SOFC Development Update at FuelCell Energy

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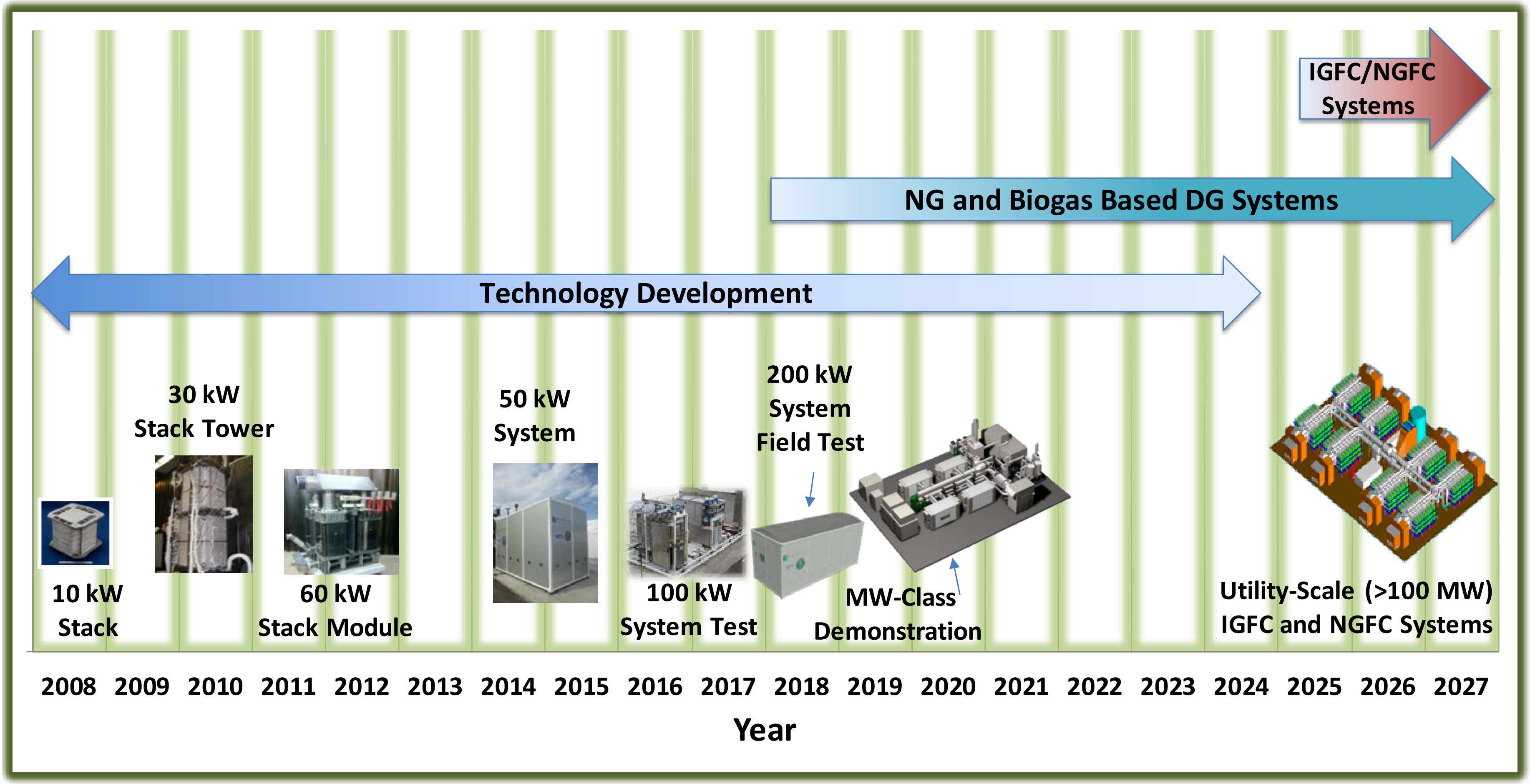
19th Annual Solid Oxide Fuel Cell (SOFC) Project Review Meeting
Washington, DC

June 13, 2018

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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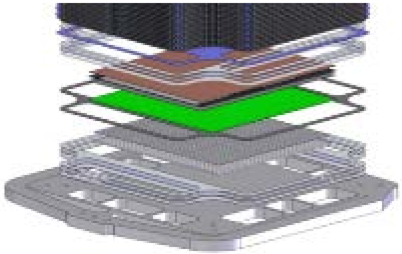
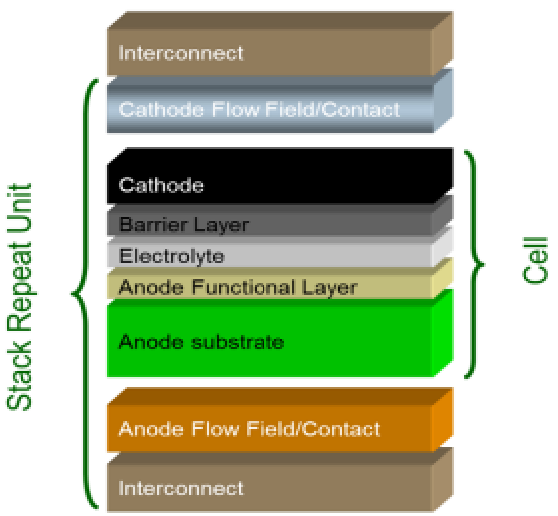
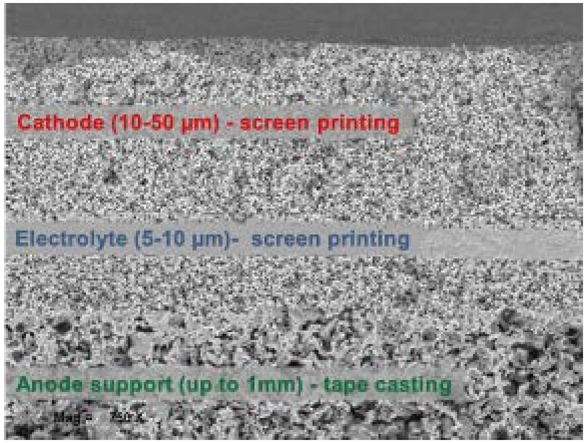
Cell and Stack Technology Overview

- Cell:
  - Planar anode supported
  - 0.6 X 254 X 254 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

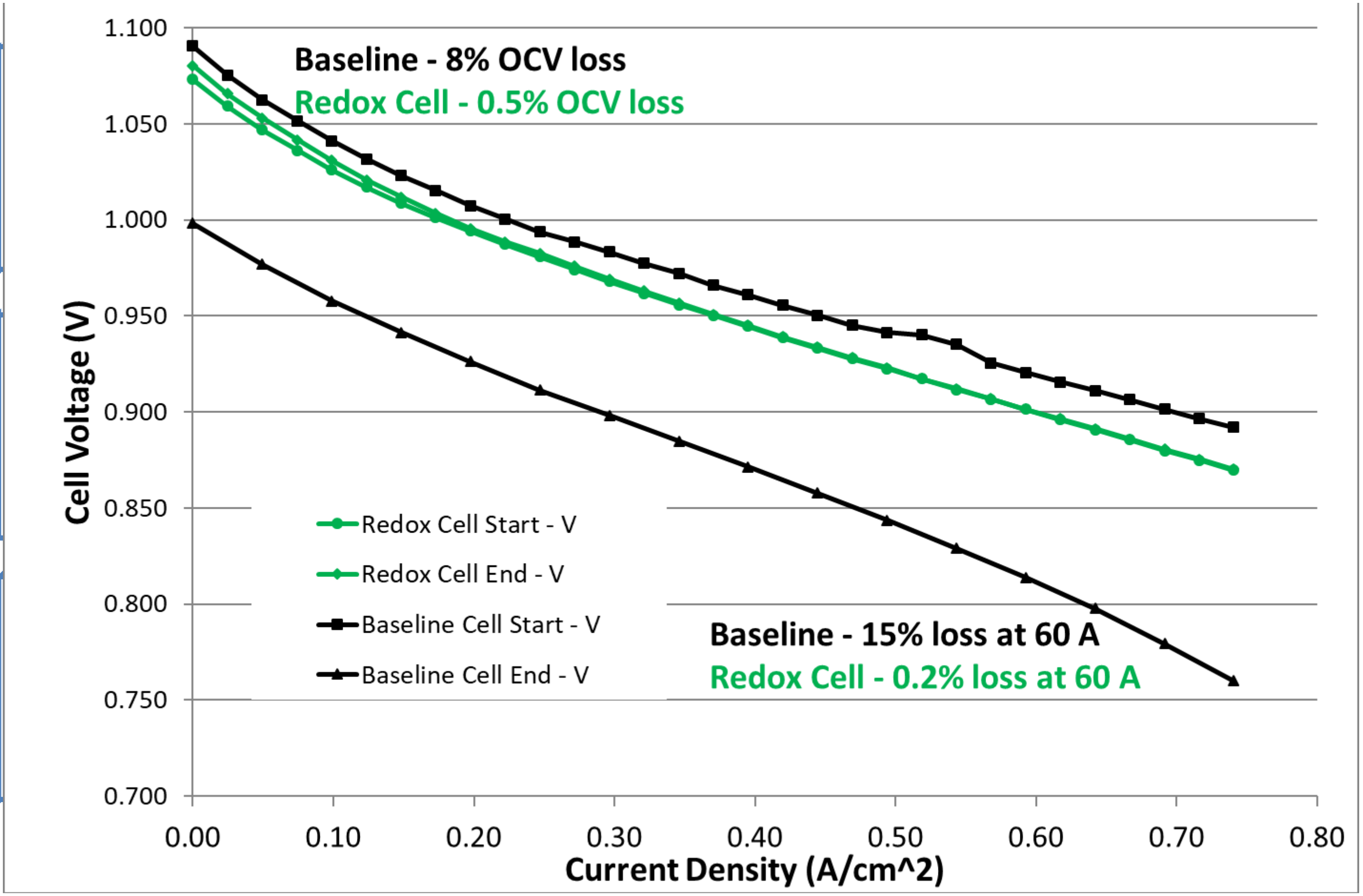






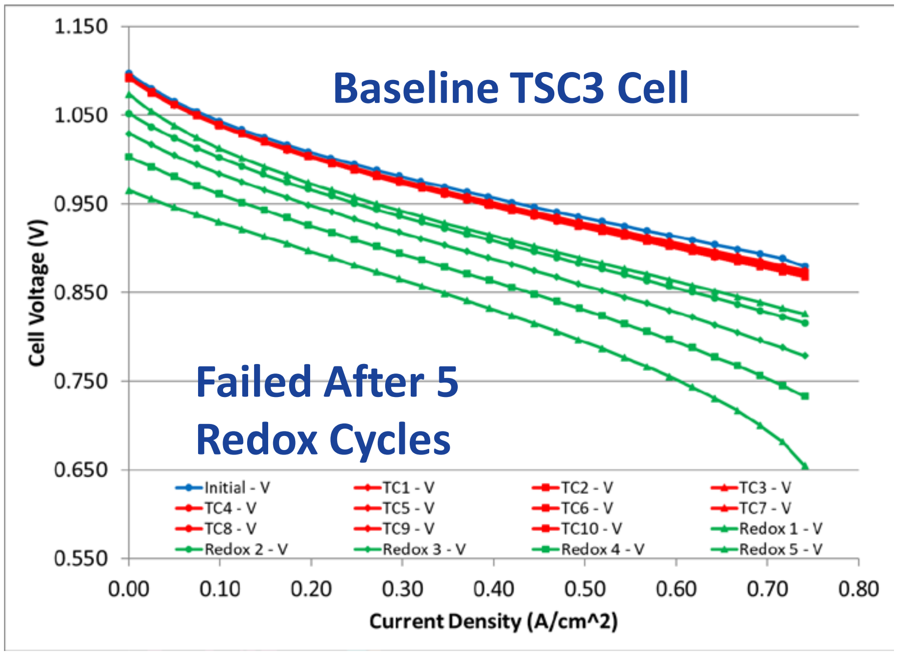
Advances in Cell Technology: Redox Tolerance Improvement

- A wide range of anode microstructures with enhanced mechanical properties were studied for improvements in redox tolerance
- Redox tolerance improved from 15% performance loss (baseline cell) down to 0.2% loss after 6 redox cycles with varying extent of nickel oxidation within the anode

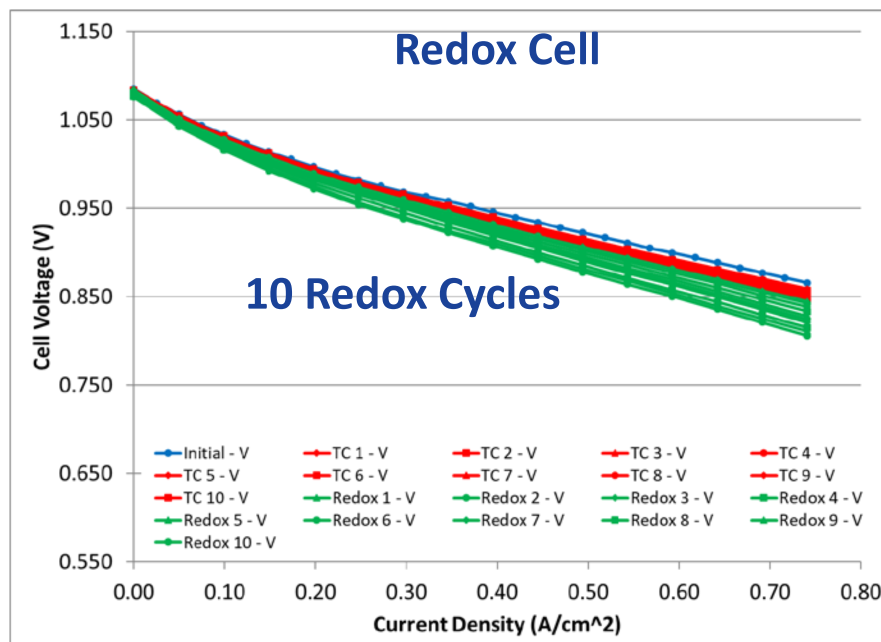


Accelerated Redox Tolerance Test Results

Multi-prong approaches were implemented to reduce anode strain upon Ni re-oxidation for achieving improvements in redox tolerance

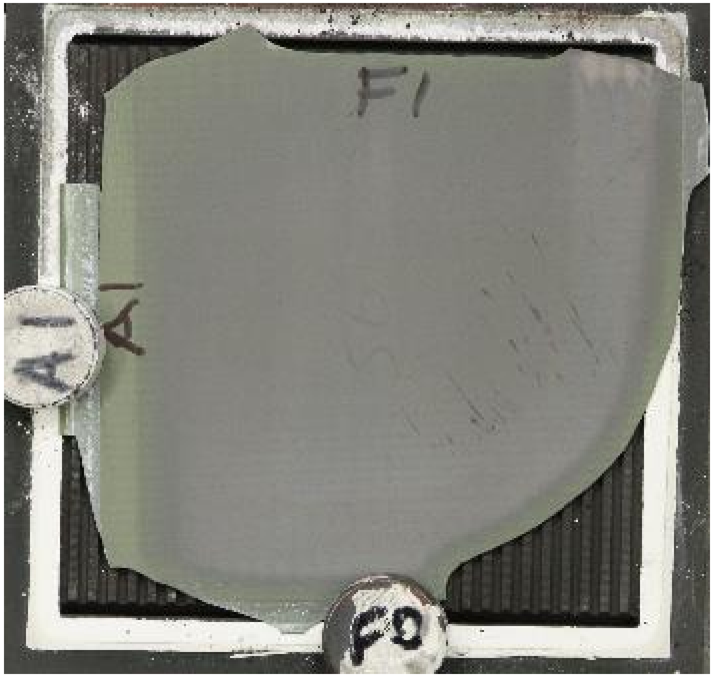


- Redox cycle conditions designed for accelerated degradation:
  - Polarization curves to 0.74 A/cm^2
  - 10 thermal cycles red lines
  - 10 redox cycles green lines



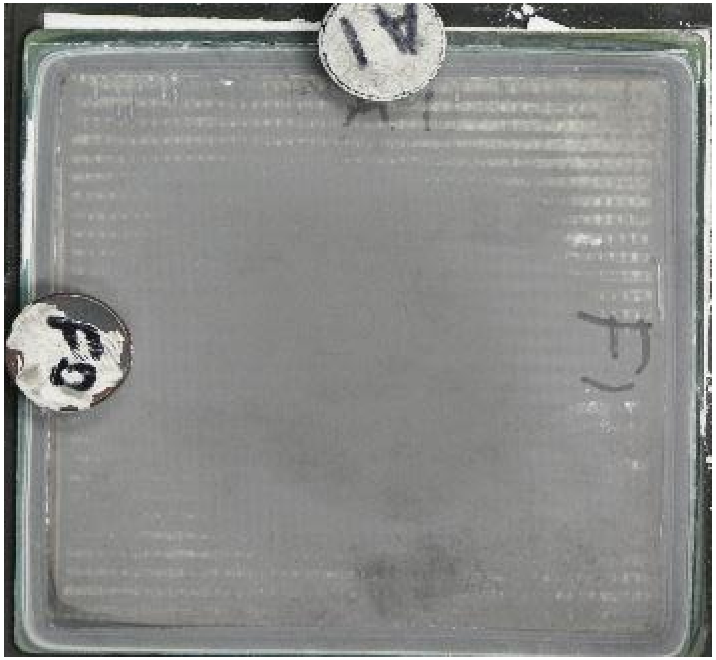
- Accelerated tests showed:
  - Baseline TSC3 cell failed after 5 redox cycles
  - Recent cell with modified anode structure is still running well after 10 redox cycle

Post-Redox Cycles Evaluation



- Standard cell (left) failed catastrophically after 5 redox cycles
- Autopsy showed broken cell with significant oxidation

- Modified redox tolerant cell (right) is fully intact
- Autopsy showed no sign of cracks and no oxidation in active area

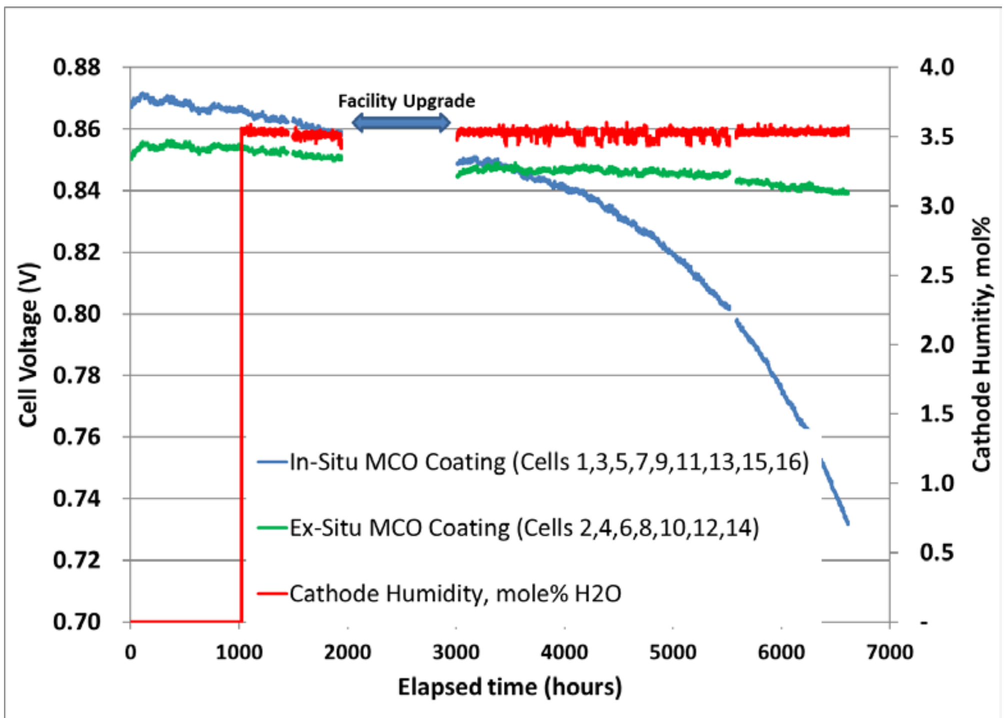


In-House Interconnect (IC) Coating

Stack fabrication process using in-situ MCO IC coating

- Sheet Metal
  - PVD Co-Coating
- Co-coated Sheet Metal
  - IC Cutting and Forming
- Co-coated IC
  - Stack Assembly
- MCO Coated IC
  - MCO Formed In-Situ during Stack Operation

- Studied both in-situ and ex-situ MCO applications as protective layers for cathode interconnects
- A 16 cell stack using baseline 550cm^2 TSC3 cells with alternating interconnect coatings was used to provide behavioral comparison of the two types of coatings
- Ex-situ MCO coatings provided better protection against Cr evaporation and lower performance degradation rate as compared to in-situ coatings

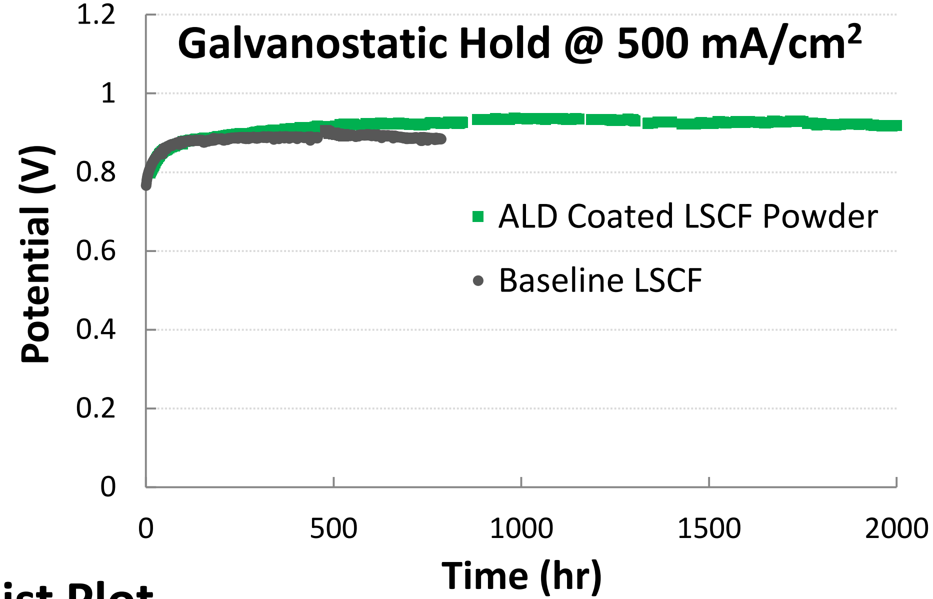


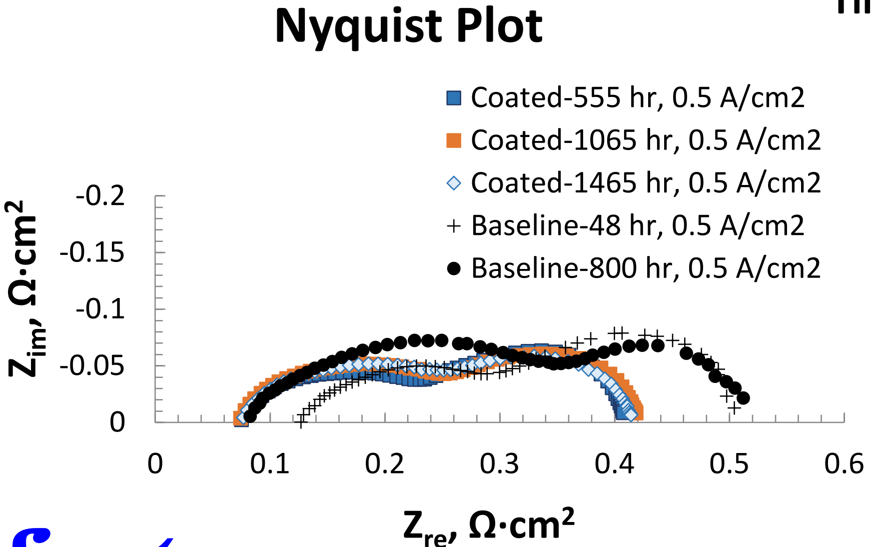
Stack fabrication process using ex-situ MCO IC coating

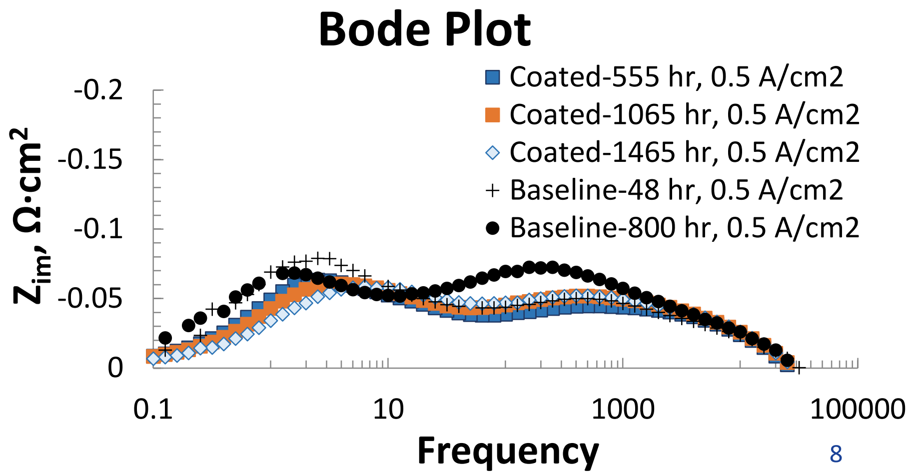
- Sheet Metal
  - IC Forming
- IC
  - MCO Coating
- Porous MCO Coated IC
  - Densification
- Dense MCO Coated IC
  - Stack Assembly

Enhanced Cathode Performance Stability Using Atomic Layer Deposition (ALD)

ALD coated LSCF powders resulted in reduced cathode degradation rate







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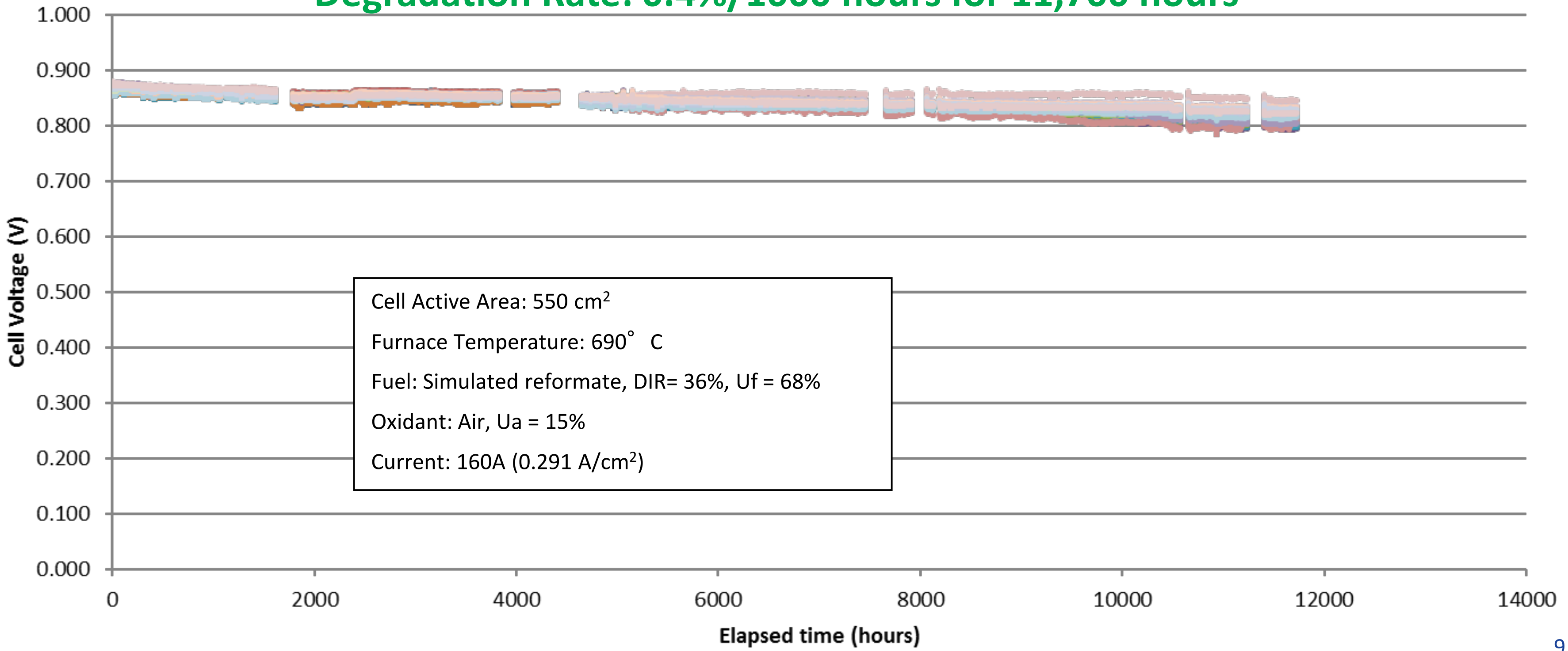
80-Cell Stack Test

- Recent cell and stack design/manufacturing advances incorporated into 80-cell stack
- Ongoing testing at system conditions shows 0.4%/1000 hours degradation rate

Test in Progress

Degradation Rate: 0.4%/1000 hours for 11,700 hours



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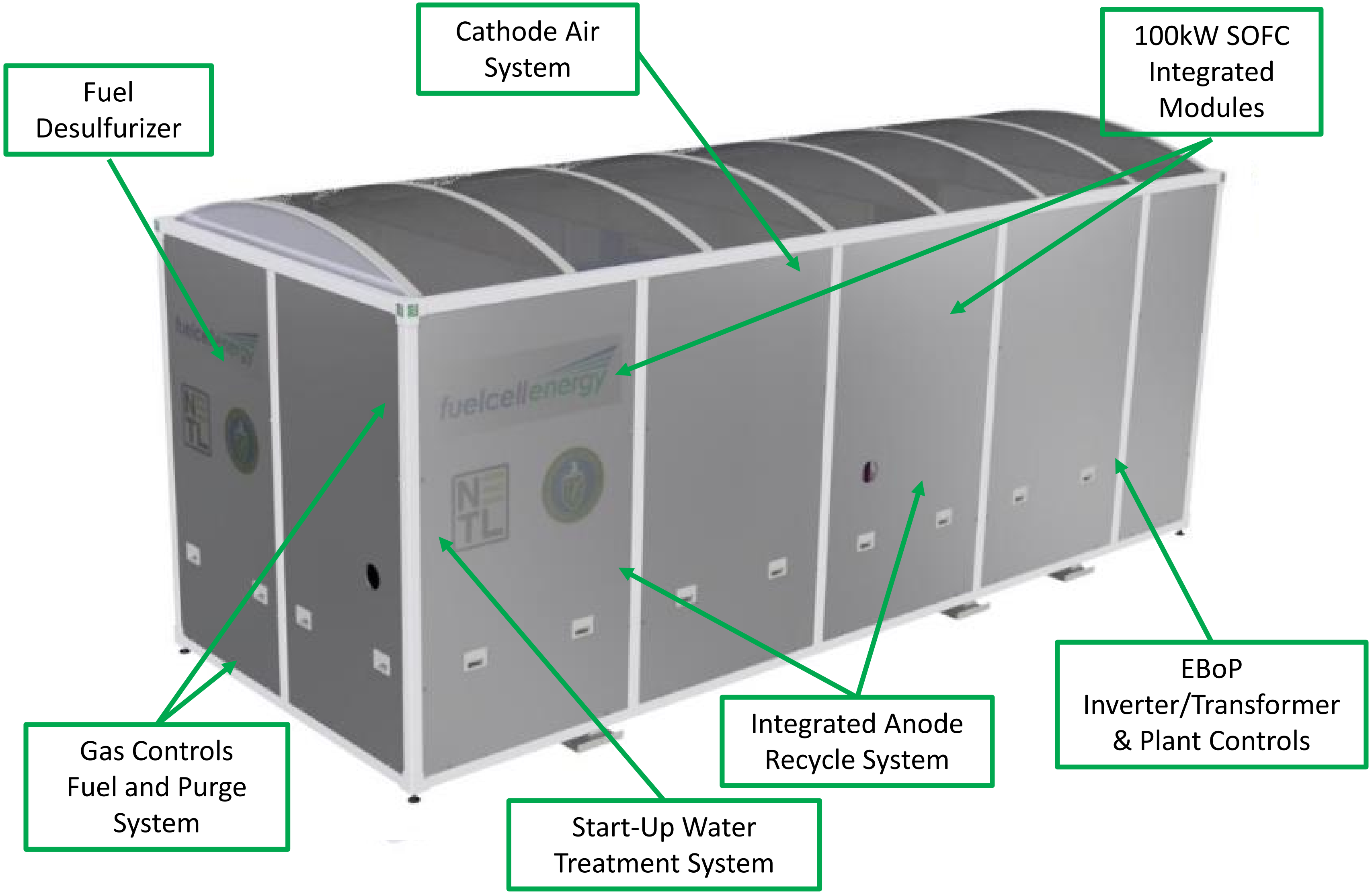
200 kW SOFC System

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 system is designed to validate stack reliability and scalability of stack-module design

200kW SOFC Power System Layout



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

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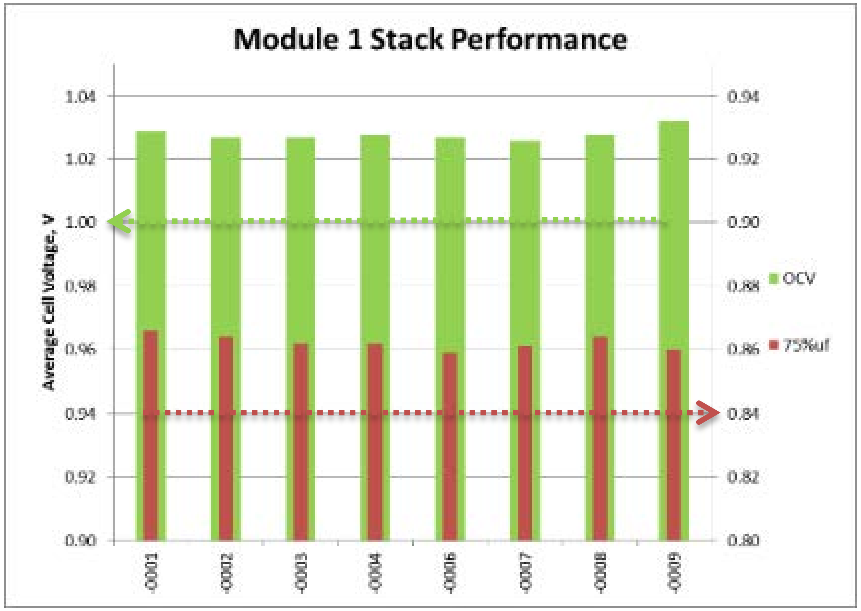
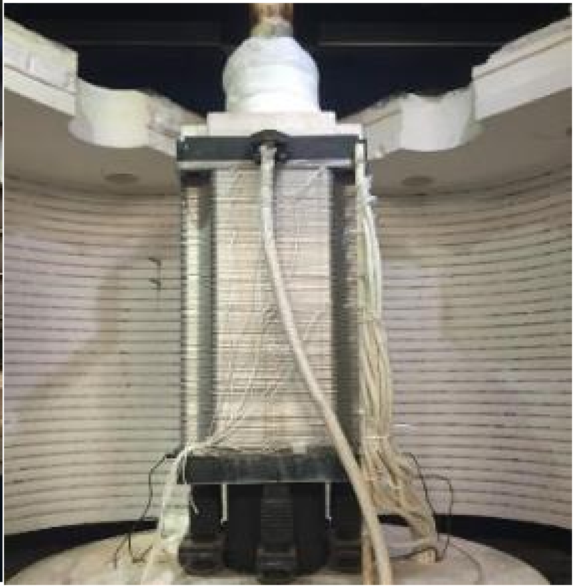
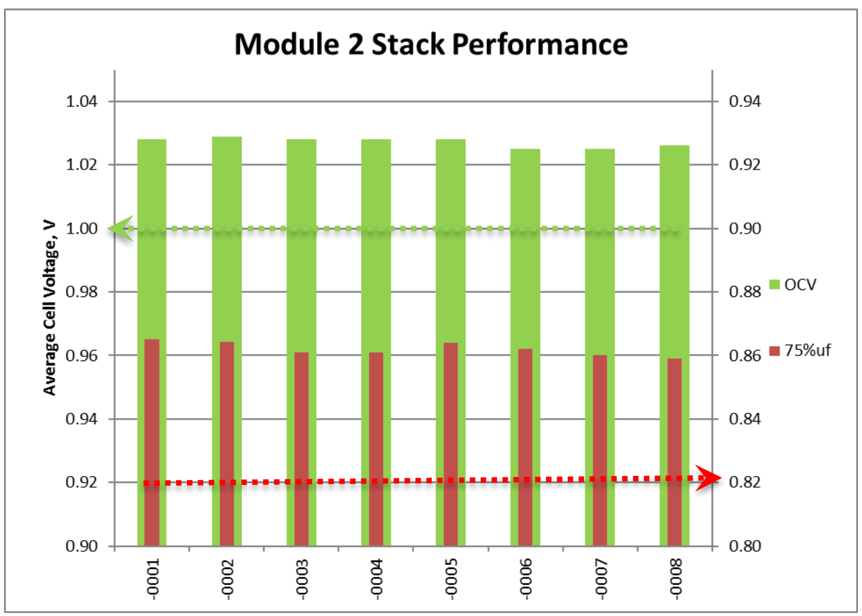
200 kW System Stack Manufacturing

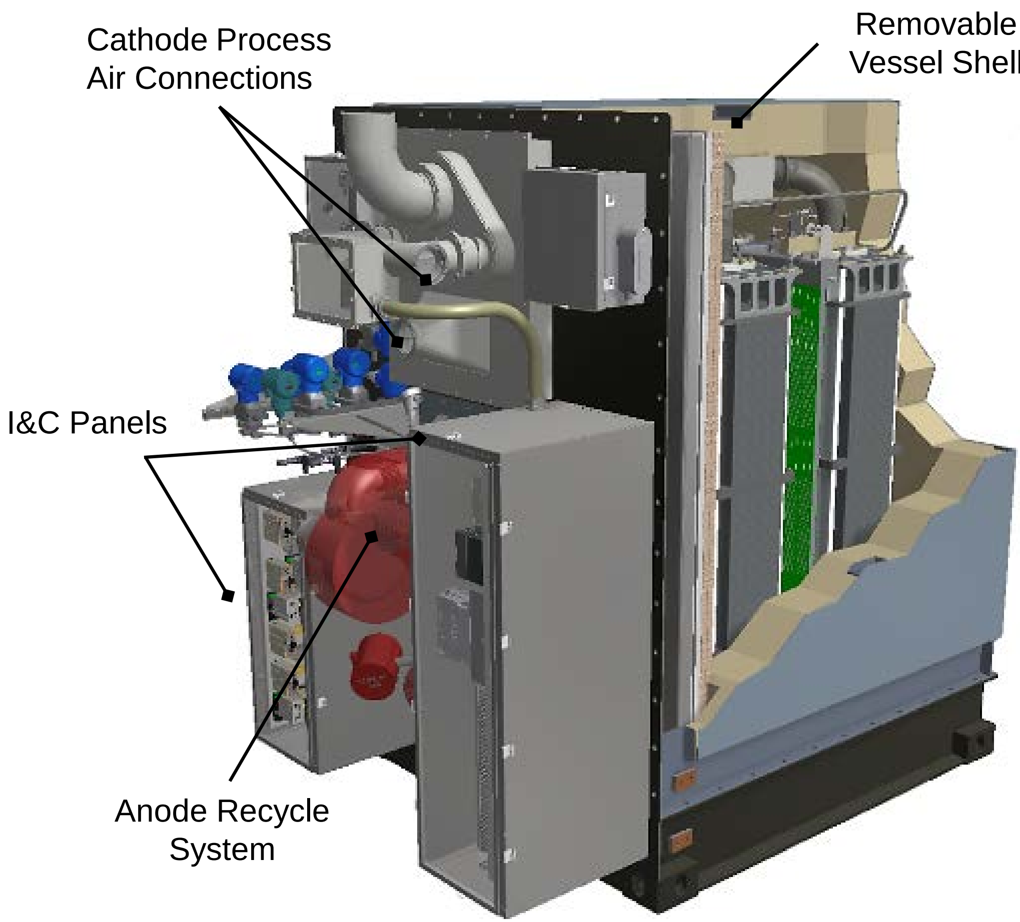






- Excellent stack to stack performance reproducibility
- Stacks for 200 kW system meet cell voltage criteria
- Stacks shipped to FCE Danbury, CT and integrated into 100 kW modules

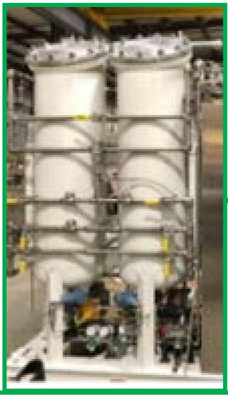
100 kW Module Design & Fabrication



100 kW Stack Module Architecture:

- 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 BoP Fabrication



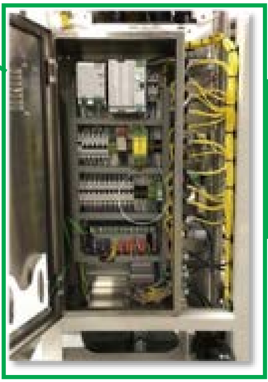
Desulfurization Units

Process Control System

Air Delivery System

Start-up Water System

Skid Support-Integrated Piping



Control Hardware Cabinet

Stack Module Integration

200 kW Bop

100 kW Stack Module

100 kW Stack Module Integration

Two 100-kW stack modules have been incorporated within the 200 kW system BoP, resulting in one transportable integrated system

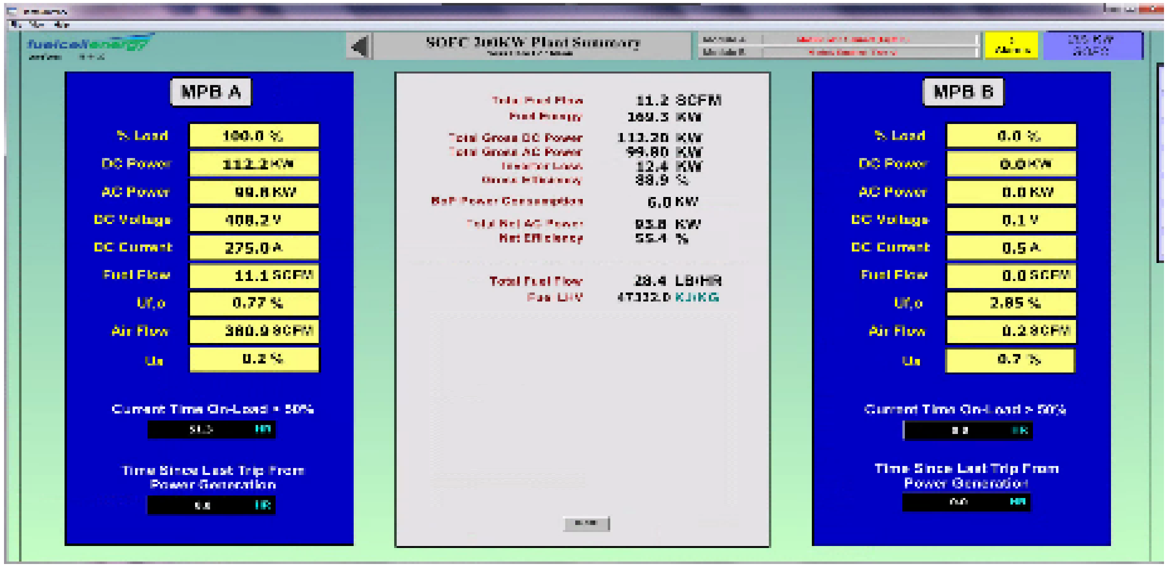
200 kW SOFC System Factory Testing

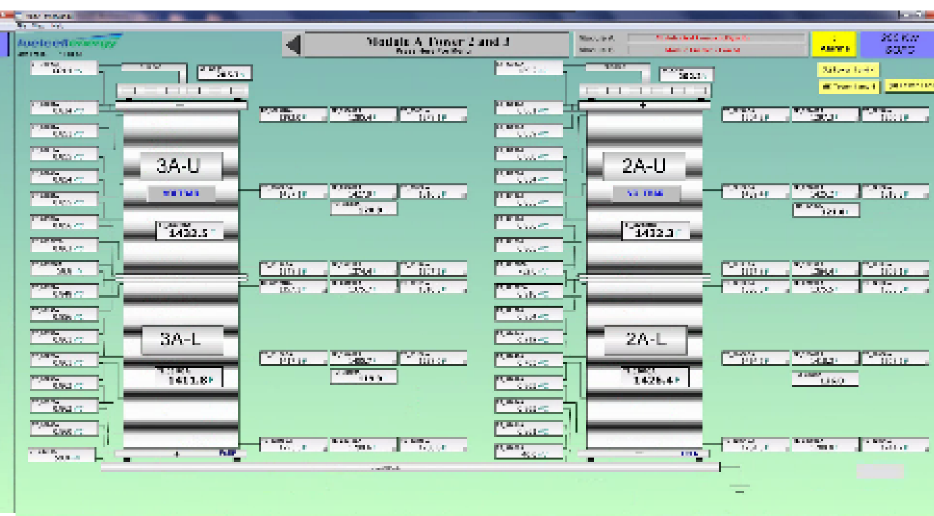
200 kW system installed at FCE's Danbury, CT Test Facility.

Factory Acceptance Testing is underway.

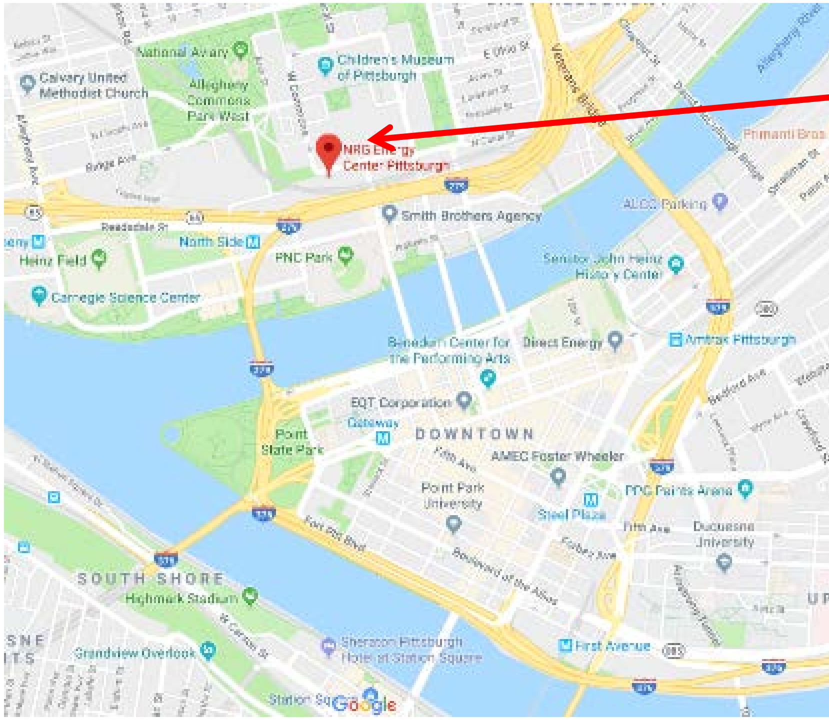
Example of 100kW Stack Module Acceptance Test Results

Screen Shot of the Power Plant HMI





200 kW System Demonstration Site Preparation



NRG Energy Center
Pittsburgh, PA

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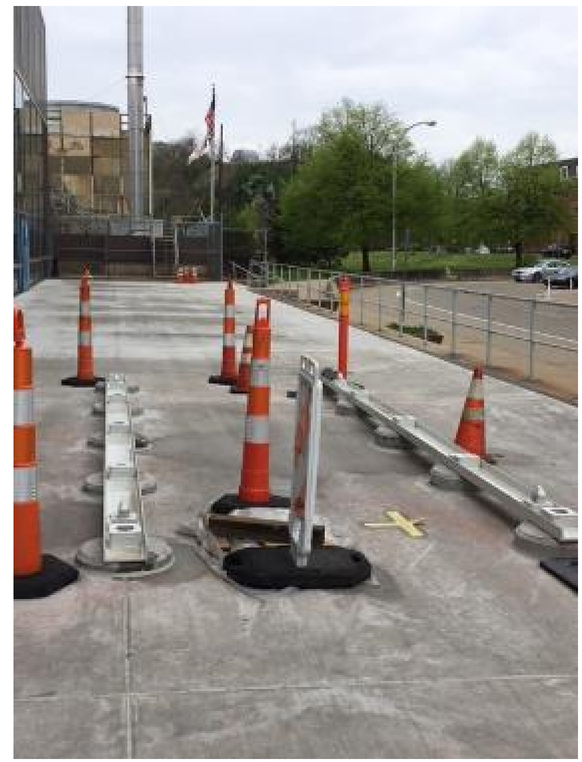
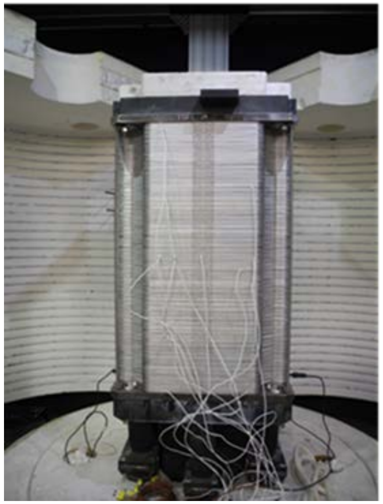


- Permitting Process Complete
- Site Preparation was completed

Next Generation Stack Technology



Baseline Large Area Stack (LAS):
- **76 W/kg**
- **185 W/L**

Compact SOFC Architecture (CSA)

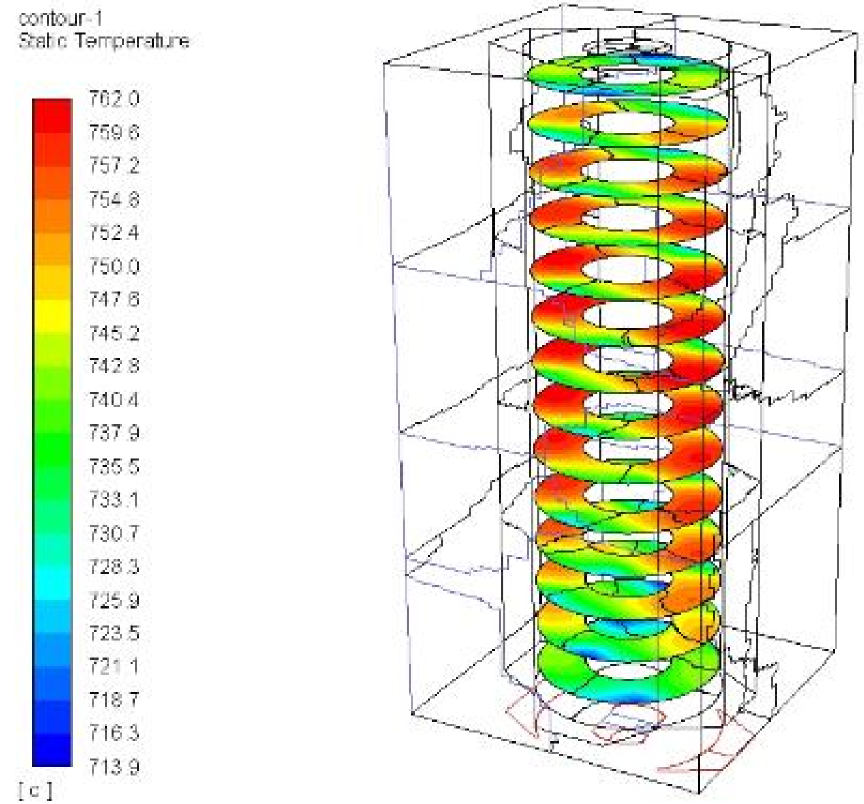
Full Height CSA Stack:
- **470 W/kg**
- **780 W/L**

Property	CSA Stack Scale			Comments
	Short	Mid	Full	
Cell count	**45**	150	350	
Fuel cell voltage, V	**38**	128	298	At 0.85 V/cell
Stack Power, kW	**0.9**	3.0	7.0	At 0.29 A/cm^2
Height, mm (in)	**91 (3.6)**	211 (8.3)	440 (17.3)	

CFD Model of CSA Stack

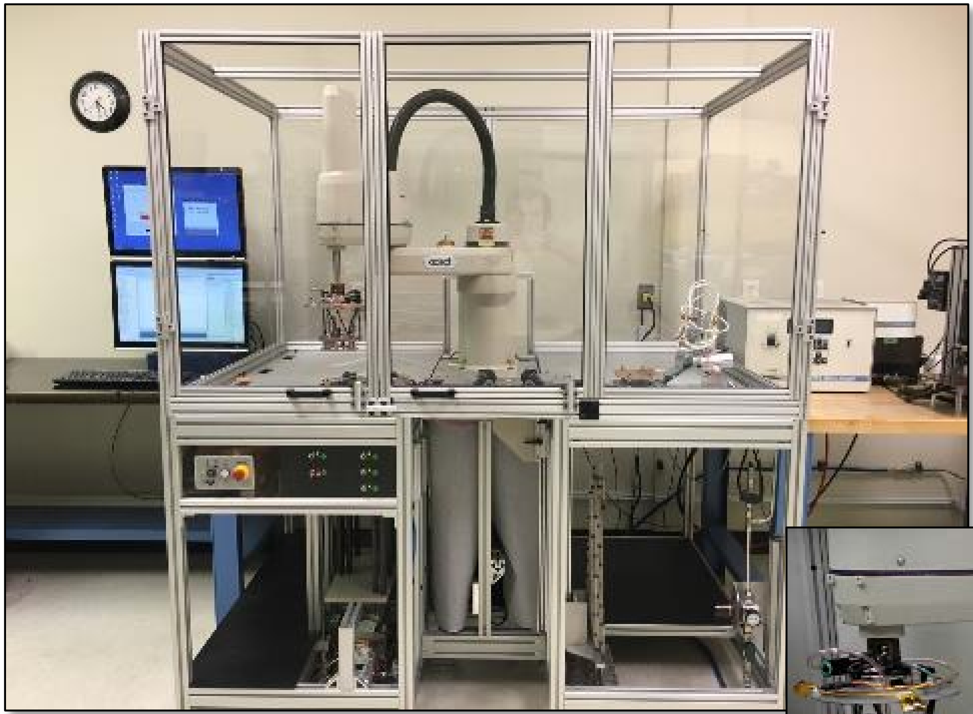
- Fully coupled CFD/electrochemical CSA stack model was developed
  - Full stack (lumped porous body model)
- High current operation and complex geometry of CSA stack requires large number of calculations
- ANSYS HPC Pack licensing and cluster computing services were used to run the model

Example Fuel Cell Run
68%Uf 40%Ua 25% internal reforming, 0.3 A/cm^2



350-cell stack
Select cell layers shown

Automated Work Cell for CSA Stack Fabrication

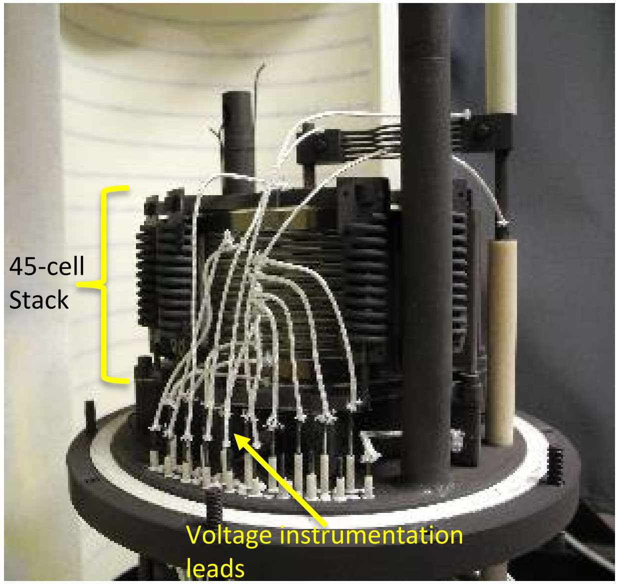


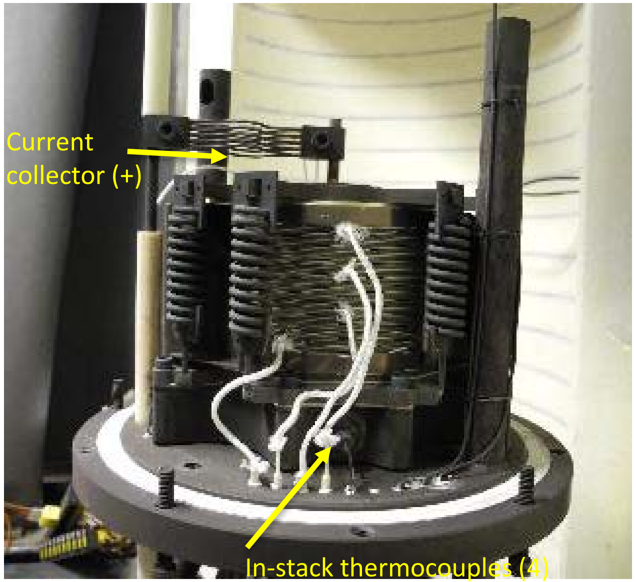
Automated work cell commissioned for:

- Stack builds
- Cell and interconnect QC

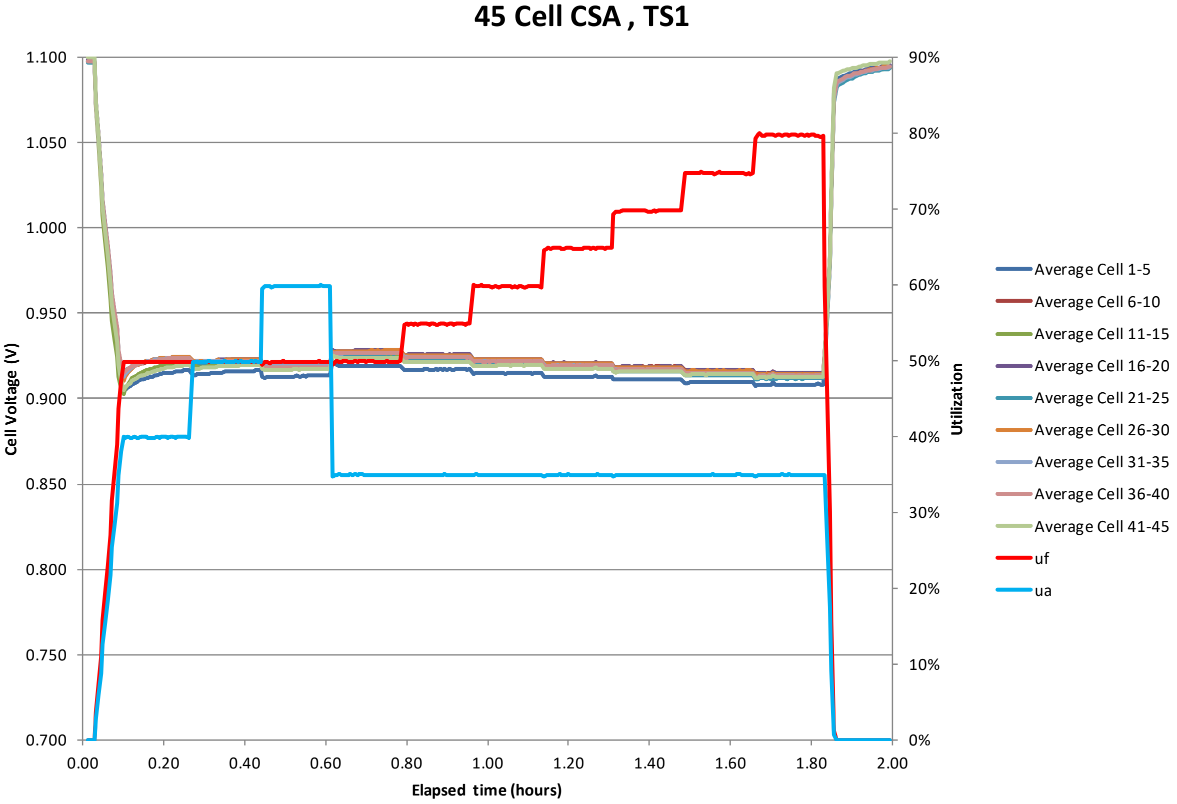
Current production rates achieved equivalent of up to 4 stacks per shift/day

CSA Stack Fabrication



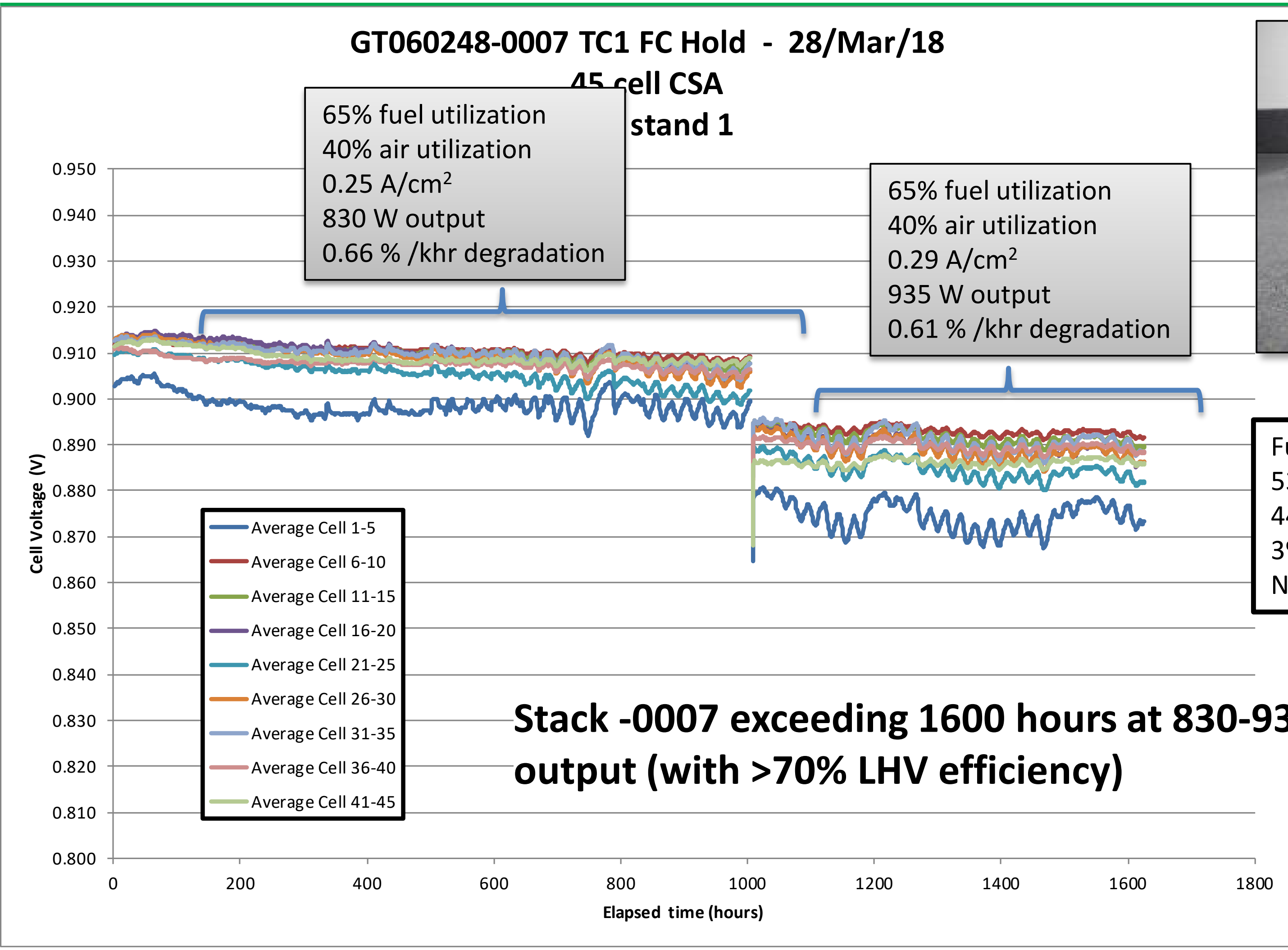


- Initial stacks of new design (CSA Stack) has been built and tested in both fuel cell and electrolysis modes



- Very strong utilization performance (>900 mV) at 80% fuel utilization at 0.25 A/cm^2
  - Demonstrates good flow distribution and even thermal conditions within the stack

CSA Testing



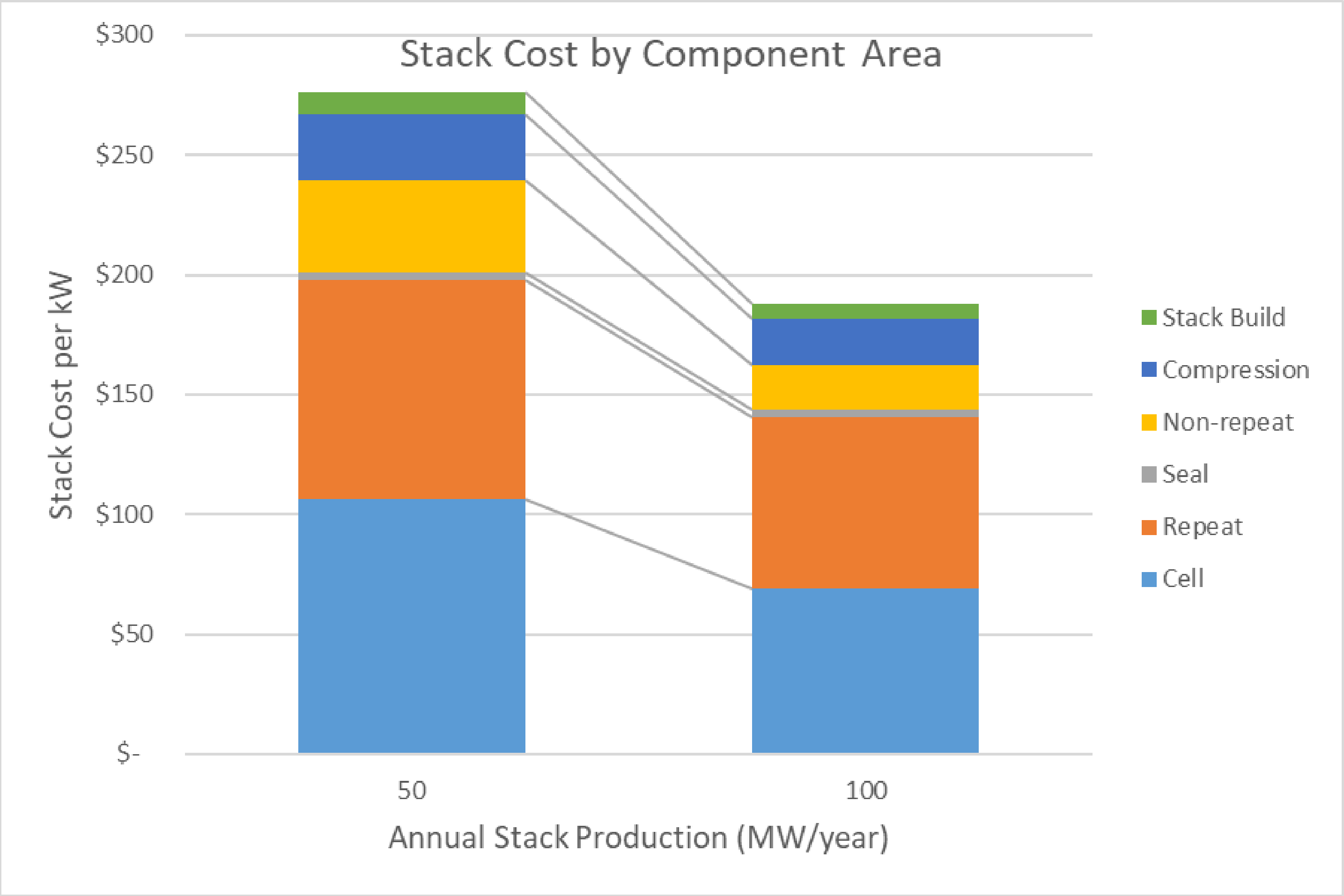
Fuel composition:
53% H_2
44% N_2
3% H_2O
Non-reforming surrogate gas

Stack -0007 exceeding 1600 hours at 830-935 W output (with >70% LHV efficiency)

- Good performance and stability
- Tight voltage spread shows good flow distribution
- Aggressive thermal conditions (lower air flow, lower pressure drop)

CSA Stack Factory Cost Estimate

CSA Stack Factory Cost Estimate as a Function of Production per Year



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Summary

Cell

- New redox tolerant cell stability was demonstrated after 10 redox cycles
- ALD coated cathode materials showed improved endurance
- In-house developed ex-situ MCO coating showed significant protection against Cr poisoning

Stack

- Baseline stack tested for >11000 hours showed <0.4%/kh degradation rate
- 17 baseline stacks were fabricated for a 200 kW SOFC power plant
- Initial trials of next generation CSA stacks have been successful

System

- 2 stack modules were built each with 8 stacks of 120 cells
- Factory tests of the 200kW SOFC system was initiated
- Preparation of the demonstration site for the 200kW SOFC system was completed

Acknowledgements

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