# SOFC Development Update at FuelCell Energy

**Stephen Jolly and Hossein Ghezel-Ayagh (PI)**

**18th Annual Solid Oxide Fuel Cell (SOFC) Project Review Meeting**
**Pittsburgh, PA**

**June 12-14, 2017**

# Outline

- **Introduction**
  - Project Objectives
  - FCE’s SOFC Development and Deployment Pathway
- **Progress in SOFC Technology**
  - Cell Technology Development
  - Cell and Stack Manufacturing
  - Transformational Technologies for Breakthrough Cost Reduction
- **System Development and Testing**
  - 200 kW System Development and Testing
  - 100 kW Modular Power Block (MPB) Development
  - MW-class Module Concept
  - Related System Applications
- **Summary**

# Project Objectives

**Develop SOFC technology suitable for ultra-efficient central power generation systems (coal and natural gas fuels) featuring ≥97% $CO_2$ capture with significantly lower costs (≥ 20% lower) than Baseline approaches**

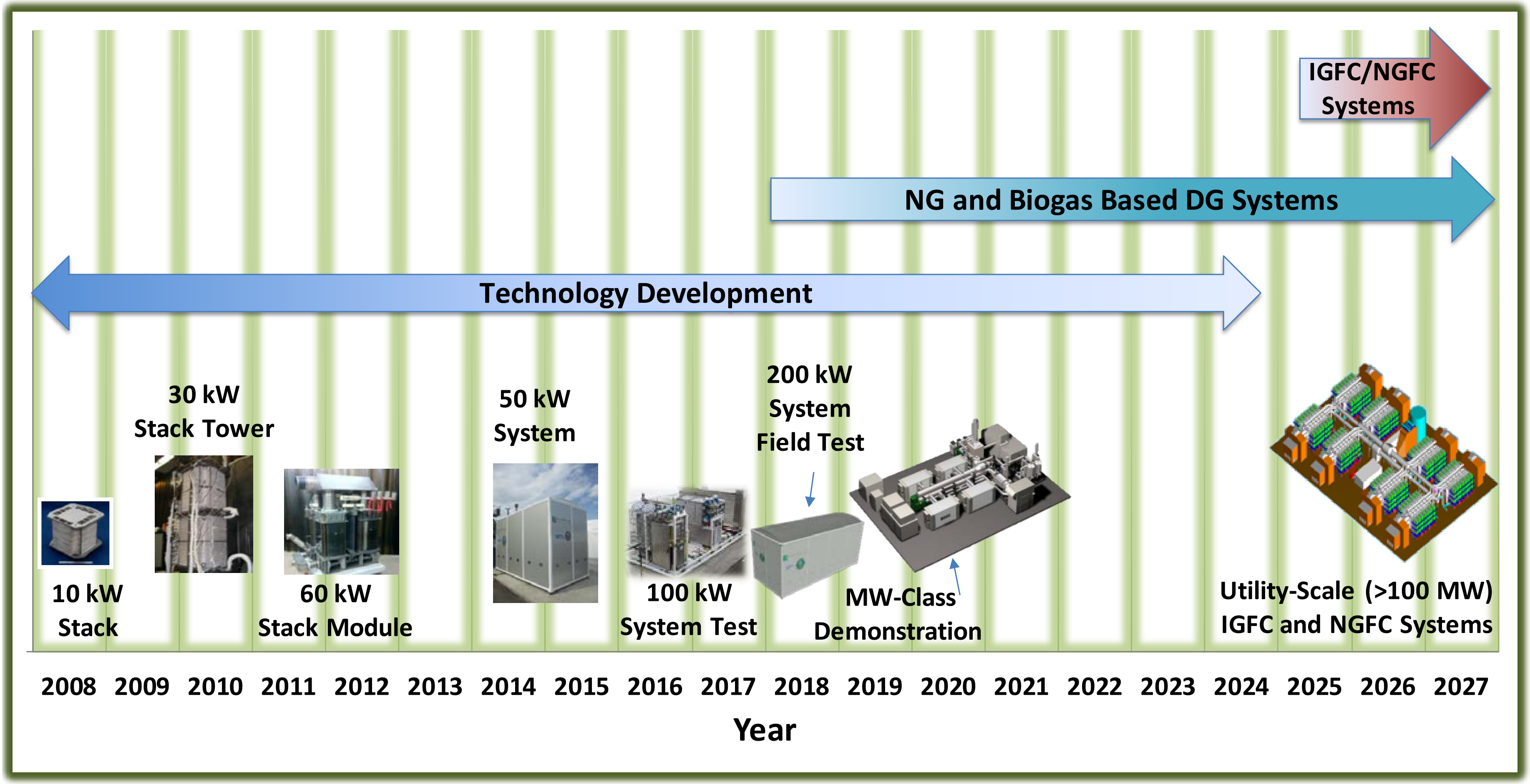
Conduct cell & stack R&D focusing on performance, reliability, cost and manufacturing enhancements

Develop Innovative SOFC cell and stack technologies with the potential for transformational performance and cost characteristics

Design, build and operate 100-200 kW demonstration systems using natural gas fuel to validate stack operation in the field

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

# SOFC Technology Development & Deployment Roadmap




- Ongoing technology development and system field testing is laying the foundation for cost-competitive DG and centralized SOFC power systems

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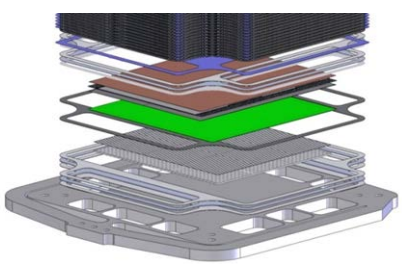
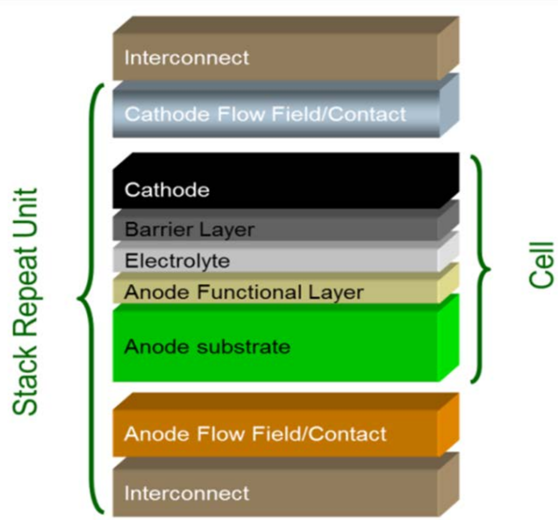
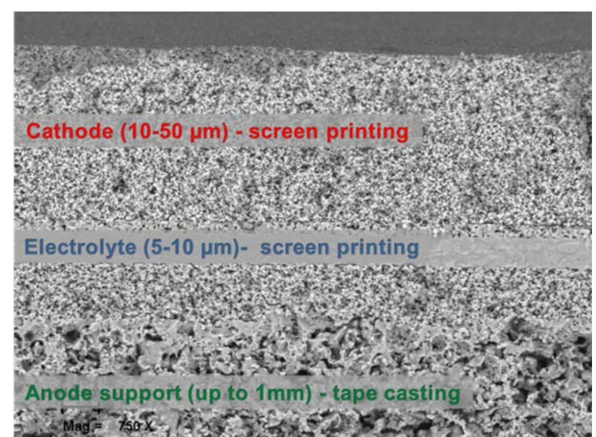
# Cell and Stack Technology Overview

- Cell:
  - Planar anode supported
  - 0.6 X 250 X 250 mm with 550 $cm^2$ active area
  - Manufactured by tape casting, screen printing and co-sintering
- Stack
  - Ferritic stainless steel sheet Interconnect
  - Compressive ceramic seal
  - Integrated manifolding with formed flow field layers
  - 120 Cells in a standard stack with 16 kW output @ 160 A

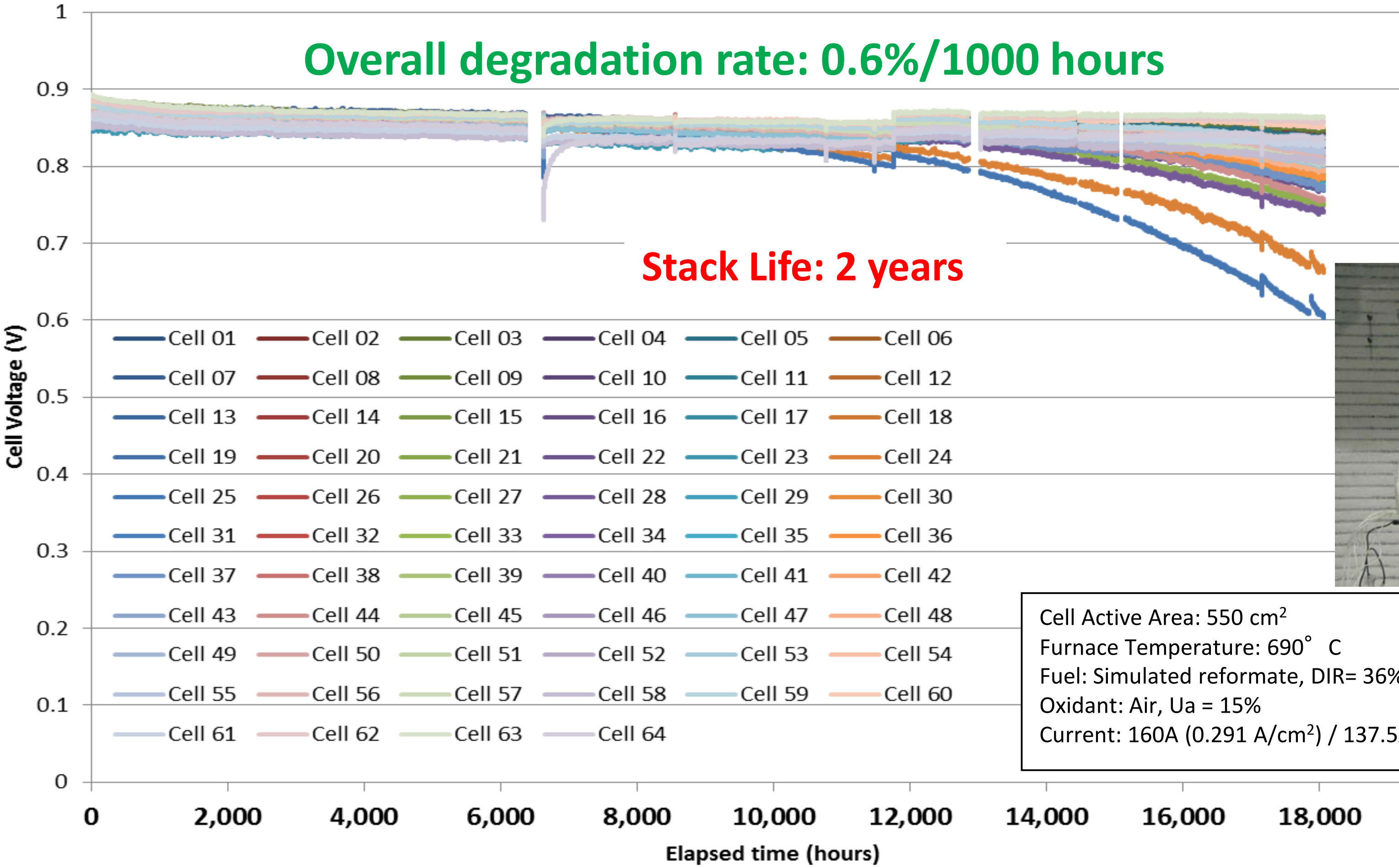




# 64 cell Large Area Stack Testing with Cr Tolerant Technology Gen 1.0




Cell Active Area: 550 $cm^2$
Furnace Temperature: 690° C
Fuel: Simulated reformate, DIR= 36%, Uf = 68%
Oxidant: Air, Ua = 15%
Current: 160A (0.291 $A/cm^2$) / 137.5A (0.250 $A/cm^2$)

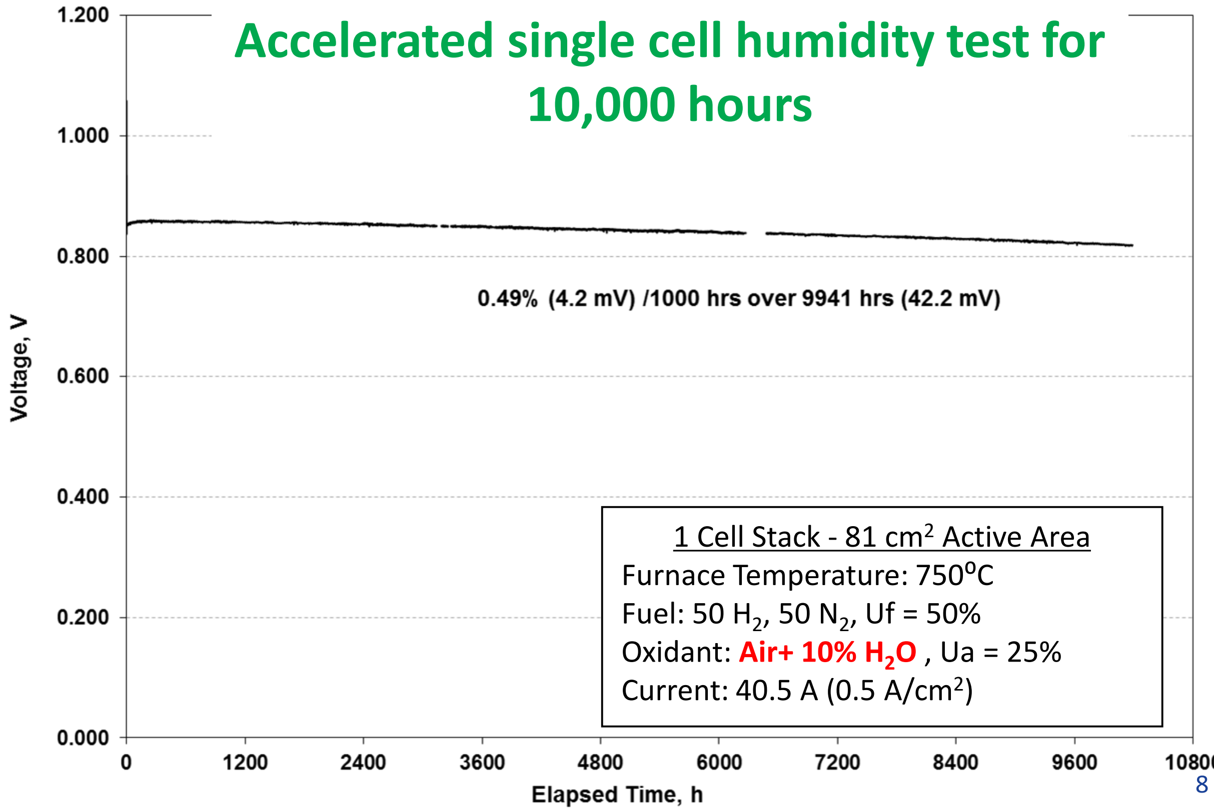
| Identified Issues | Improvement |
|---|---|
| Inadequate contact | Contact paste and contact / seal balance optimization |
| Cr poisoning | Cr tolerant technology development |
| Manufacturing Reliability | Gage R&R, production and QC tooling improvement |

# Improving Cr Getter and Interconnect Coating

- Improve coating coverage
- Ce doped Co-coated IC
- Gen 2.0 Cr Getter

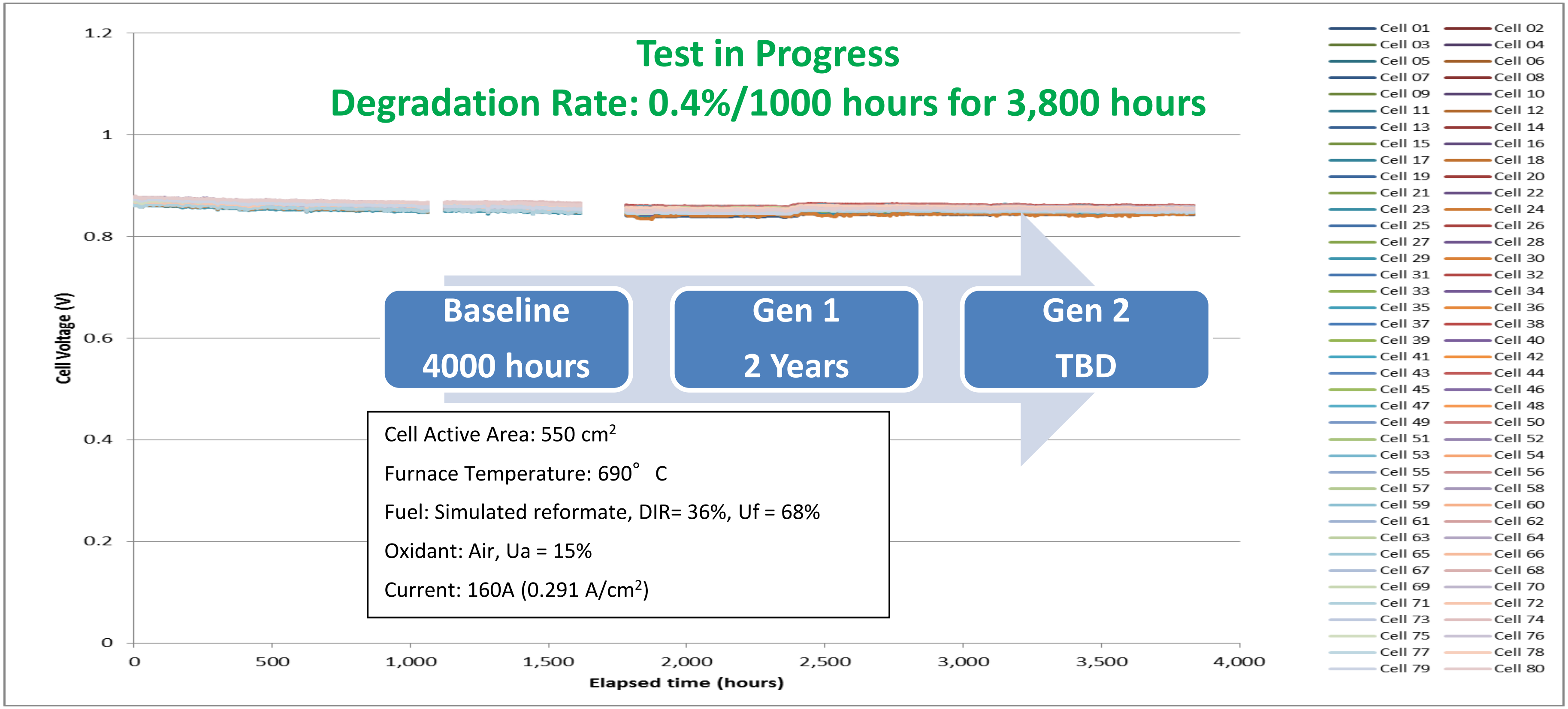
| Baseline | Gen 1 | Gen 2 |
| --- | --- | --- |
| > 15%/1000h | 0.63%/1000h | 0.49%/1000h |

- Gen 2.0 Cr Getter development was focused on improving stability and compatibility of the Cr Getter
- Unique fabrication process was developed to make on-cell Cr Getter stable
- Optimized Cr Getter composition and design were down selected as Gen 2.0 Cr Getter technology for stack

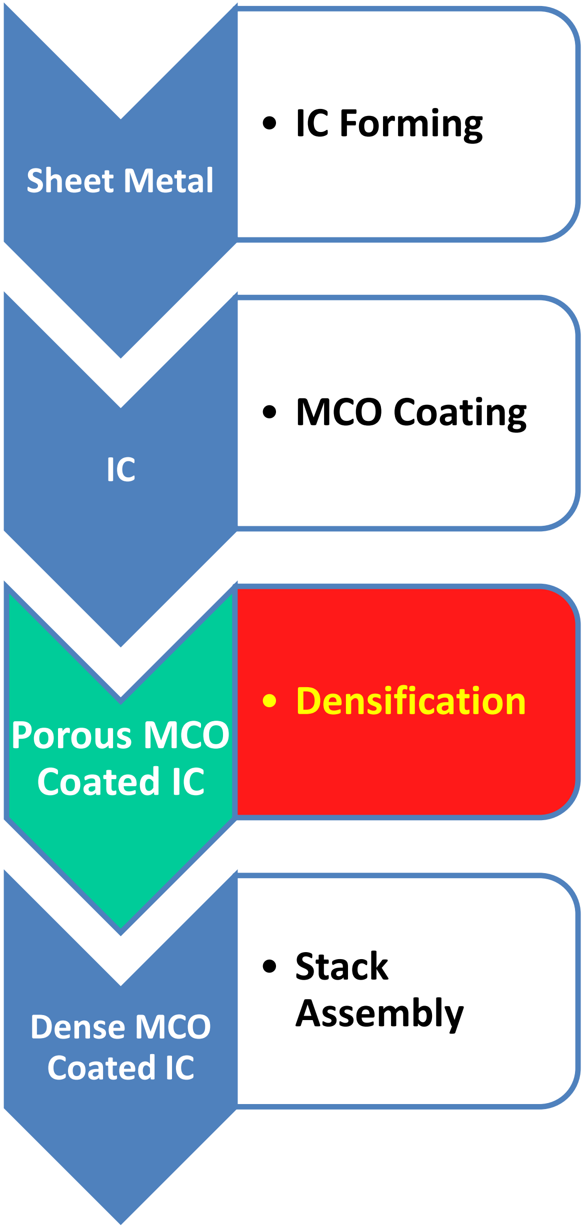


# Validation Test: 80-Cell Large Area Stack with Gen 2 Cr Tolerant Technology

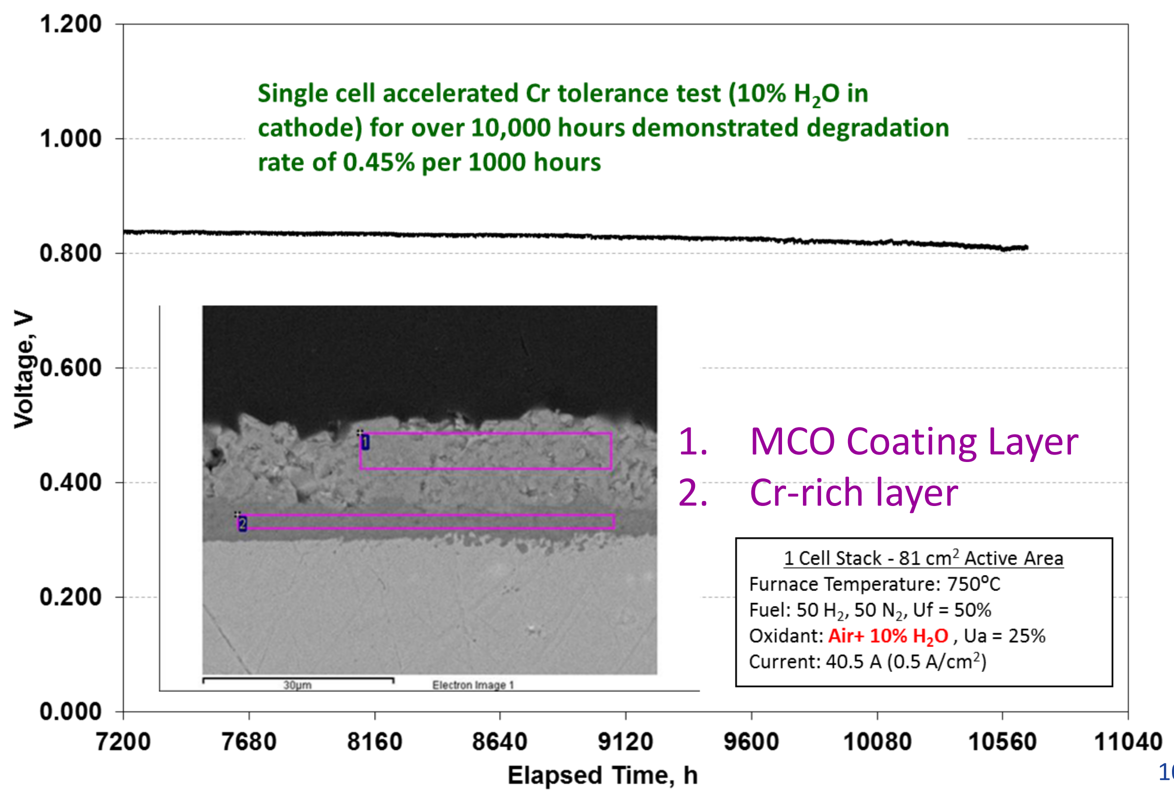
| Identified Issues | Improvement | Results |
|---|---|---|
| Inadequate contact | Contact paste and contact / seal balance optimization | Less than 20 mV voltage spread after 3800 hours of stack operation |
| Cr poisoning | Cr tolerant technology development | Gen 2 Cr tolerant technology is under evaluation with a 80-cell stack. So far the degradation rate is 0.4% per 1000 hour |
| Manufacturing Reliability | Gage R&R, production and QC tooling improvement | Incorporated in the cell/stack manufacturing for ongoing production and future deliverable stacks |



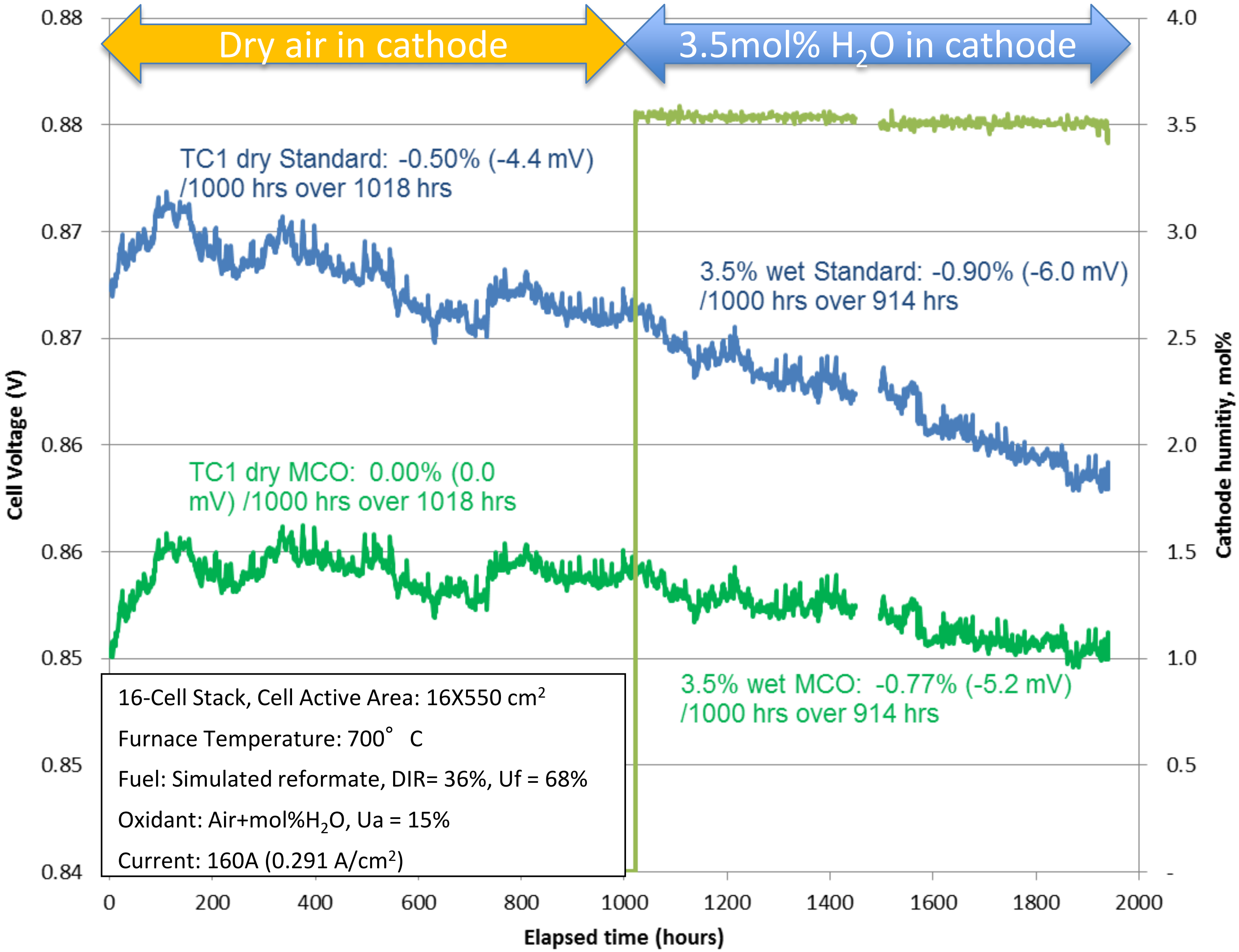
# Ex-situ MCO Coating Technology




- Issues with ex-situ MCO coating
  - **High-temperature (>800 °C) reducing atmosphere densification process leads to high cost and oxides forming at anode side IC**
- FCE MCO coating focus on simpler densification process at lower temperature
- Various sintering aids were added to MCO coating



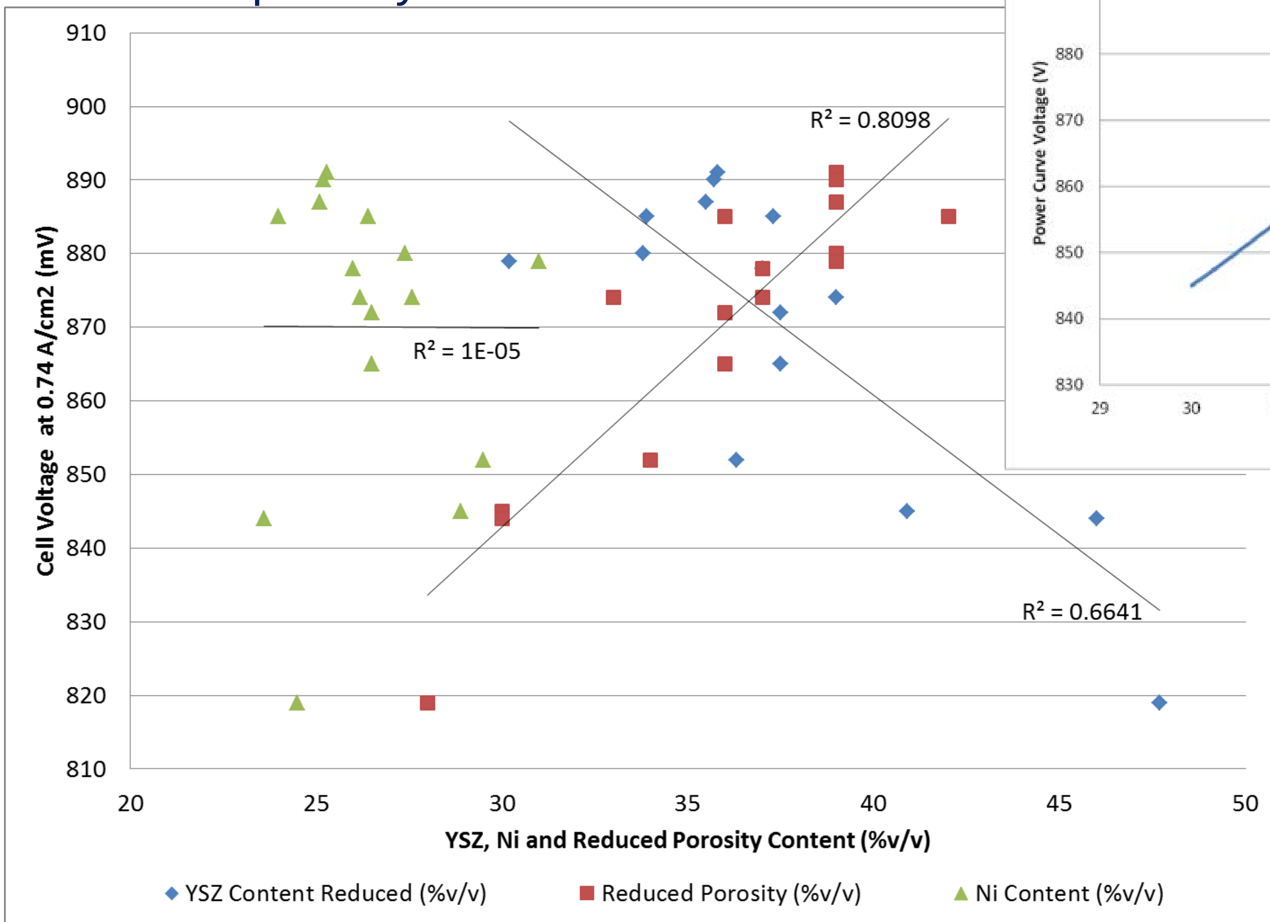
# 16-Cell Parametric Stack Testing (In Progress)
# Standard Co-Coating vs. MCO Coating

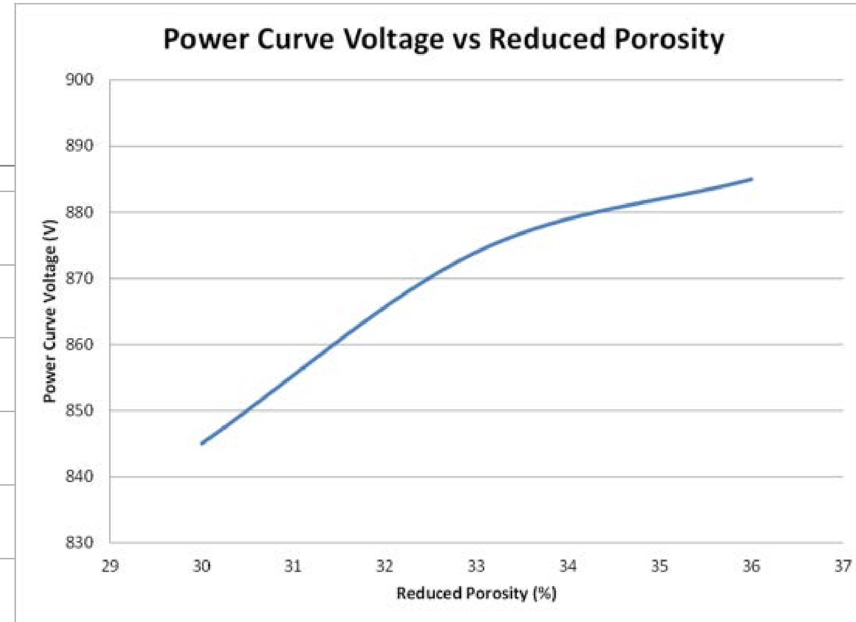


# Advanced Cell Development: Anode Substrate Structure Optimization

Cell performance has:

- Strong and positive correlation with anode porosity



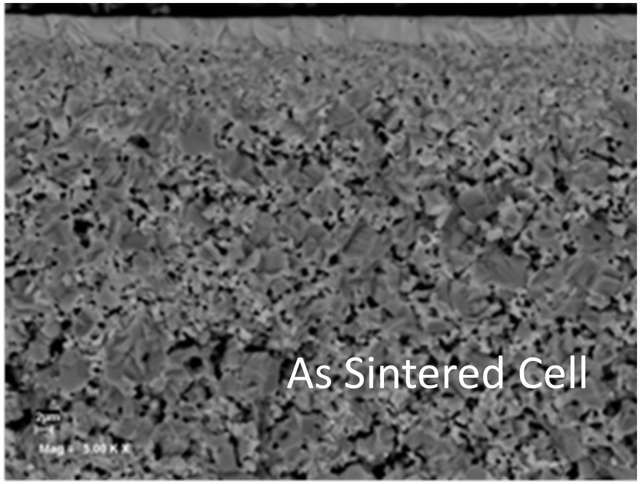



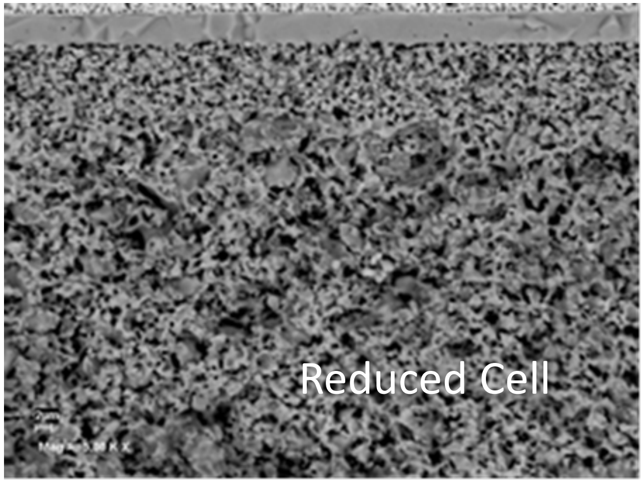

Cell performance has

- Weak and negative correlation with YSZ volume
- No correlation with Ni volume

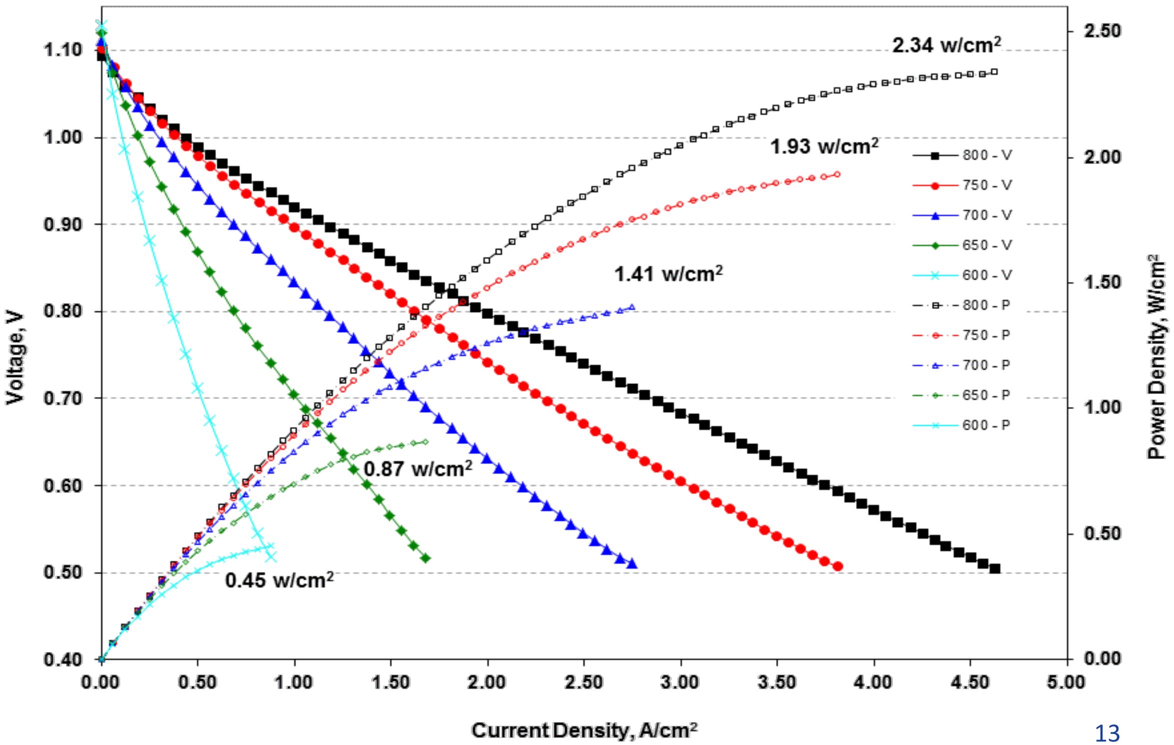
# Advanced Cell Development: Anode Substrate Thickness Reduction

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




**Recent anode development has further improved cell performance (2.34 W/cm² at 4.7 A/cm²)**



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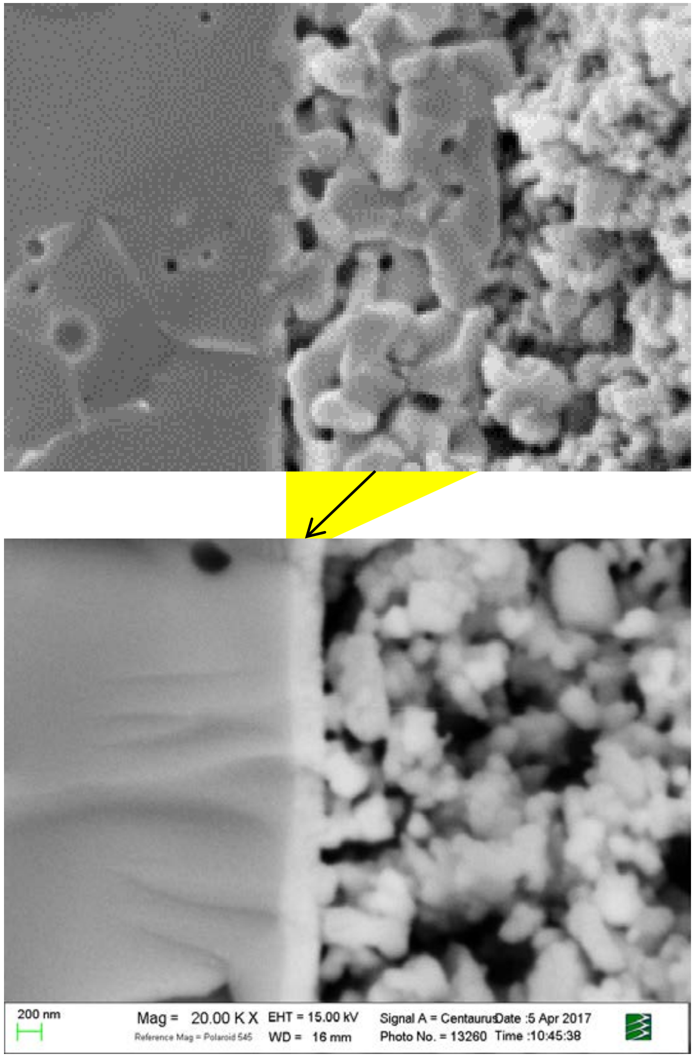
# Advanced Barrier Layer Manufacturing

**_Objective:_**

Reduce thickness and increase density of the GDC barrier layer utilizing advanced manufacturing techniques to reduce cost and improve performance



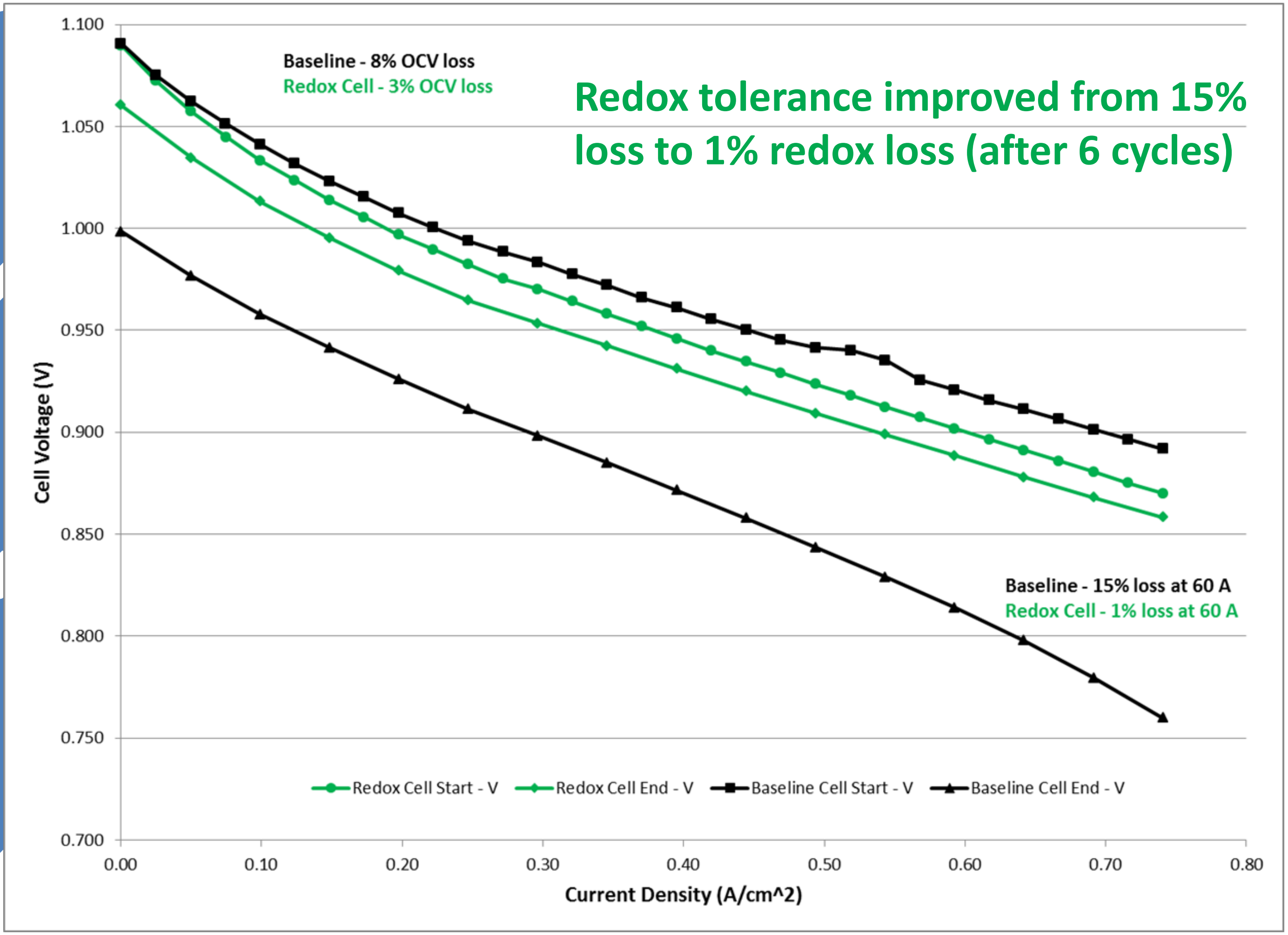

**_Innovative Solutions Being Explored:_**

1. **Atomic Layer Deposition (ALD)** to form a very thin (tens of nanometer) and fully dense barrier layer
   - ALD is commercially used in a wide variety of applications, including ZrO2 films for DRAM capacitors and barrier coatings for displays
   - ALD can be scaled up cost effectively (large batch processing)

2. **Reactive Spray Deposition Technology (RSDT)** for cost-effective manufacturing of dual-layer GDC barrier layer and cathode electrode on sintered half-cells
   - RSDT is a low cost, rapid processing method that can be performed in one continuous process without the need for long sintering times at elevated temperatures
   - Deposition is highly customizable (manipulation of process parameters), thereby allowing a single process to deposit a dense or a porous layer

# Status of Redox Tolerance Improvement

Implementing multi-prong approaches in developing innovative redox tolerant anode-supported cell through reducing anode strain upon Ni re-oxidation

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# Baseline Cell Manufacturing Process Flow

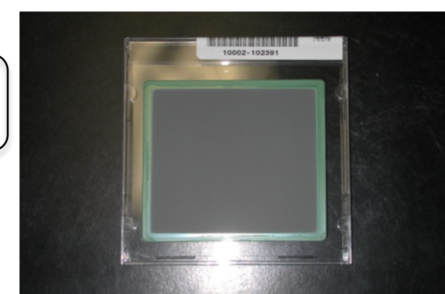

Raw Materials


Raw Materials

Anode Tape


Unfired Cell

Fired Cell



# Cell and Stack Manufacturing Top-Level Process

## Cell Manufacturing

1. Powder & Paste
2. Half Cell Production
3. Cell Completion

## Seal Manufacturing

## Metallics Manufacturing

1. Anode and Cathode Flow Fields
2. Spot welding
3. Component kitting
4. Sub-assembly manufacturing

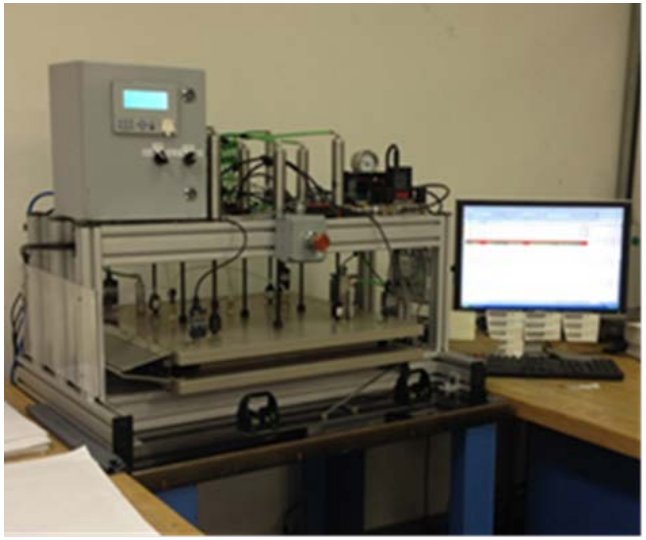
**Every Stack is Individually Conditioned and Undergoes Rigorous Factory Acceptance Tests**

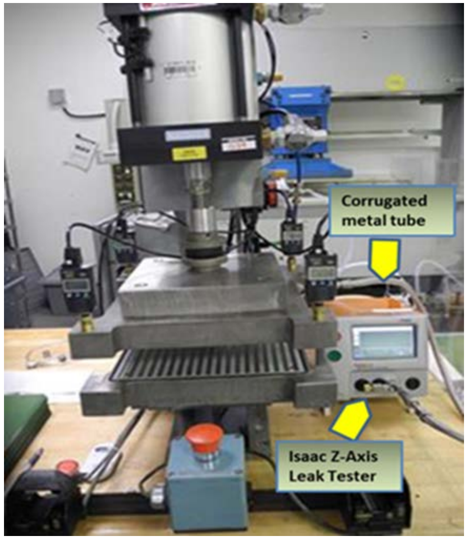
Stack Assembly → Conditioning & Acceptance Testing → Stacks for Module

**25kW Test Stands for Factory Acceptance Testing**

# Cell and Stack Manufacturing Quality & Quality Control - Example

- Individual stack performance is limited by weakest unit cell, so high reliability is required
- New cell thickness + leak test QC station implemented simulating thickness when compressed in stack with Total Gage Reproducibility and Repeatability (Gage R&R) of 6% (desired target < 30%) with 0.04 mm total tolerance



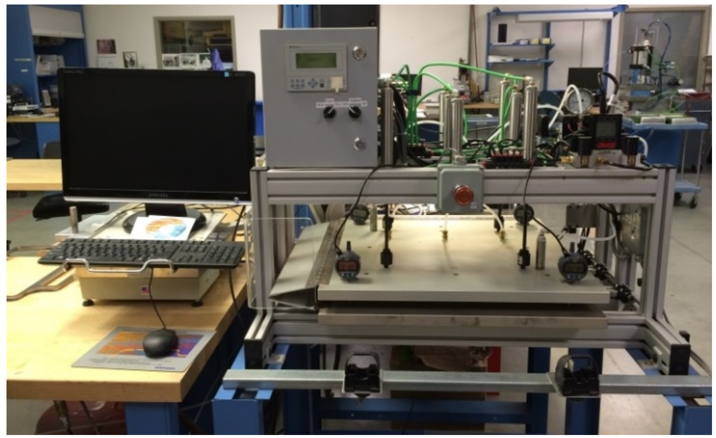



New High-Throughput & Combined Function QC Stations Ensure Quality Cell Components

# Cell and Stack Manufacturing
# Quality & QC Focus – Stack Metallics

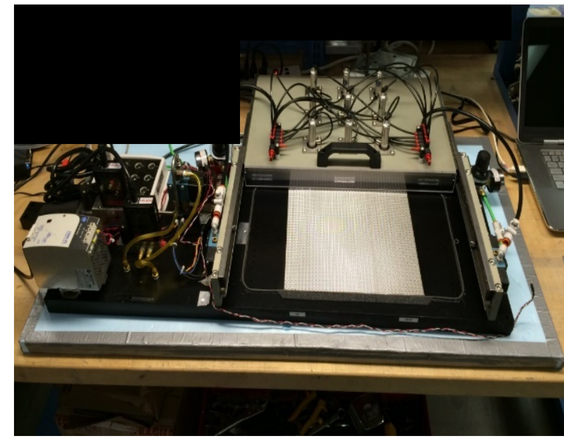

**Metallic Part QC Station**

*For smaller footprint contact / flow field materials*



**Double Hinge QC Station**

*For full footprint interconnect and shims*

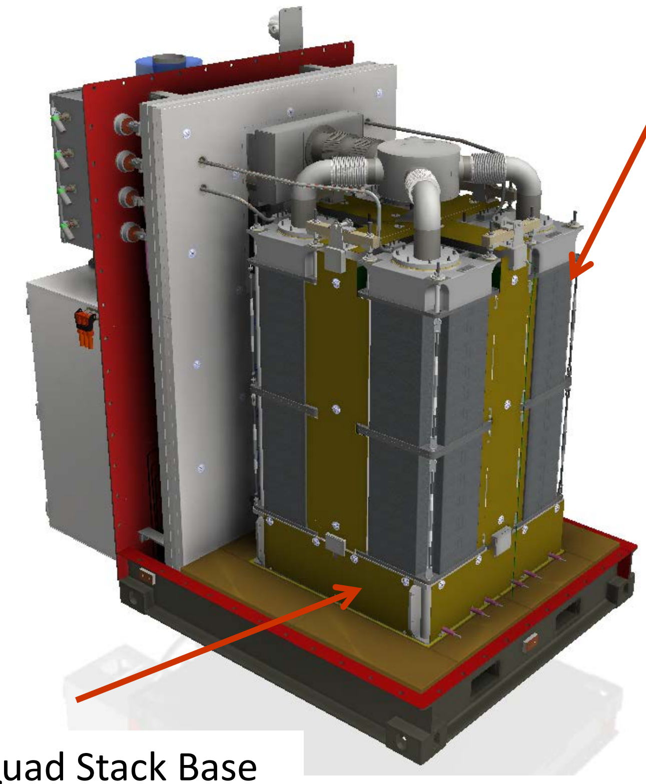


**Flow Field QC Station**

*For anode flow field screening*

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

# Stack Build & Acceptance Status for 200 kW System Field Test



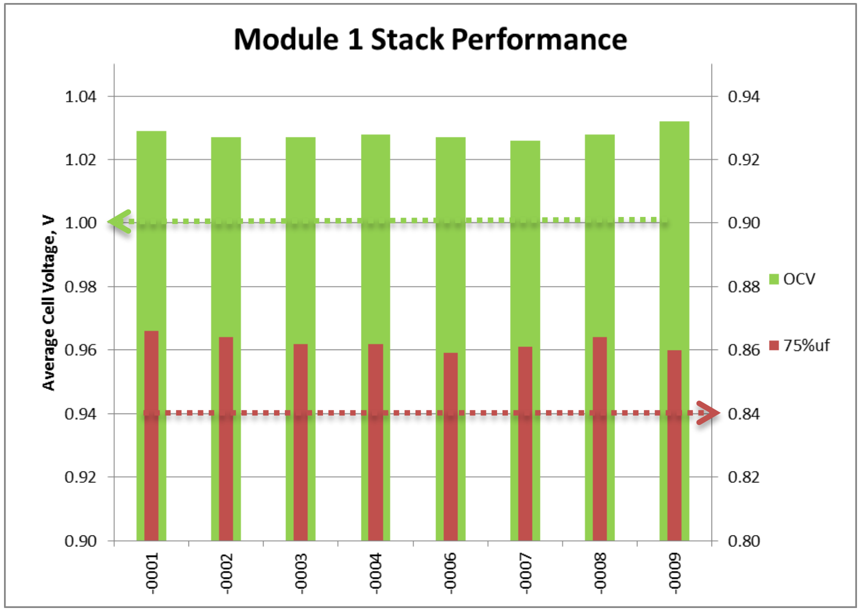

**Each 100 kW Stack Module includes 8 x 120-cell stacks (or 960-cells)**

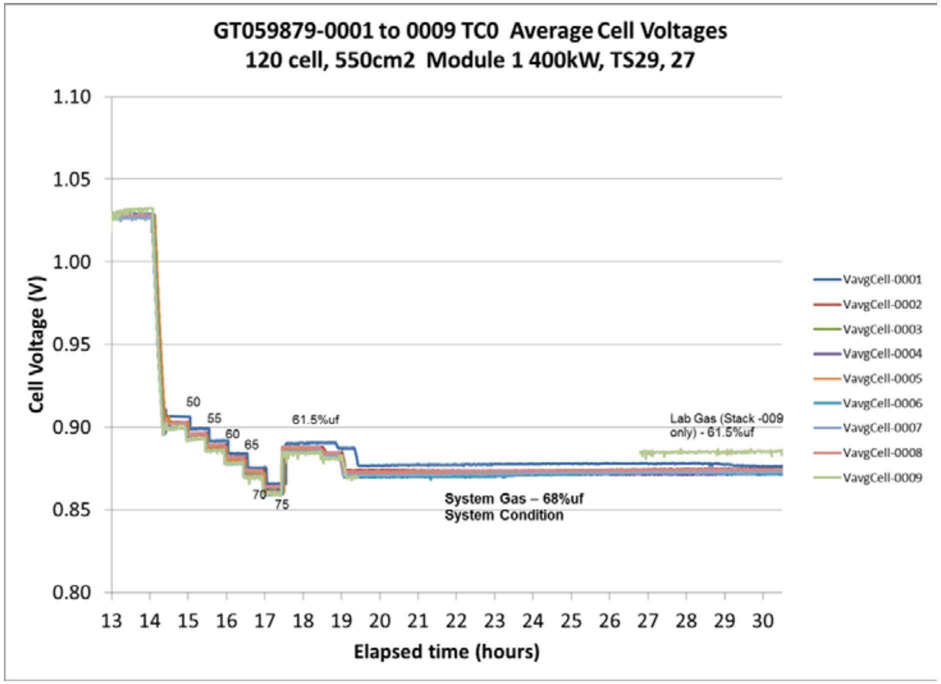
| Module 1 (100-01) (100 kW) | | Module 2 (100-02) (100 kW) |
|---|---|---|
| GT059879-0001 | | GT060322-0001 |
| GT059879-0002 | | GT060322-0002 |
| GT059879-0003 | | GT060322-0003 |
| GT059879-0004 | | GT060322-0004 |
| GT059879-0005 | | GT060322-0005 |
| GT059879-0006 | | GT060322-0006 |
| GT059879-0007 | | GT060322-0007 |
| GT059879-0008 | | GT060322-0008 |
| GT059879-0009 | | |

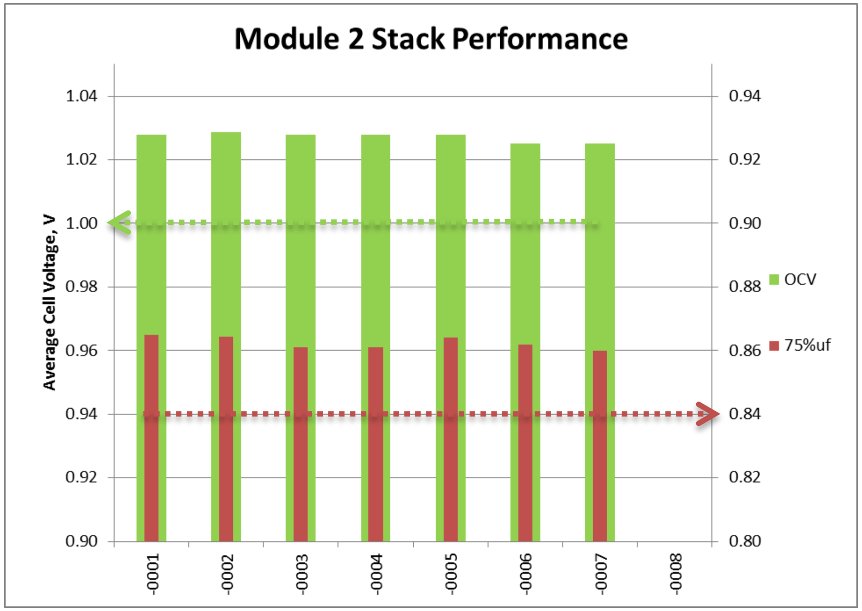
- **200 kW SOFC System: 15/16 = 94% complete (and 94% yield)**

*GT059879-0005 lost due to error in the stack assembly (One anode flow field was placed in reverse)

# Cell and Stack Manufacturing Factory Acceptance Testing Summary

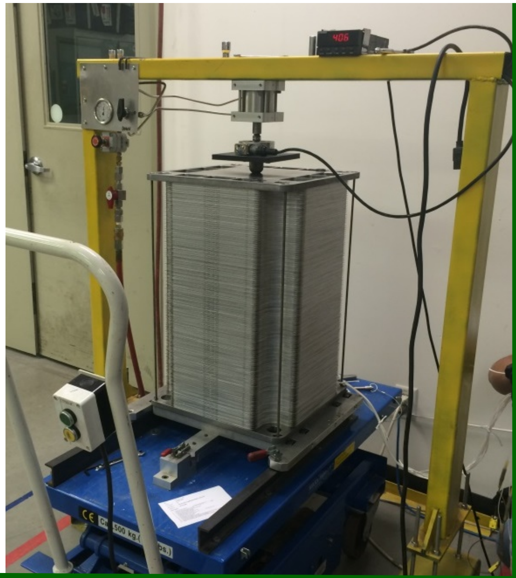


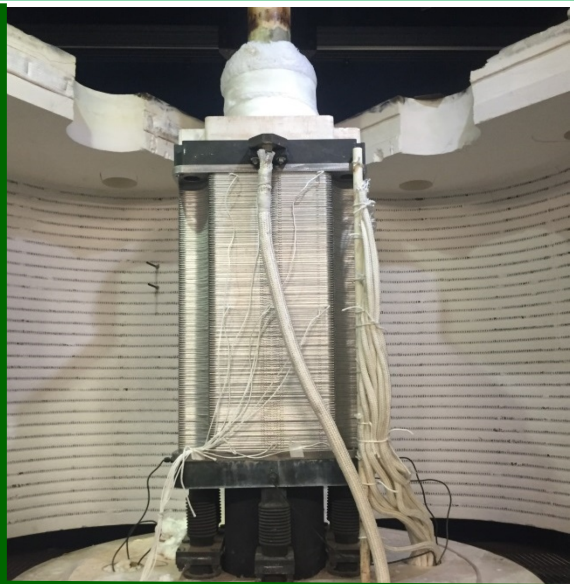




- Excellent stack to stack performance reproducibility at high fuel utilization
  - 0.8% difference (or +/- 0.4%) in average stack voltage
  - 7 mV standard deviation in individual cell voltages
- Stacks for Module 1 + 2 meet cell voltage criteria

# Stacks Built Will be Shipped to Danbury Facility for Module Integration





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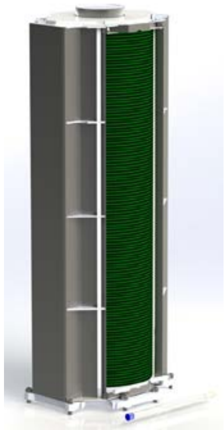
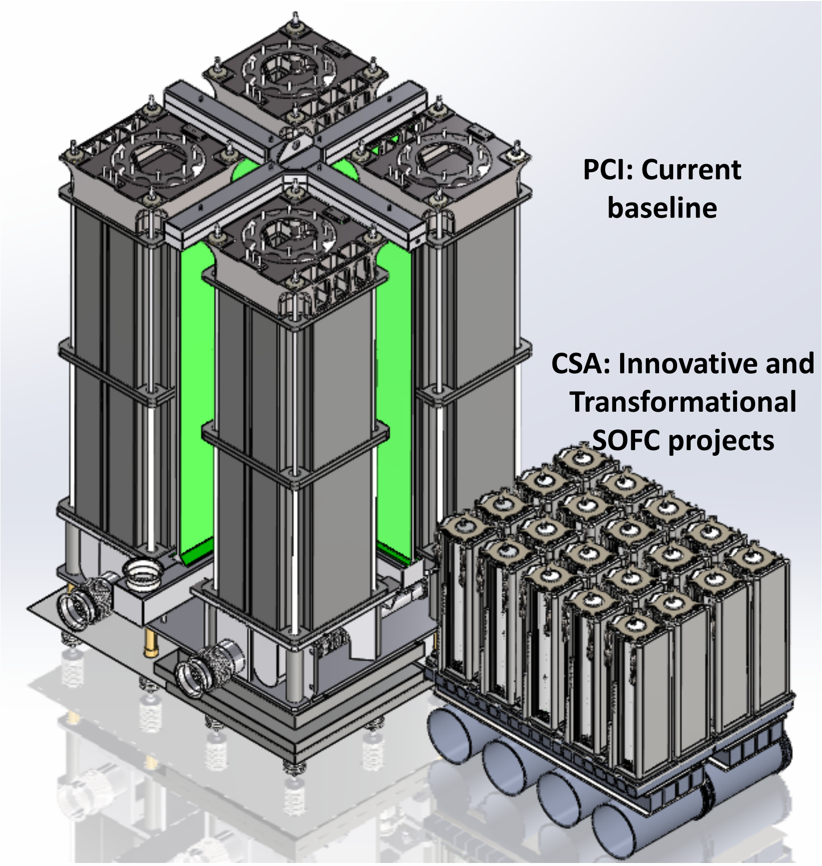
# Transformational SOFC Concepts

Current Pre-Commercial Integrated Manifold (PCI) Stack



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




Comparison of 100 kW Stack Modules

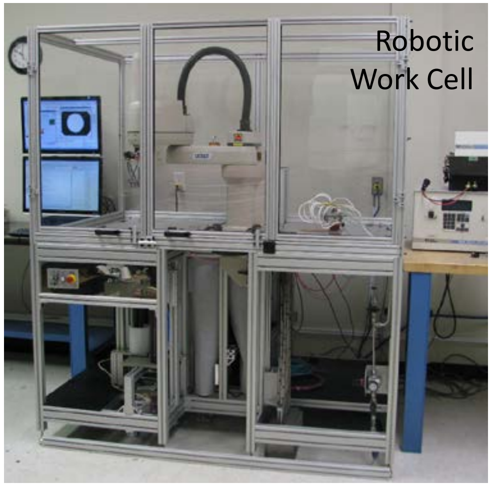
## Objective

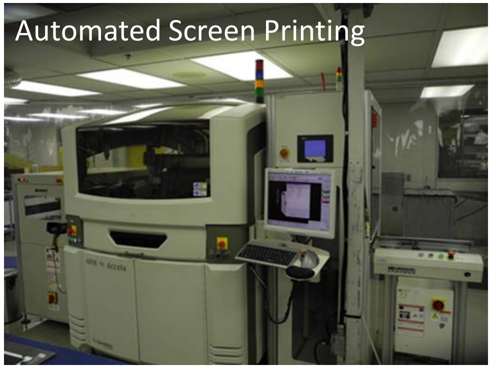
Develop an innovative stack design enabling significant (> 50%) reduction in stack cost relative to baseline stack design (PCI)

## Approach

Target significant savings in both cell and stack materials and production labor

# Approach to Cost Reduction




## Design Philosophy

- Thinned cell and stack components to reduce material content without impacting performance
- Stack design choices that simplify assembly steps and reduce unit cell part counts
- Increased cell count per stack (>300 cells)
- Use of same cell, interconnect and coating materials validated in the large area stack (PCI) platform

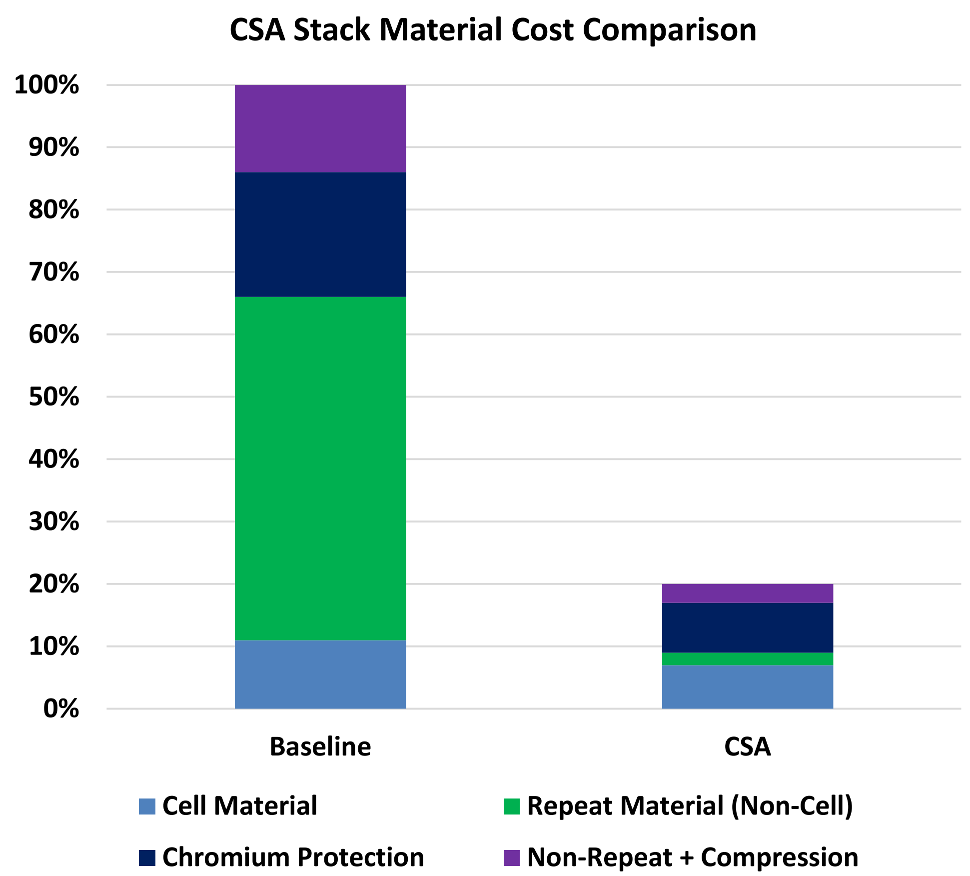
## Manufacturing Approach

- Design for advanced high-throughput manufacturing technologies for thin components taking cues from CD / DVD manufacture
- Utilize high speed pick and place robot (Adept i600) for efficient sub-assembly build, cell and component QC and precise cell / stack assembly
- Further innovation in cell and seal manufacture, as well as greater automation such as high speed automated screen printing

# Stack Materials

## Low Volume Raw Material Cost Comparison

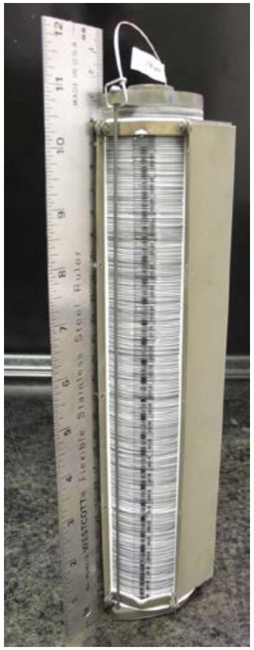
- Direct raw material content (steel, powders) of the baseline large area stack and CSA stack platform were compared from detailed bill of materials
- Basis:
  - Present day (0.3 MW/yr) material costs were selected
  - Stack performance on a per active area basis is identical

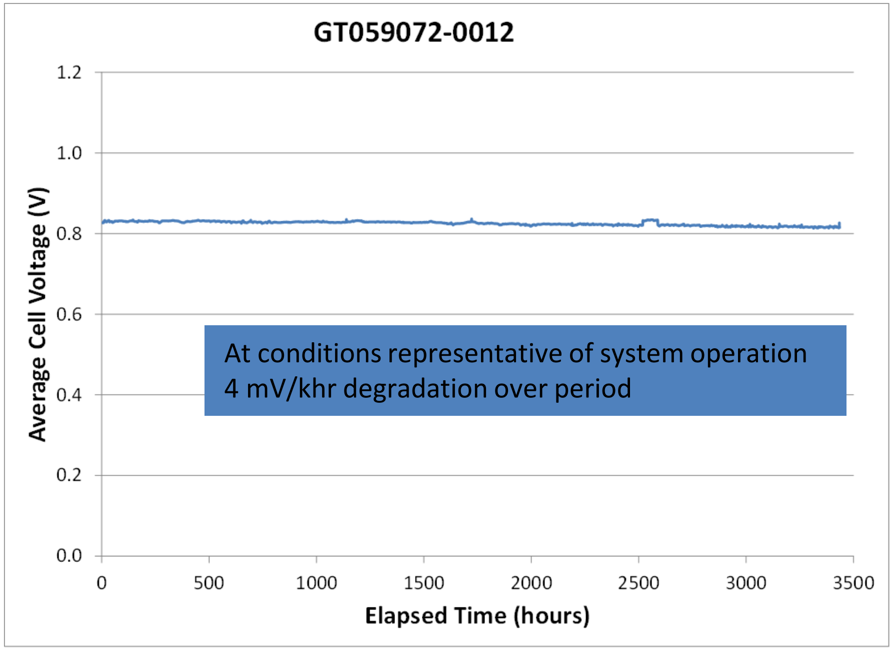



➢ Lightweight stack design translates directly to low amount (and cost) for input raw materials.

# CSA Stack Validation Status

- Initial detailed design for CSA stack completed
- Majority of parts in-house or on order
- Robotic manufacturing work cell 80% complete
- Targeting first build trials and stack testing starting in Q3 this year
- Thin cell performance and degradation successfully demonstrated and looking positive for stack integration



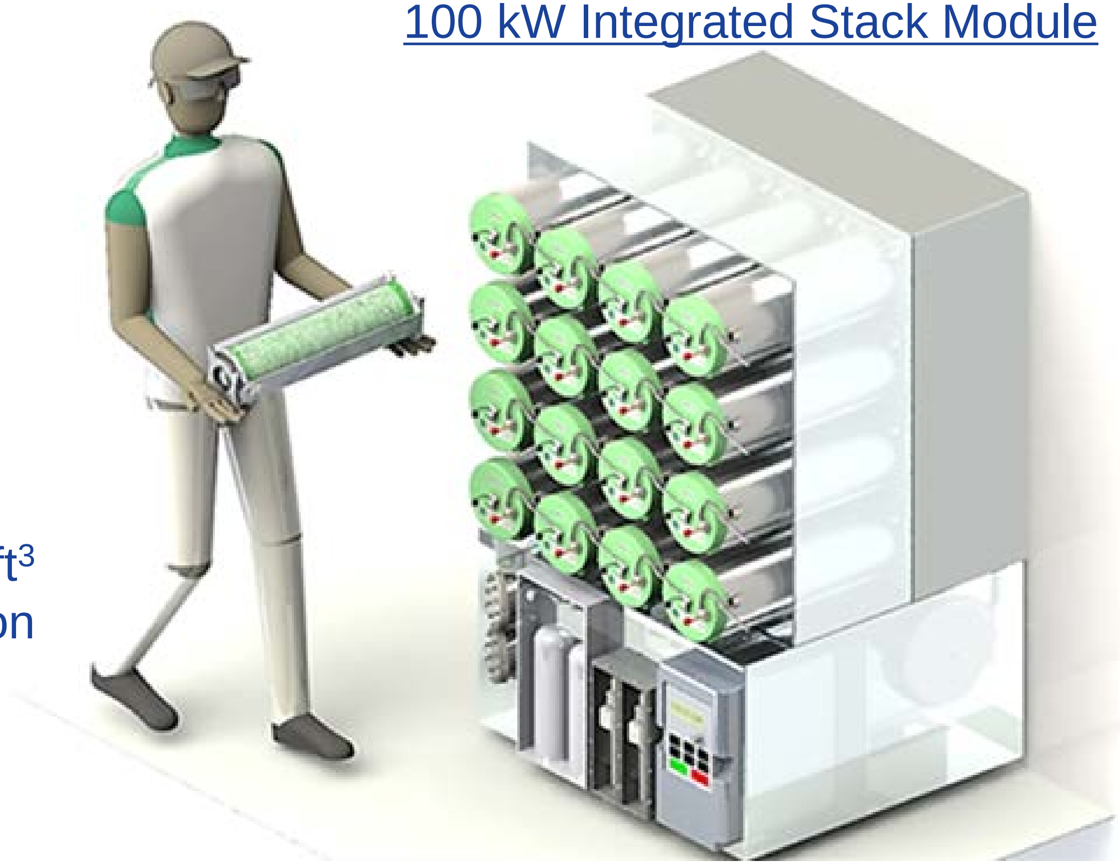



CSA-like Sub-Scale Demonstration Stack
Test under System Gas fuel conditions

# Integrated Module Design

- Includes close-coupled hot-BoP components
- Serviceable by a single technician, minimal tooling
- High availability due to sparing philosophy
- Potential for significantly lower $/kW and higher kW/ft$^3$ due to process intensification and compact stack design benefits

100 kW Integrated Stack Module



(Inverter and Fuel Desulfurization not shown)

➢ Transformational stack enables low-cost and compact hot-module designs that are scalable for MW-class systems

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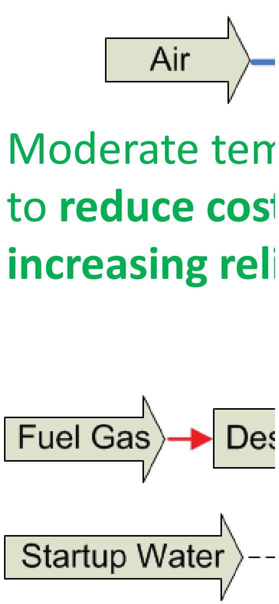
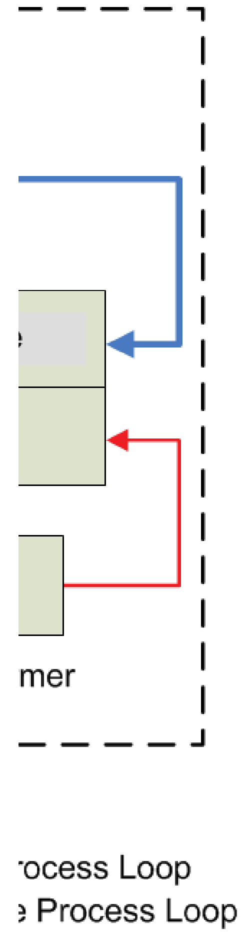
# 200 kW SOFC System




Moderate tem
to **reduce cos**
**increasing reli**

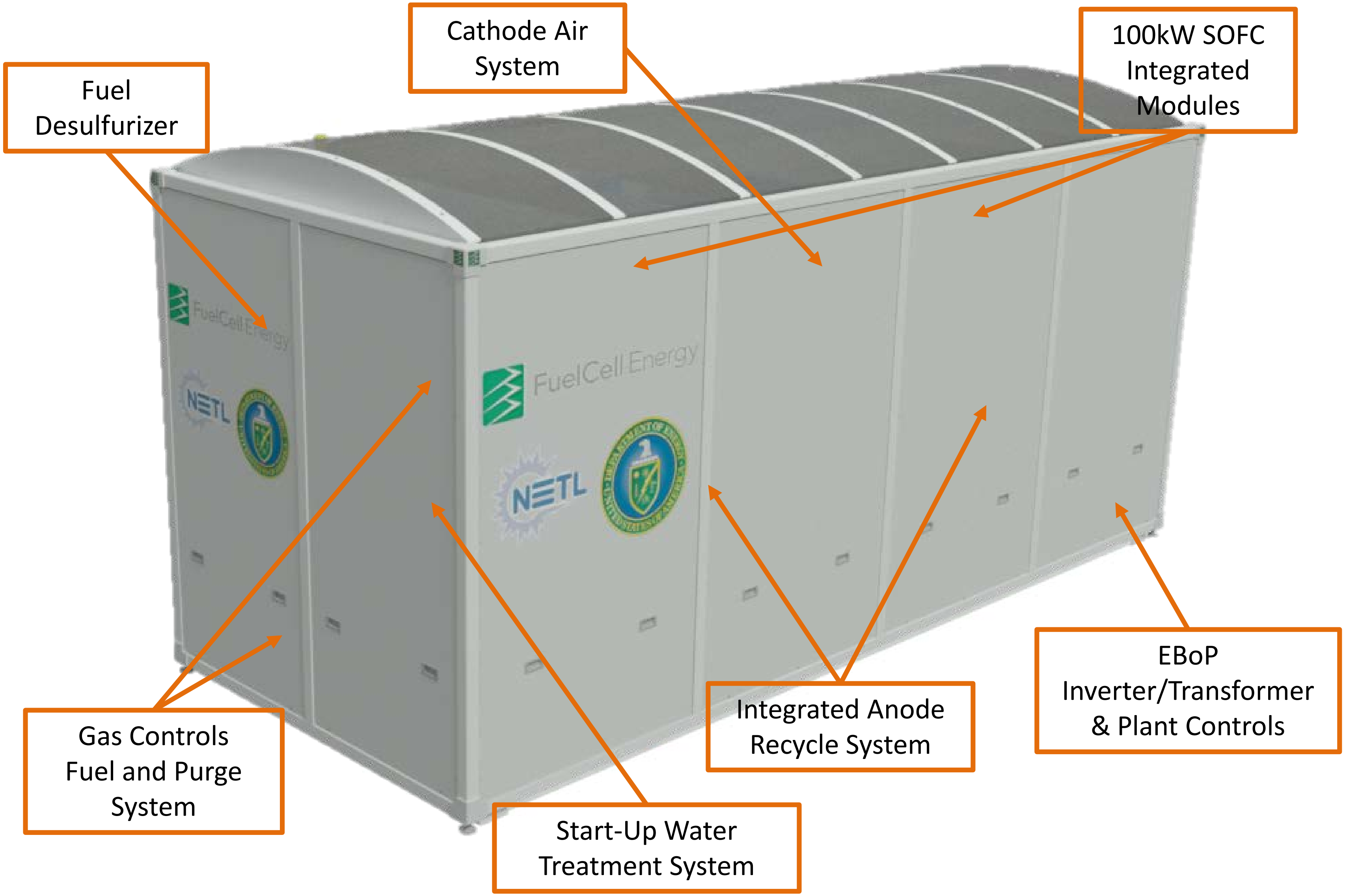
**200 kW SOFC System Performance Summary**

| **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** | **%** |



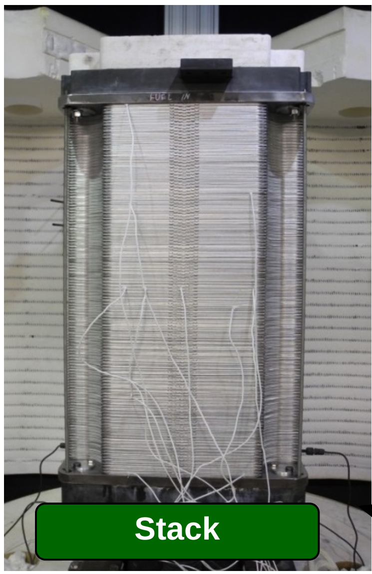

➡ **200 kW Modular Power Block (MPB) system is designed to validate stack reliability and scalable stack-module design.**

# 200kW SOFC Power System Layout

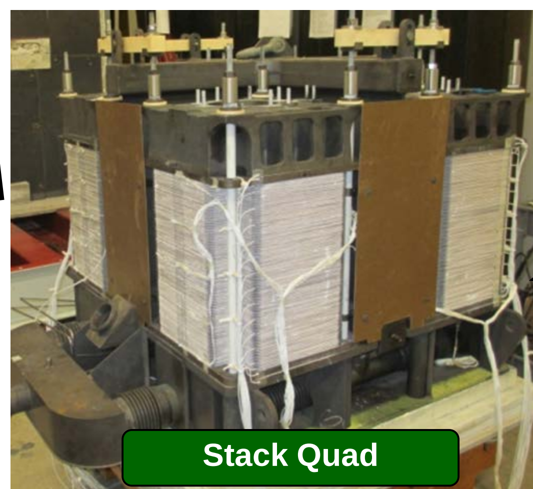


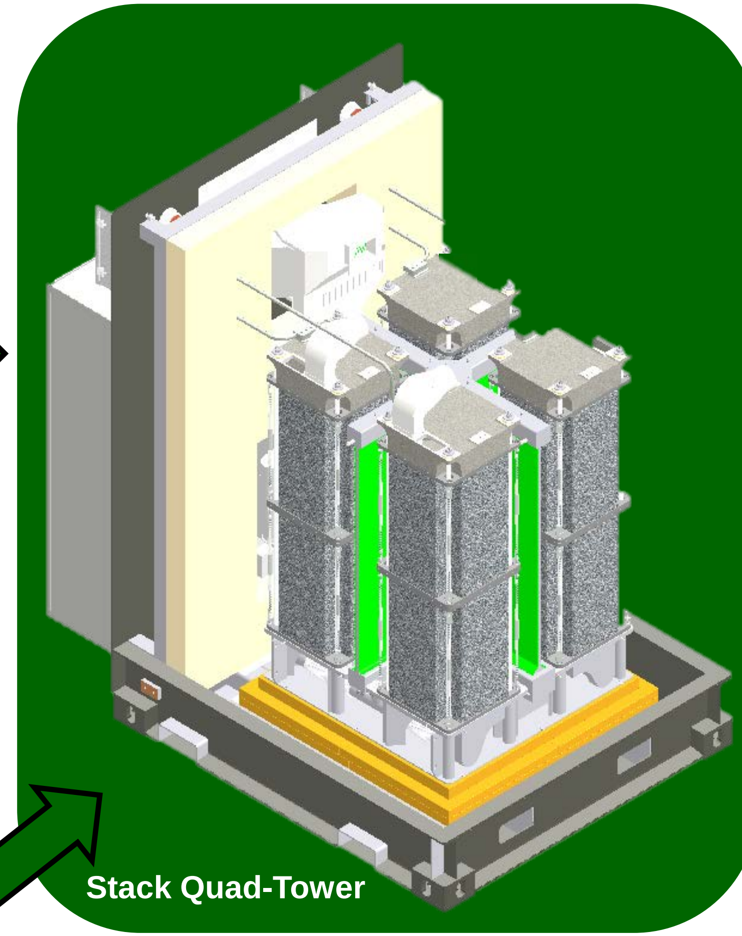

- Includes (2) 100kW SOFC Module Power Blocks (MPB) designed to operate independently
- Factory assembled & shipped as a standard ISO 20' x 8' container

# 100 kW Modular Power Block (MPB) Stack Arrangement

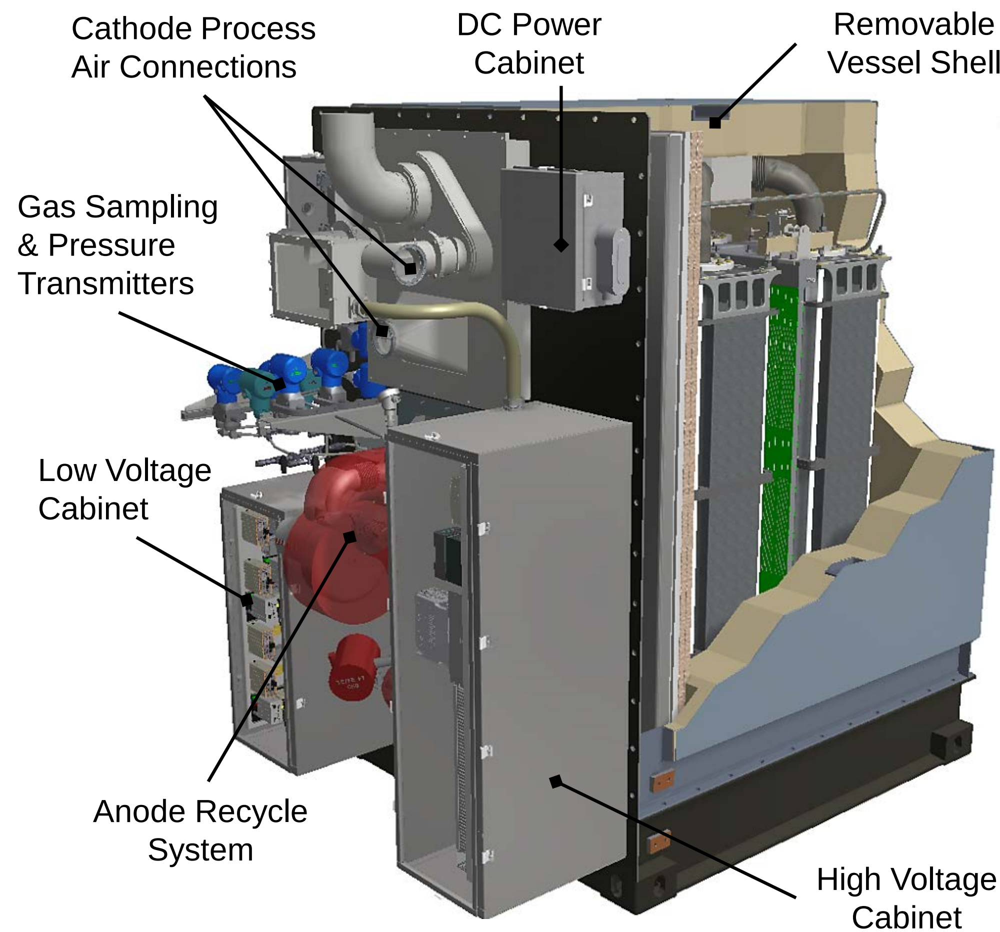






# 100 kW MPB Design & Fabrication

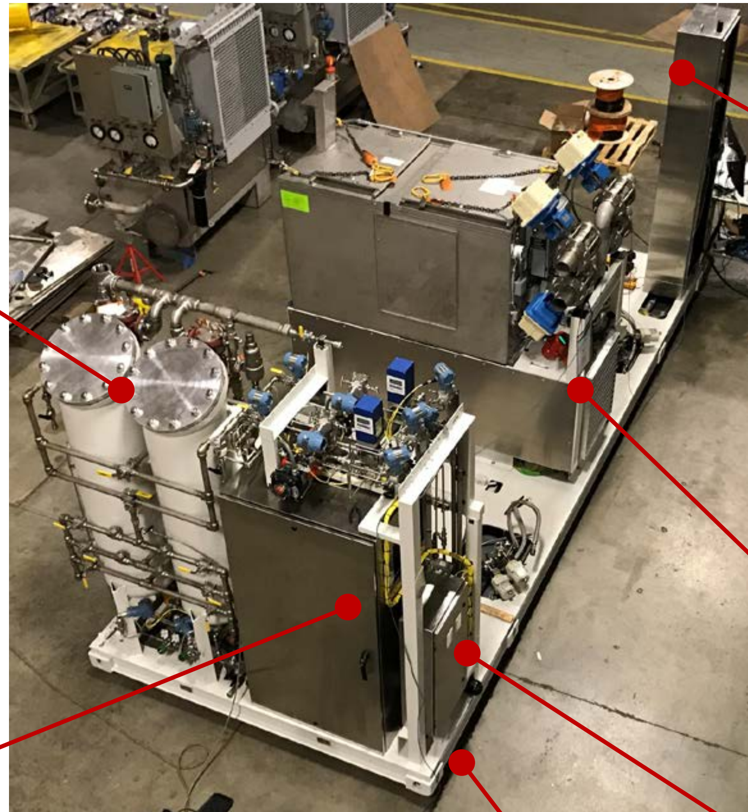



<u>100 kW MPB Architecture:</u>

- Fully integrates all hot BoP equipment within the module
- Eliminates high-temperature plant piping & valves
- Reduces Cr evaporation protective coatings within plant/module
- Integrated anode blower & module-specific instruments greatly decreases plant footprint

# 200 kW MPB BoP Fabrication

Desulfurization Units



Process Control System (PCS)

Air Delivery System

Start-up Water System

Skid Support-Integrated Piping

Remote I/O Cabinet (RIO)

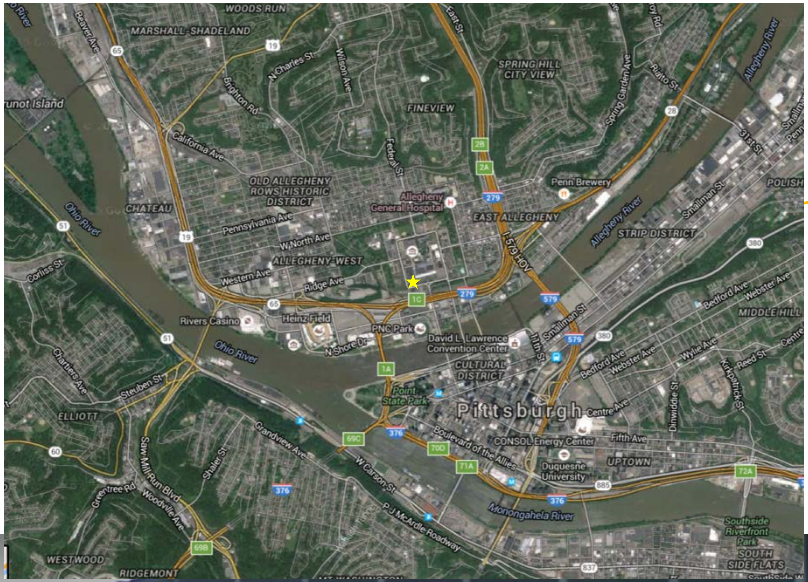
# 200 kW SOFC MPB System Balance of Plant

1-Piece Ship & Install

➡ **200 kW BoP (operating with 1 Module) installed at FCE's Danbury, CT Test Facility. BoP/Module validation testing is underway.**

fuelcellenergy

# 200 kW System Field Testing

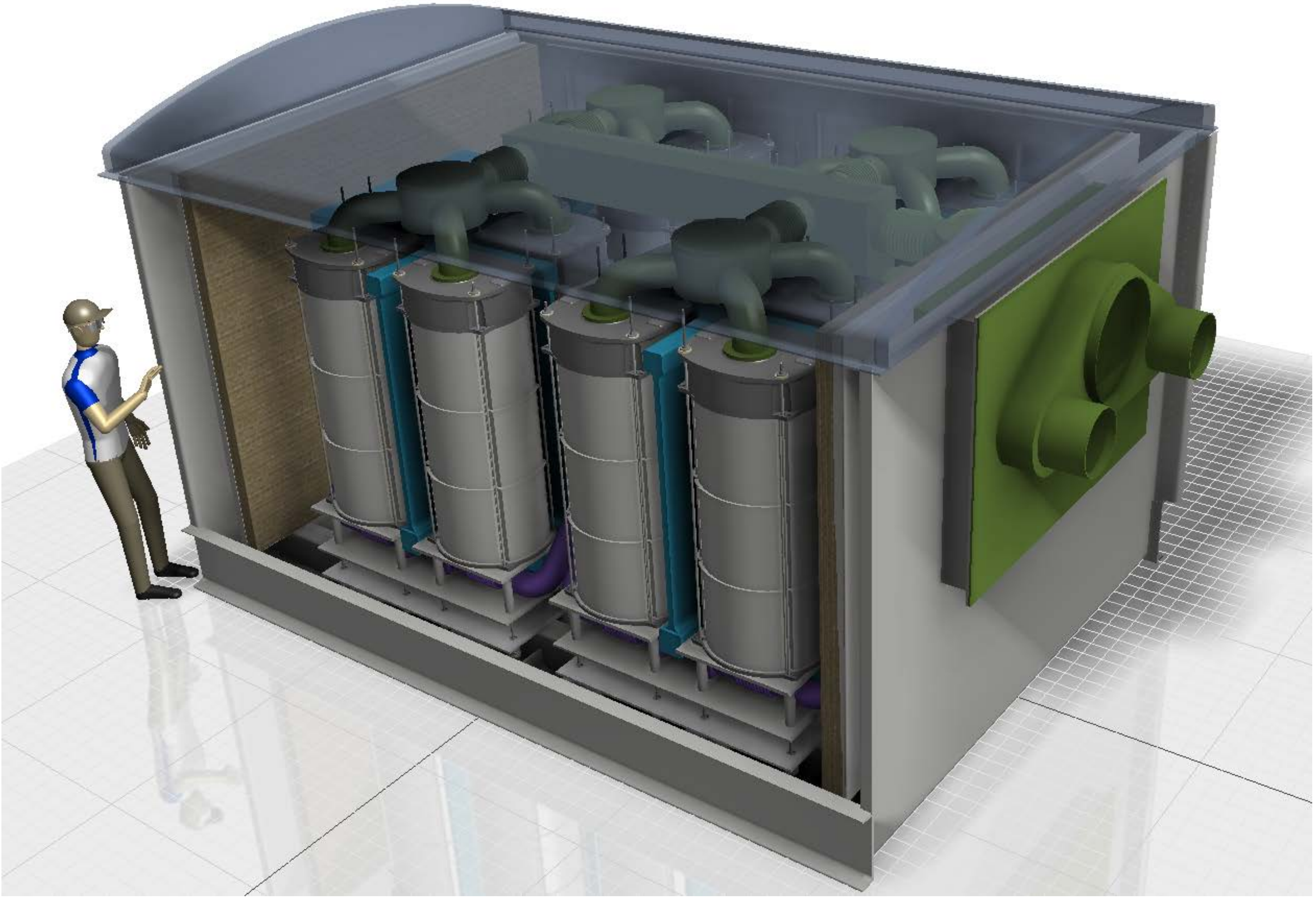



**NRG Energy Center**
**111 S Commons,**
**Pittsburgh, PA 15212**

nrg®

**System Installation**
**Planned Q3 – 4, 2017**

# MW-Class Module Conceptual Design

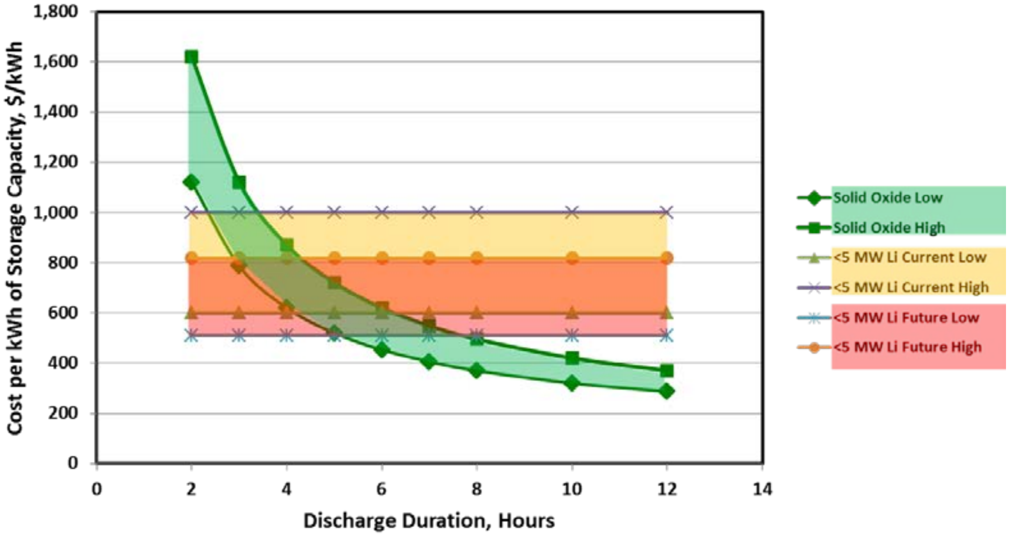


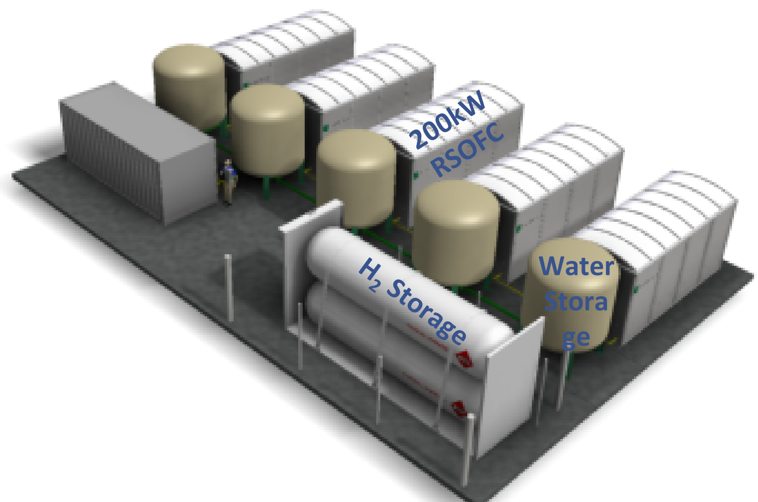
- MW-Class concept design utilizes proven quad-base SOFC stack tower configuration to minimize scale-up risk.
- Integrated hot-BoP components to minimize cost and footprint
- Module power density (0.7 $kW/ft^3$), nearly twice the value for 100 kW module (.4 $kW/ft^3$)

# Energy Storage Application

- In addition to the opportunities for low-cost power production, CSA-style stacks have been demonstrated in electrolysis (SOEC) and reversible (RSOFC) modes
- Advantage over conventional storage:
  - Long duration achieved by adding hydrogen storage, without adding stacks
- Advantage over other hydrogen-based storage:
  - Efficiency advantage – due to higher efficiency of SOFC in fuel cell and electrolysis modes of operation

**Baseline 20 cell CSA-style stack: Demonstrated stable electrolysis operation at 2 A/cm$^2$**




**6 MWh RSOFC System (1MW x 6 h)**

# Summary

- Incorporated Gen 2 Cr-mitigation technology into 80-cell stack demonstrating low degradation (0.4%/kh) in ongoing test
  Gen 2 Cr-mitigation now being manufactured into 120-cell (16 kW) stacks for System Demo
- Developed cells with improved redox tolerance (94% lower loss after 6 redox cycles) to extend life in real-world system operating environment
- Improved SOFC manufacturing & enhanced Quality Control specifications, tools and procedures increasing stack reliability and endurance
- Developed and initiated fabrication of new Compact Stack Architecture (CSA) stack with potential significant reduction in raw material cost, and scalability for MW-class systems
- Completed fabrication and initiated testing of a highly integrated 100 kW Modular Power Block and 200 kW SOFC system balance of plant
  Preparations for a 200 kW System Demo Field Test are underway

# Acknowledgements

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Guidance from NETL Management team: Shailesh Vora, Joseph Stoffa, Patcharin Burke, and Heather Quedenfeld