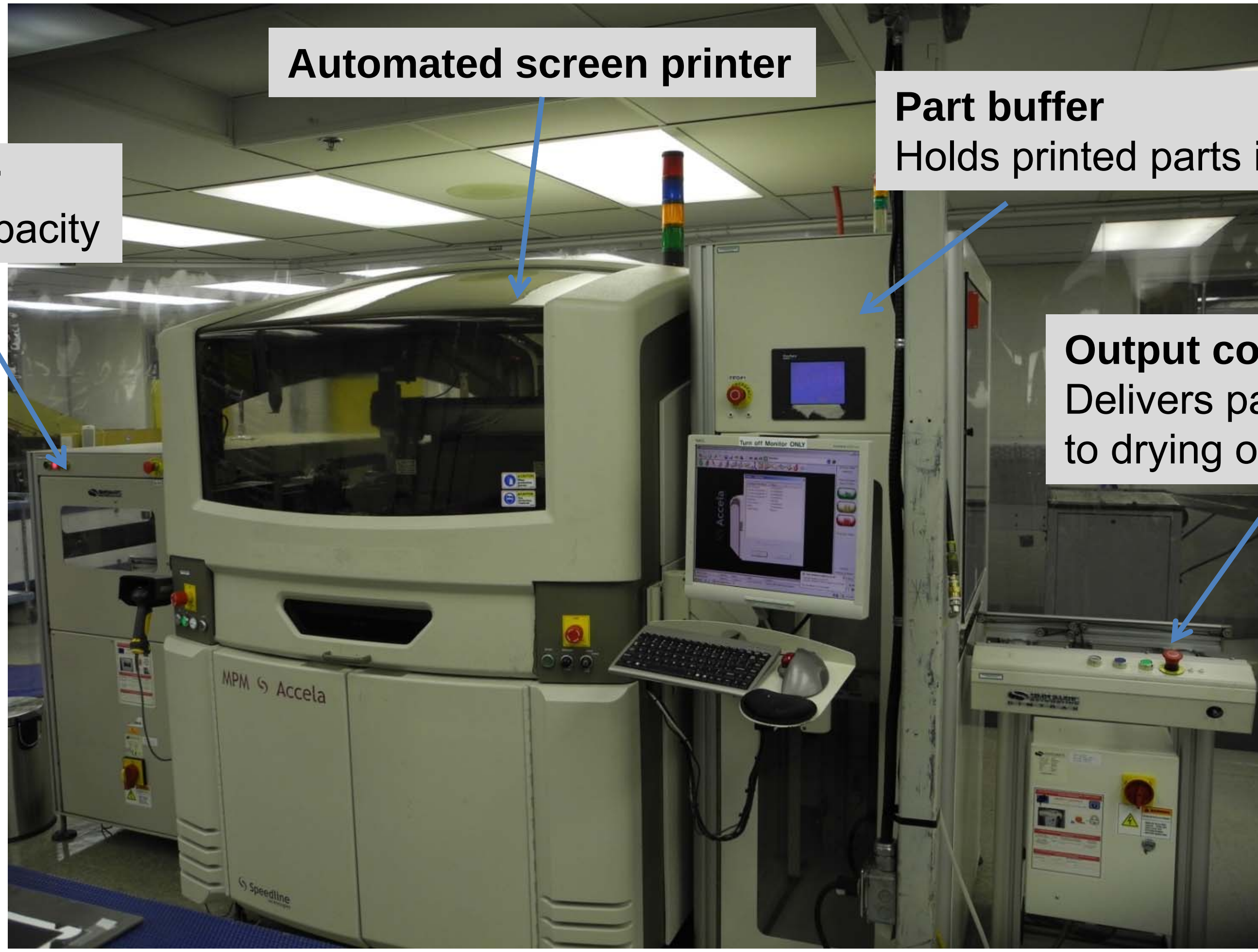
# *Automated Cell Printing*




- Off-the-shelf equipment from electronics industry
- Automatic cell handling and alignment
- Reduced labor and improved quality

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# *Stack Development Path*


6-cell short stack

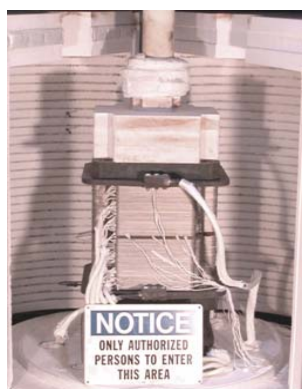

16-cell short stack

## Scale Up
- Scaled up cell active area from 121 to 550 cm²
- 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

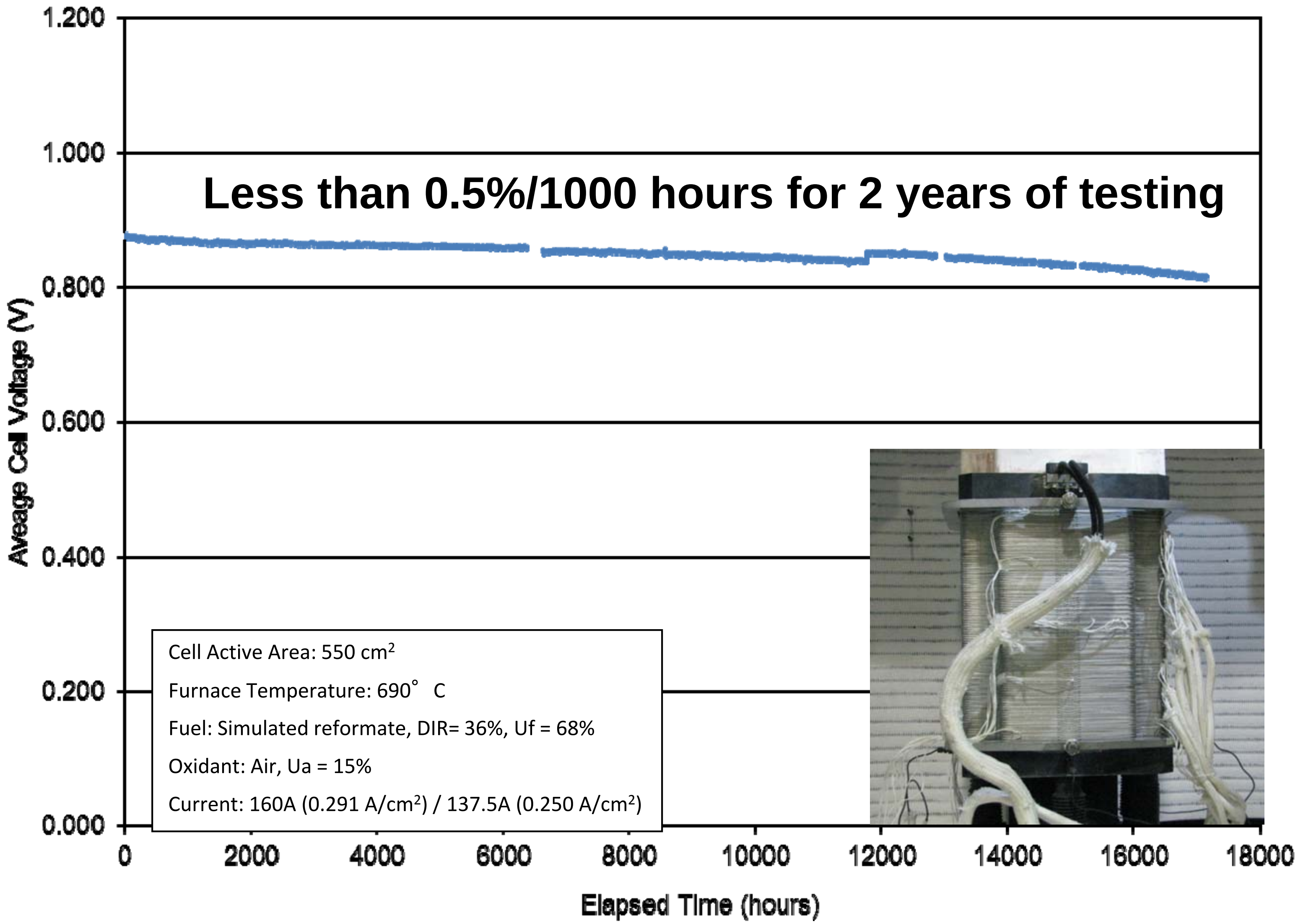

120-cell stack block

# 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 |

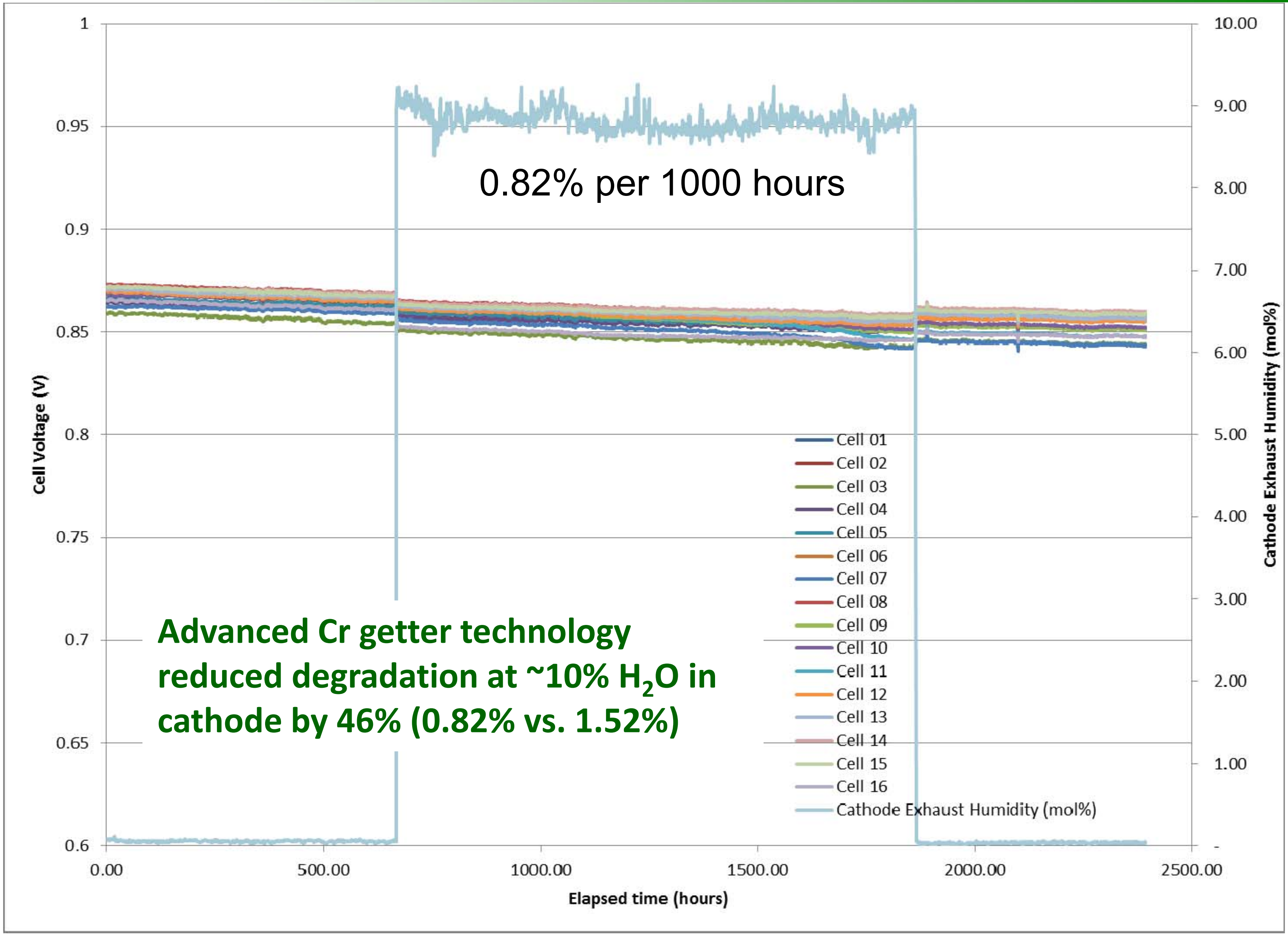
| | |
|---|---|
| Cell Size | 25 x 25 $cm^2$ |
| Active Area | 550 $cm^2$ |
| Number of Cells | 120 |

# *Tall Stack with Improved Reliability & Gen 1.0 Cr Tolerant Cell*




GT058139-0002

# *Cr Tolerant Technology Gen 2.0*
# *Cr Getter Improvement*




**Advanced Cr getter technology reduced degradation at ~10% $H_2O$ in cathode by 46% (0.82% vs. 1.52%)**

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  - SECA Coal-Based SOFC Program Overview
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# 50kW Proof-of-Concept (POC) System Fabrication and Installation

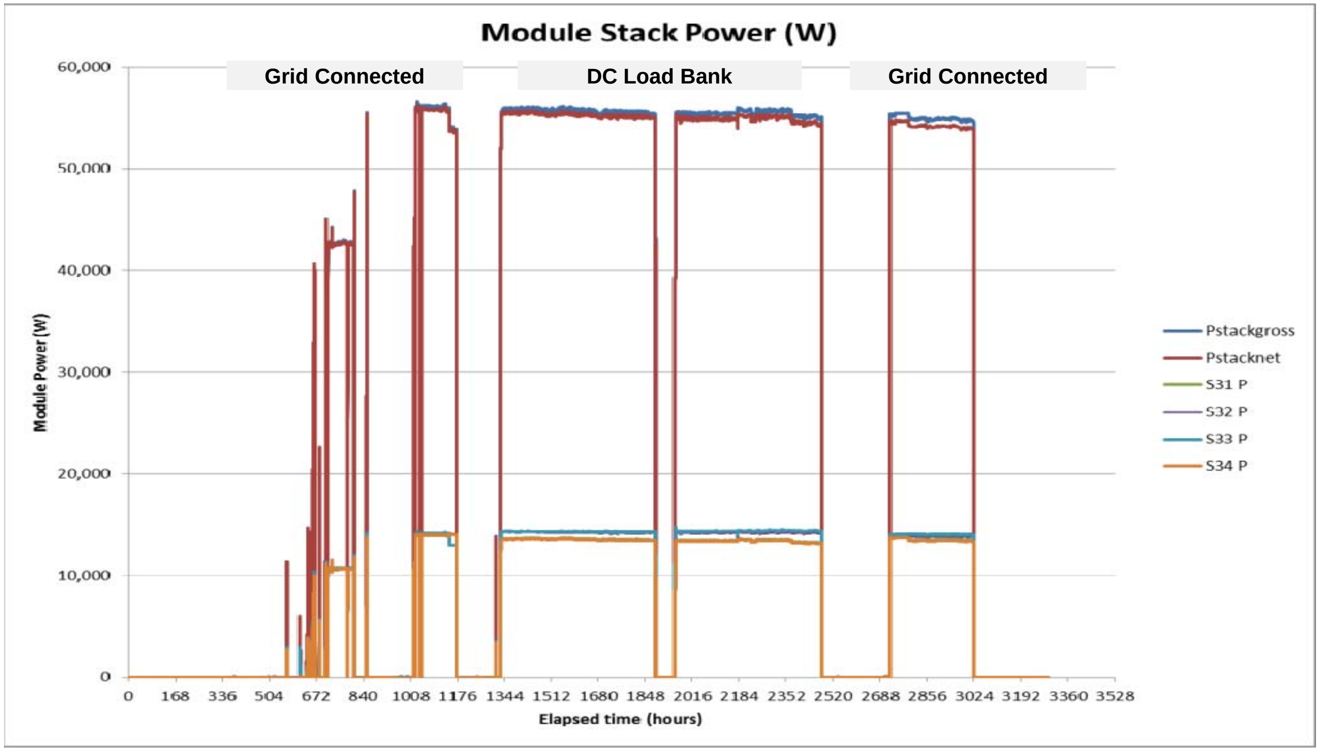
## Balance-of-Plant Fabrication

## Installation

## Module Fabrication

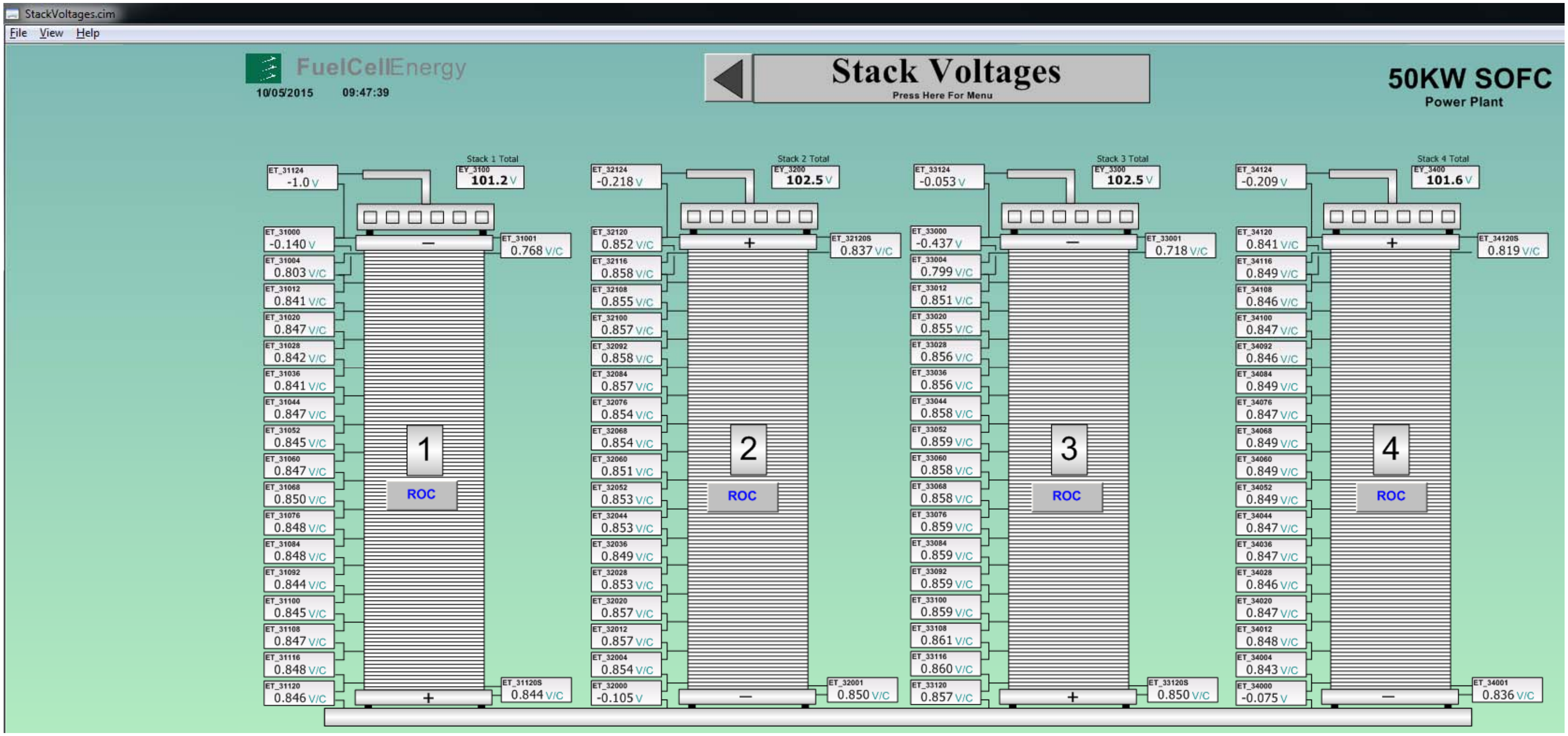
## Module/BoP/Façade Integration

# 50 kW System Performance Testing




| | |
|---|---|
| Stack Currents | 137.5 A |
| Average Cell Voltage | 851 mV |
| Average Stack Voltage | 102.1 V |
| Total Hot Run Time | >2500 hrs |

# 50 kW System Control System Screen Shot

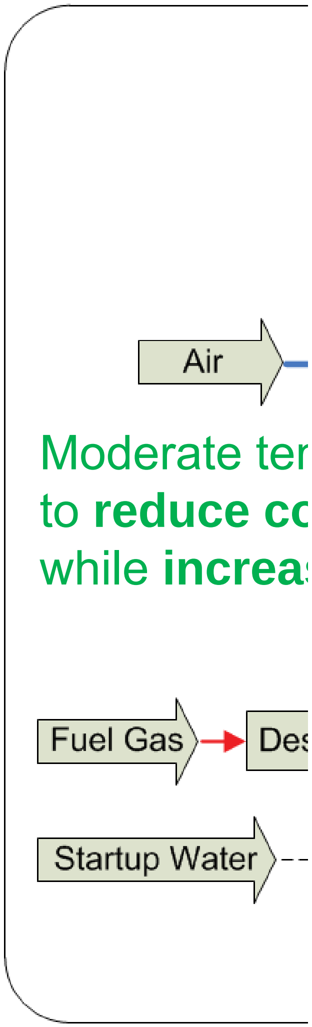



**Uniform voltage distribution from all four stacks were measured**

# 50 kW System Performance Summary

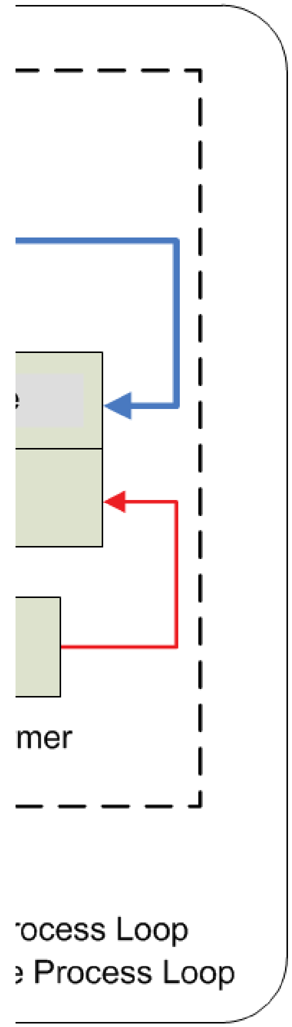
| | Design | **Actual** |
|---|---|---|
| DC Power (gross) | 55.1 kW | **56.2 kW** |
| Natural Gas Fuel Flow | 4.9 scfm | **5.03 scfm** |
| Fuel Energy (LHV) | 80.8 kW | **82.7 kW** |
| Water Consumption | 0 | **0** |
| Gross Module DC Efficiency (LHV) | 68.2% | **67.9%** |
| Total on Load Time | 1500 hrs | **>1500 hrs** |
| Overall Stack Performance Degradation | <1% per 1000 hrs | **<1% per 1000 hrs** |

# 200 kW SOFC System



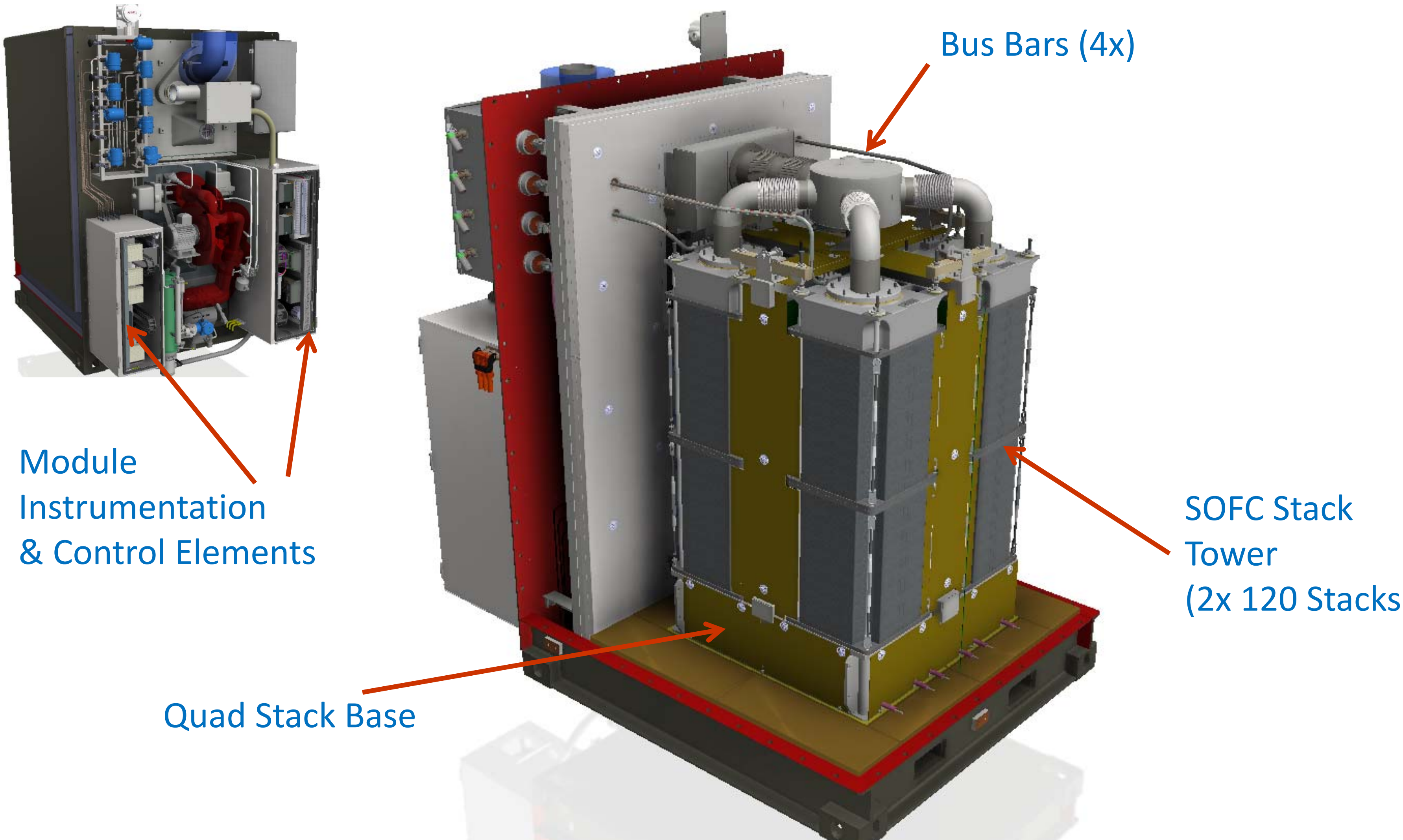

**200 kW SOFC System Performance Summary**

| SOFC Gross Power | Normal Operating Conditions | | Rated Power | |
|---|---|---|---|---|
| **DC Power** | **225.0** | **kW** | **244.0** | **kW** |
| **Energy & Water Input** | | | | |
| Natural Gas Fuel Flow | 19.7 | scfm | 21.6 | scfm |
| Fuel Energy (LHV) | 323.2 | kW | 355.5 | kW |
| Water Consumption @ Full Power | 0 | gpm | 0 | gpm |
| **Consumed Power** | | | | |
| AC Power Consumption | 10.8 | kW | 12.5 | kW |
| Inverter Loss | 11.3 | kW | 12.2 | kW |
| **Total Parasitic Power Consumption** | **22.0** | **kW** | **24.7** | **kW** |
| **Net Generation &Waste Heat Availability** | | | | |
| **SOFC Plant Net AC Output** | **203.0** | **kW** | **219.3** | **kW** |
| **Available Heat for CHP (to 48.9°C)** | **84.7** | **kW** | **90.8** | **kW** |
| **Exhaust Temperature - nominal** | **370** | **°C** | **370** | **°C** |
| **Efficiency** | | | | |
| **Electrical Efficiency (LHV)** | **62.8** | **%** | **61.7** | **%** |
| **Total CHP Efficiency (LHV) to 48.9°C** | **89.0** | **%** | **87.2** | **%** |



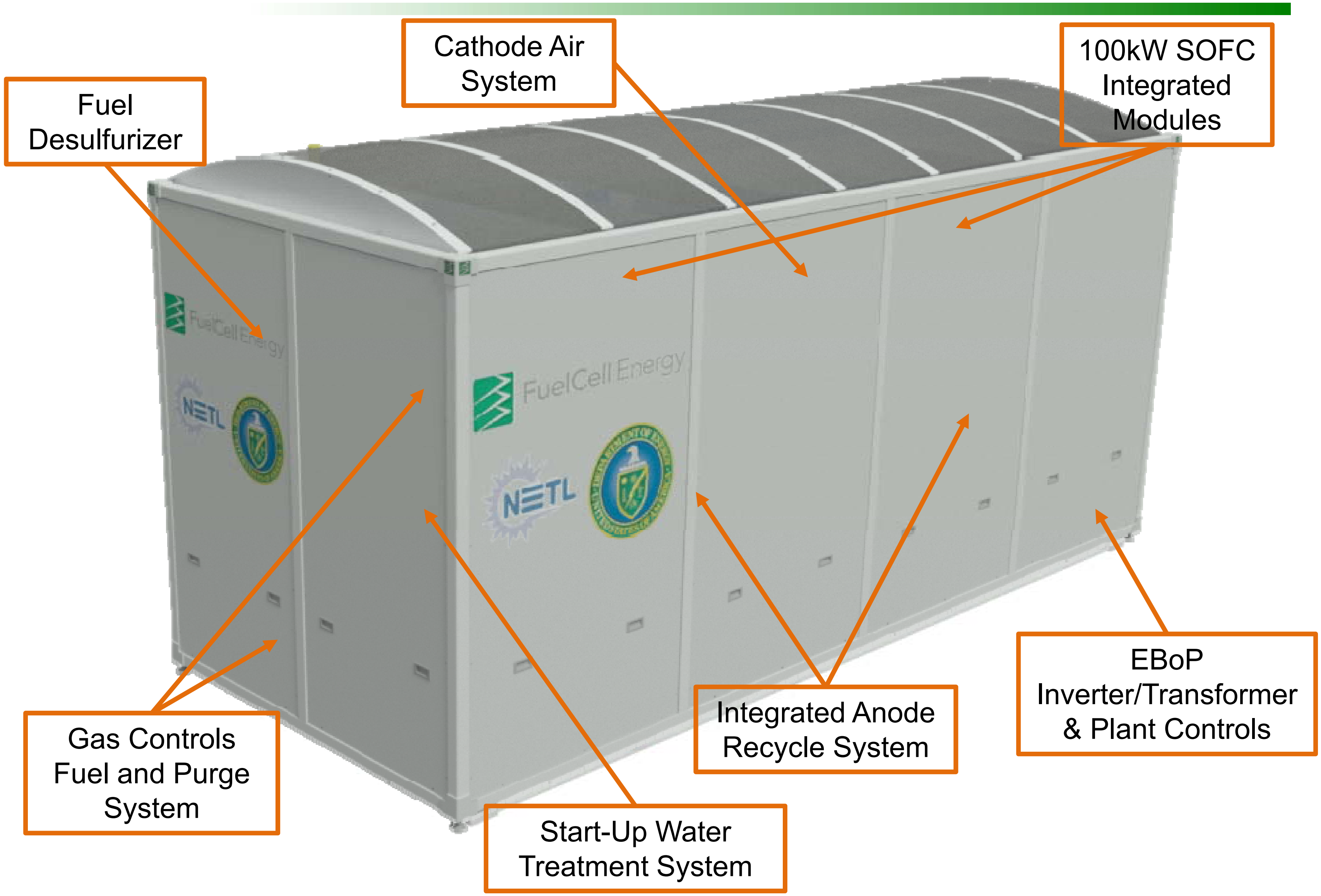

➡ **200 kW Modular Power Block (MPB) system is designed to validate stack reliability and serve as FCE's market-entry SOFC product.**

# *100kW SOFC Modular Power Block (MPB)*




100 kW SOFC Module Includes 8 Baseline Stacks Arranged in 4 Towers of Two Stacks Each

# *200kW SOFC Power System Layout*




- **Includes (2) 100kW SOFC Module Power Blocks (MPB) designed to operate independently**
- **Factory assembled & shipped as a standard ISO 20' x 8' ontainer**

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# 400kW SOFC System Project


- The 400 kW SOFC system consists of two 200 kW SOFC power plants
- Each 200 kW skid is sized as standard ISO 20’ x 8’ shipping container
- Thermally integrated modules enable compact and lower cost system
- Unattended Operation with Remote Monitoring
- >60% Electrical Efficiency
- >5000 hours of operation
- Heat recovery capability for up to 80% total thermal efficiency

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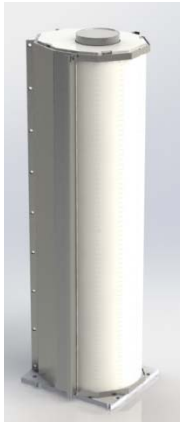
# *Innovative SOFC Concepts*

Current Pre-Commercial Integrated Manifold (PCI) Stack

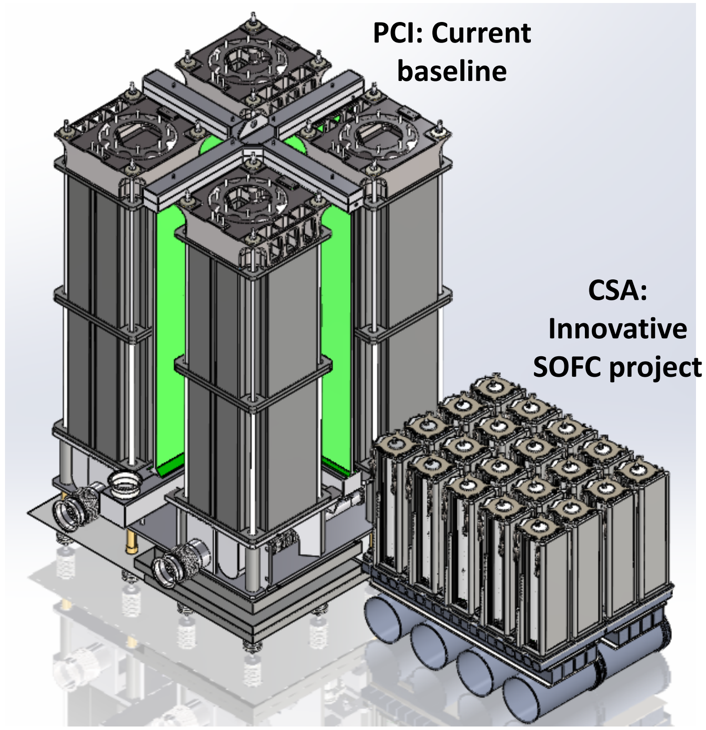


Compact SOFC Architecture (CSA) Stack with ~10-fold Increase in W/kg Power Density

- **Objective**

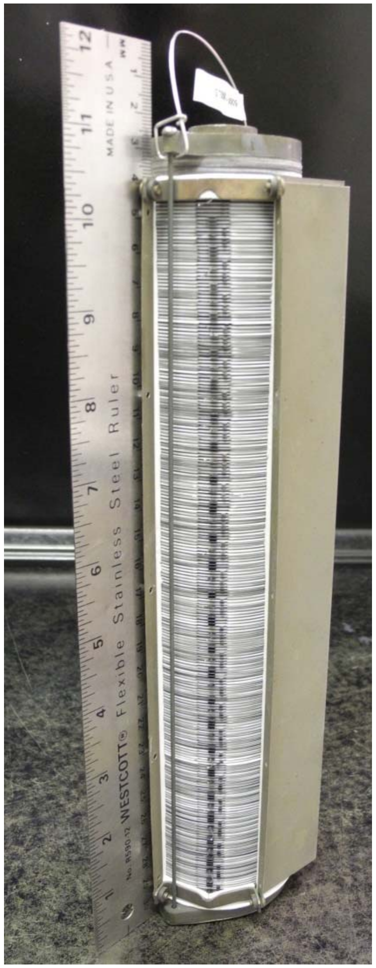
  Develop an innovative stack design enabling significant reduction in stack cost relative to baseline stack design (PCI)

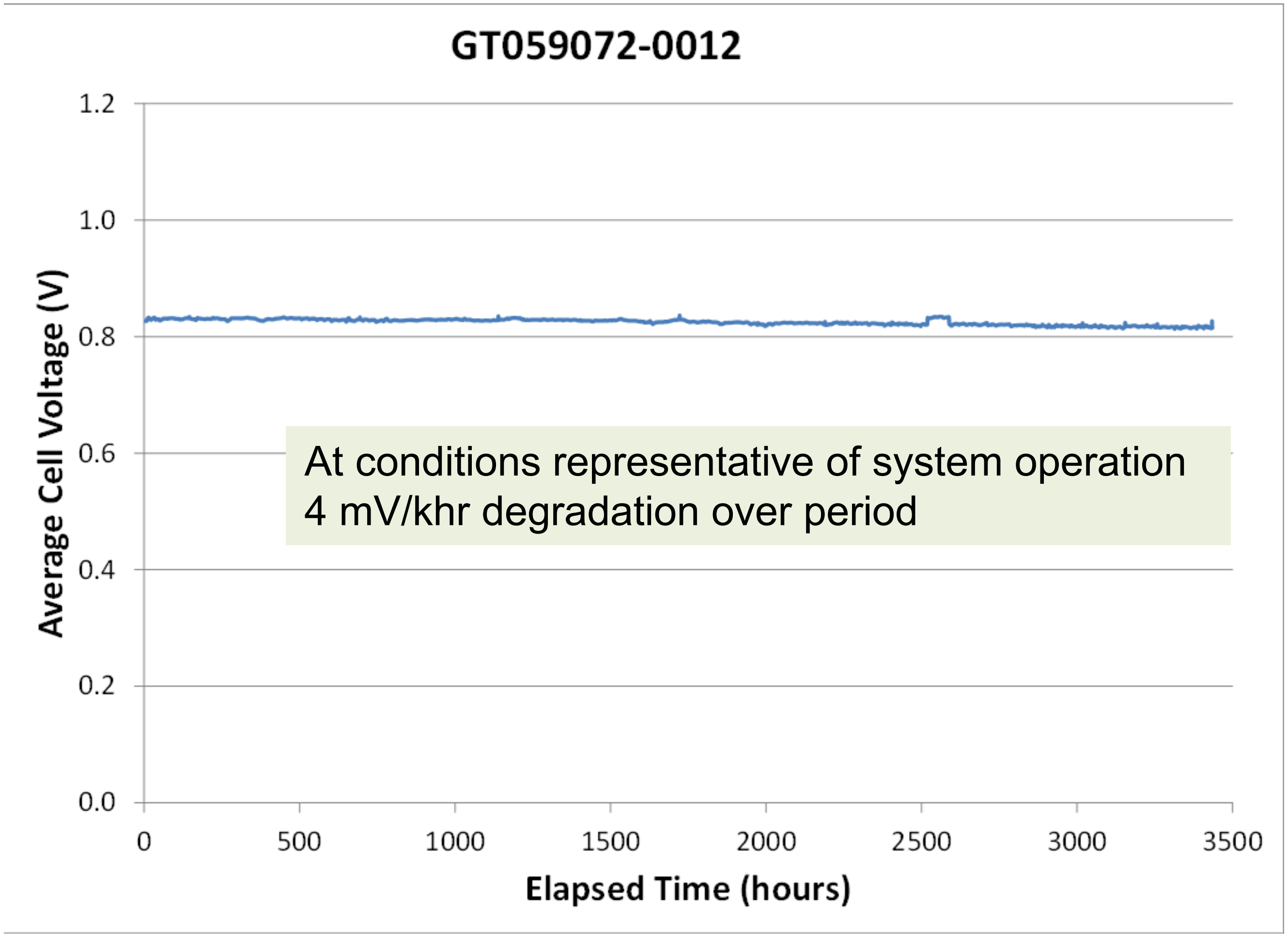
- **Approach**
  - Thinned components to reduce stack material content
  - Use of same cell, interconnect and coating materials validated in the PCI platform
  - Increased cell count per stack and simplified end plates
  - Designed for automated assembly
  - Simplified and fewer discrete components
  - Optimized thermal and flow design to control temperature variations




Comparison of 100 kW Stack Module Based on Current PCI Stack Design (Left) and CSA Stack Design (Right)

# Progress to Date on Key Technical Issues




225-cell CSA Style Stack – Fabrication and Test

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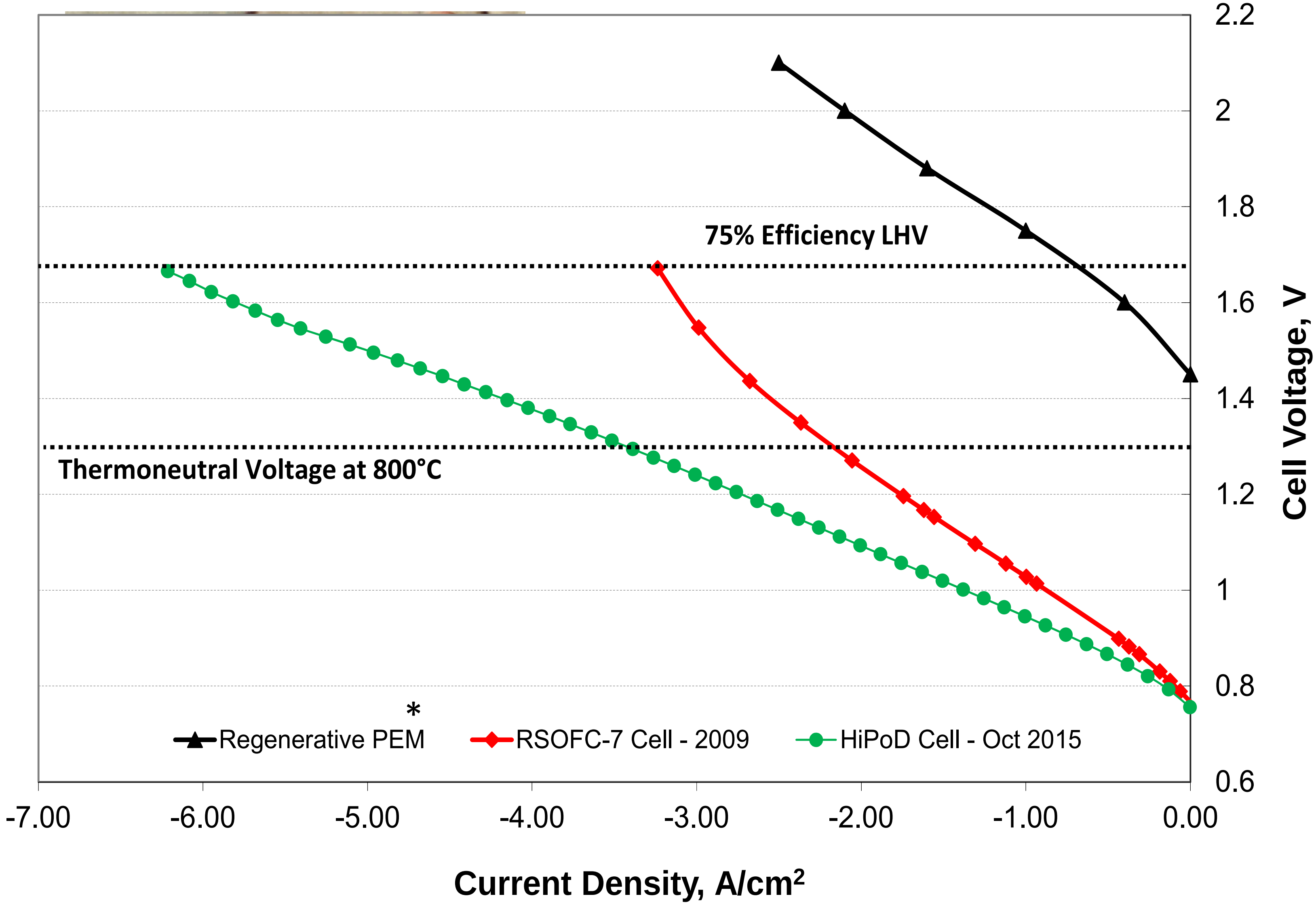
# High Power Density Cell Polarization Comparison




* *Research Advances towards Low Cost, High Efficiency PEM Electrolysis.* **K.E. Ayers, E. B. Anderson, C. B. Capuano, B. D. Carter, L. T. Dalton, G. Hanlon, J. Manco and M. Niedzwiecki.** 1, 3-15, s.l. : ECS Trans., 2010, Vol. 33.

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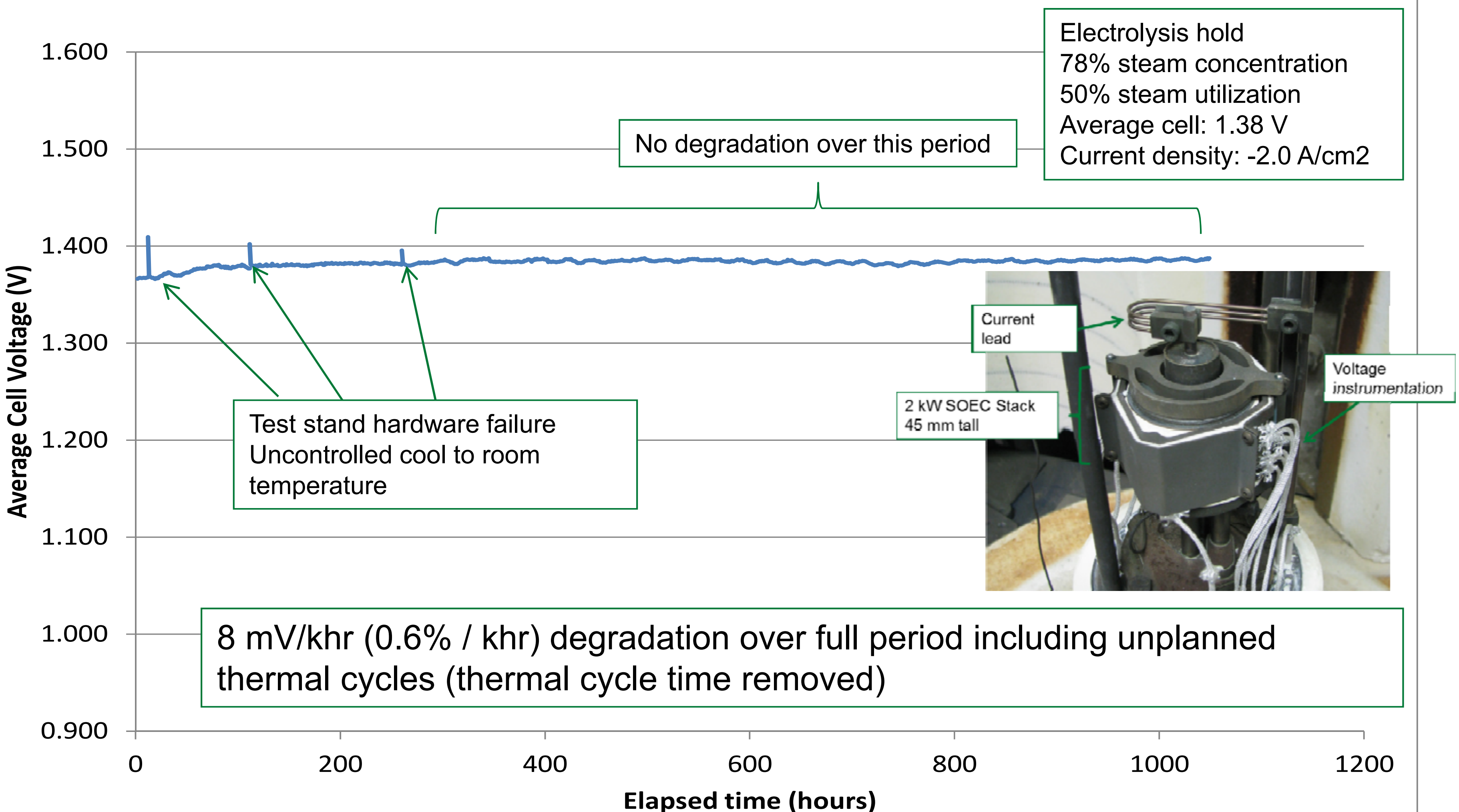
# *Electrolysis Stack Endurance*



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# Achievements

- Developed new Gen 2.0 Cr-mitigation strategies (interconnect coatings and Cr-tolerant materials) and validated the optimized materials sets in single-cell tests with 10% $H_2O$ concentration in cathode air
- Achieved fabrication of thin cells (~ 300 micron) with excellent performance and endurance, capable of operating at high fuel utilizations (>95%)
- 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 about 2 years
- Completed fabrication and testing of a highly integrated 50kW Proof-of-Concept (POC) system for testing of 4 large-area full height stacks in system environment
- Completed 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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