Progress in SOFC Technology Development at FuelCell Energy

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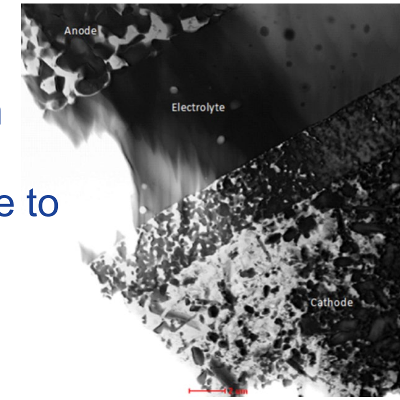
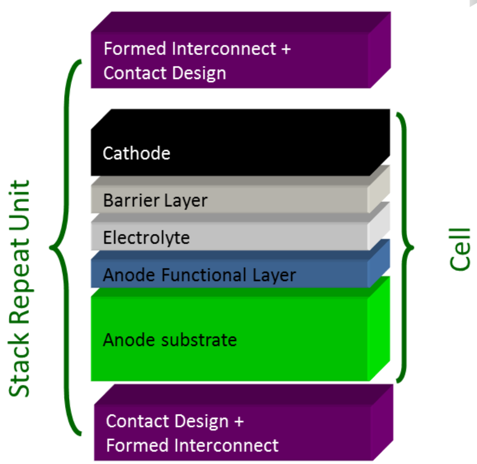
2020 Annual Merit Review
June 2, 2020

TSC Cell Manufacturing Process

- Cell fabrication process evolved from laboratory to pilot-production in 2001
- Techniques utilized are tape casting, screen printing and electric tunnel kiln for continuous firing
- These processes are flexible & scalable to high volume and low cost production

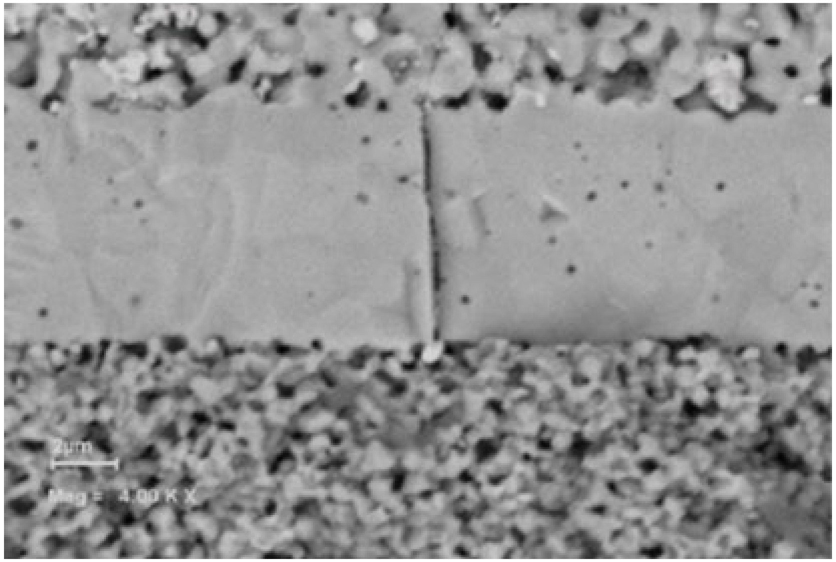




Component	Materials	Thickness
Cathode	Perovskites	~ 50 μm
Barrier	CGO	~ 4 μm
Electrolyte	YSZ	~ 5 μm
AFL	Ni/YSZ	~ 8 μm
Anode Substrate	Ni/YSZ	~ 350 μm

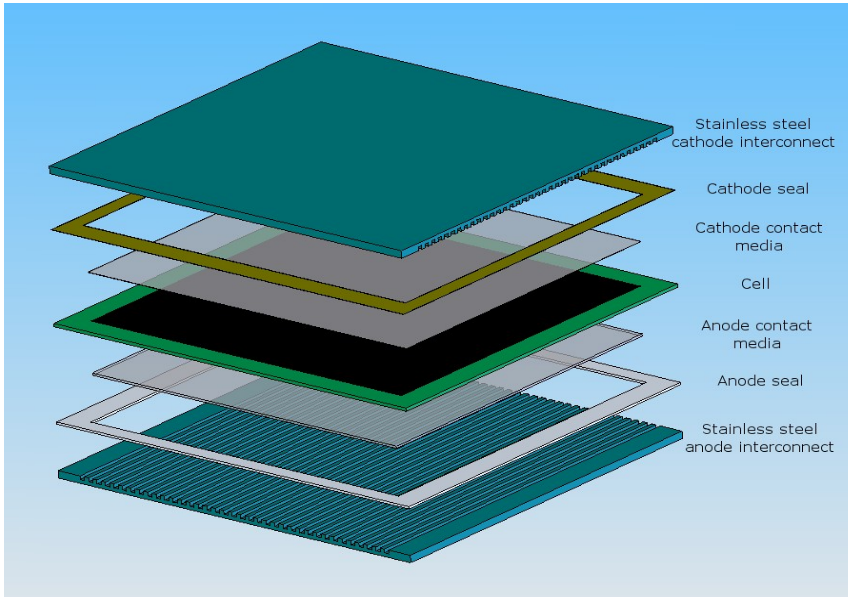
Developing Redox Tolerant Anode Supported SOFC

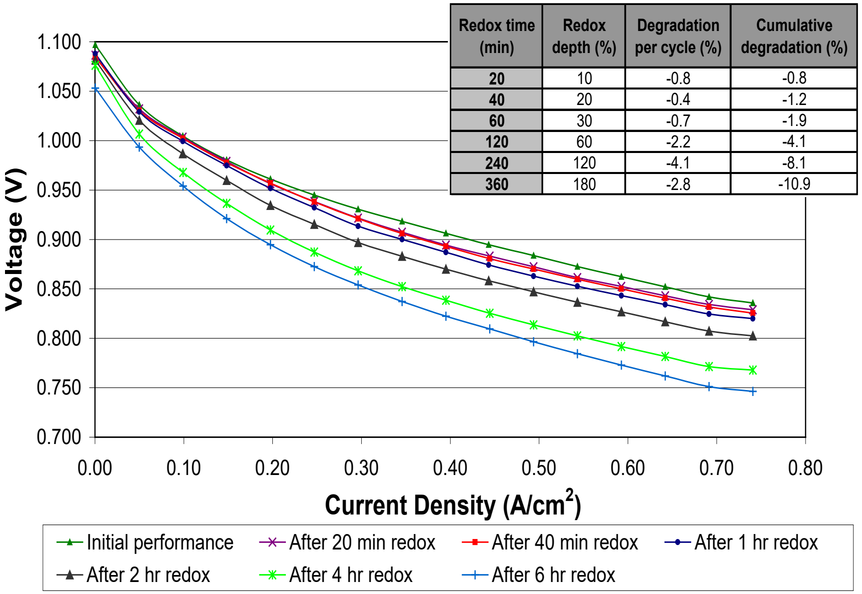
- **Objective**
  - Develop cell materials that are tolerant to reduction and oxidation cycling (Redox cycling) which can be expected in real-world system operation
- **Approach**
  - Building on FCE's strong anode-supported cell development experience since 1997
  - Leveraging cell and stack advancements from previous SECA projects
  - Implementing multi-prong approaches in developing innovative redox tolerant anode-supported cell through reducing anode strain upon Ni re-oxidation
- **The Mechanism of Redox Failure**
  - Nickel in anode support expands 69% by volume upon oxidation to nickel (II) oxide
  - Anode-supported cells fail by tensile cracking of electrolyte and may tolerate very limited anode expansion using 7-8 μm electrolyte
  - Redox tests of baseline cells showed electrolyte cracking in SEM posttest analysis



Redox Depth Approach

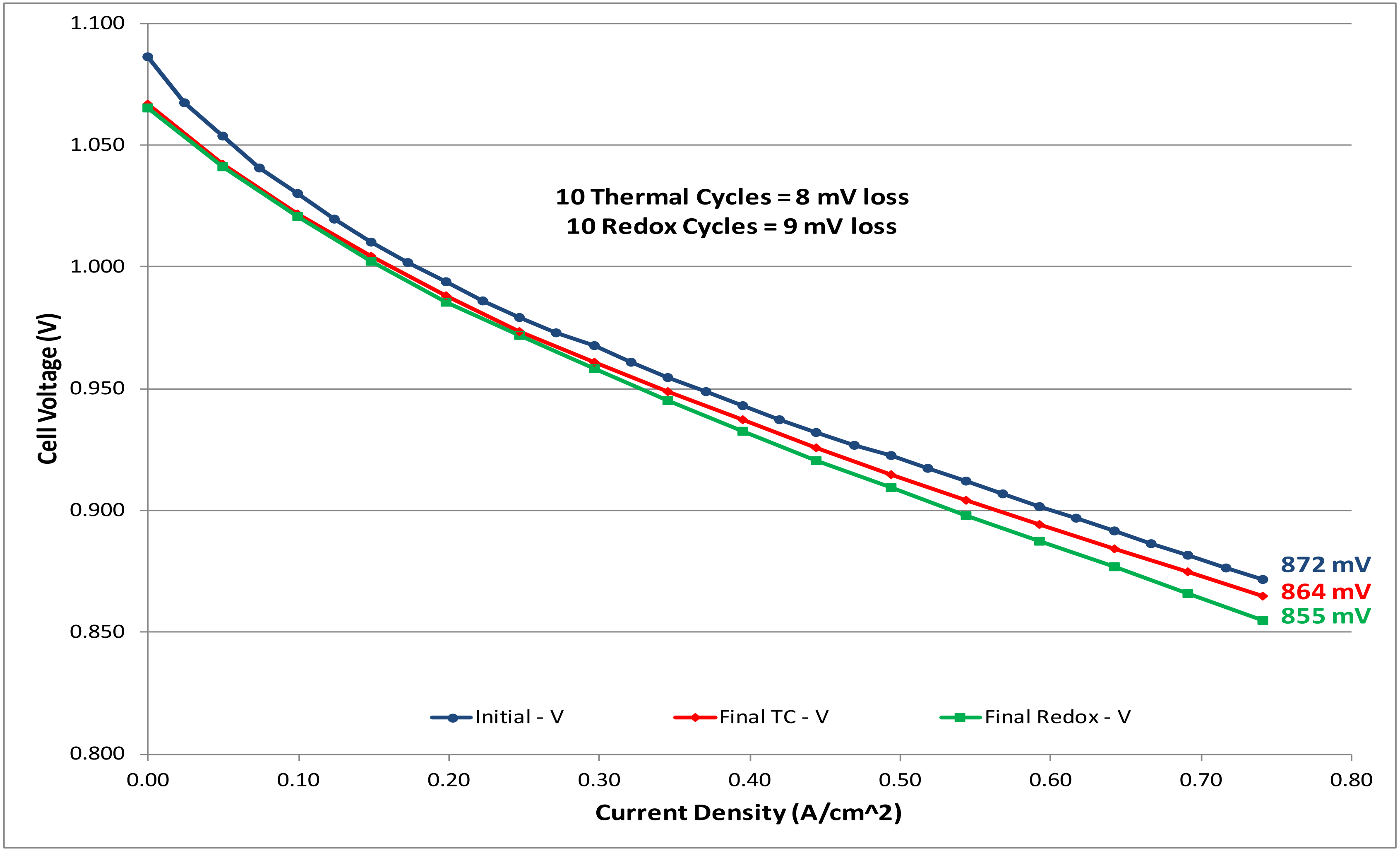
- Baseline electrochemical testing was performed comparing initial current-voltage curves and steady-state degradation testing with tests after redox cycles.
- A redox depth approach was developed in order to determine the length of redox cycle times. For details see:
  (D. Waldbillig, A. Wood, D. Ivey, *J. Power Sources*, accepted for publication (2005).)
- This analysis uses the amount of Ni within the cell and the flow rate of air to predict the amount of time it would take to oxidize the cell to a specific redox depth. The approach assumes all of the oxygen in the air feed to the test is used up to oxidise nickel (i.e., fast kinetics). This was confirmed to 60% redox depth by measuring the length of time taken before oxygen was detected in the outlet gas using gas chromatography.
- Redox cycles to a redox depth of 10%, 20%, 30%, 60%, 120% (excess air flow) and 180% (excess air flow) were performed corresponding to 20, 40, 60, 120, 240 and 360 mins at 120ml/min air flow into the test jig.





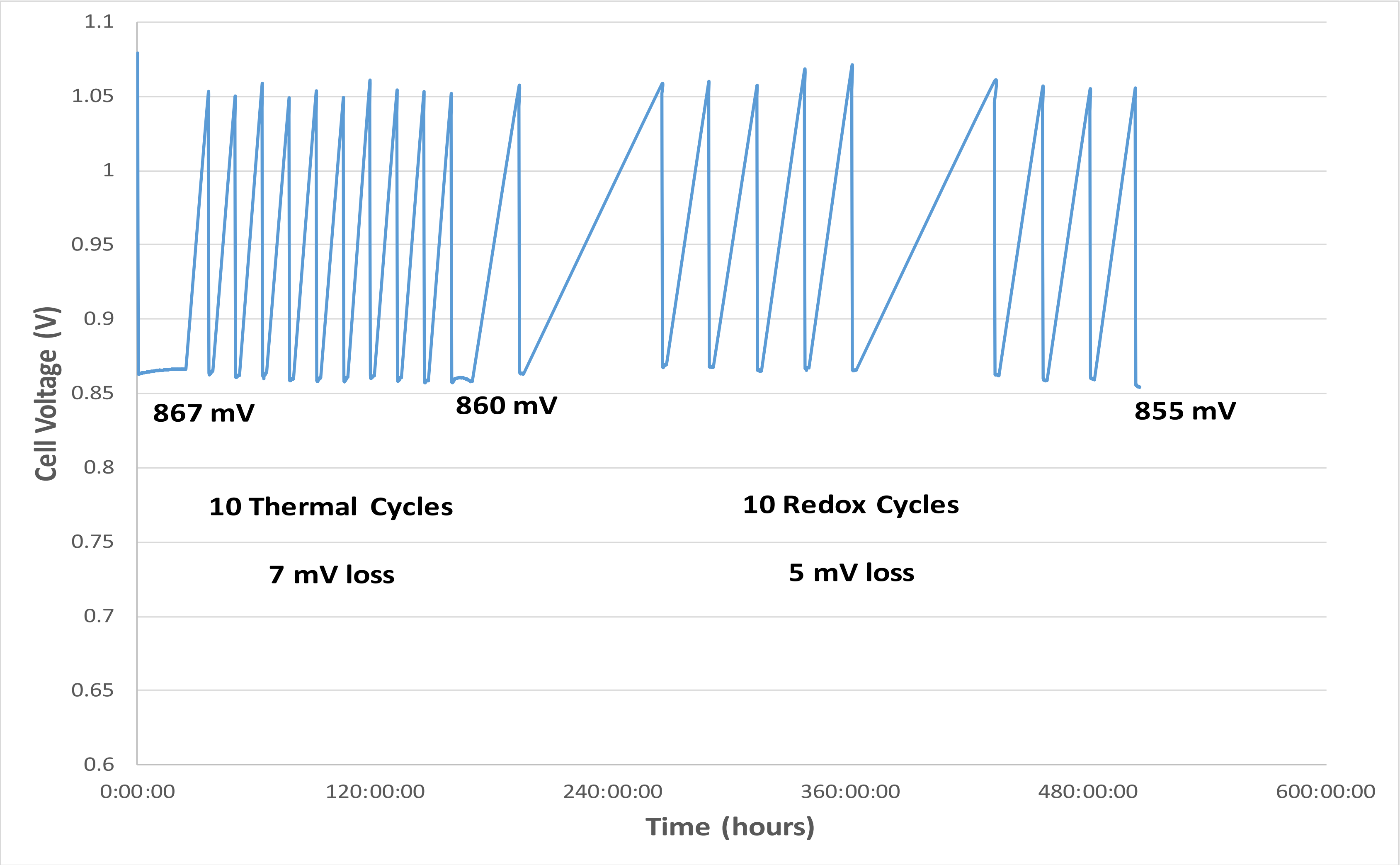
Redox time (min)	Redox depth (%)	Degradation per cycle (%)	Cumulative degradation (%)
20	10	-0.8	-0.8
40	20	-0.4	-1.2
60	30	-0.7	-1.9
120	60	-2.2	-4.1
240	120	-4.1	-8.1
360	180	-2.8	-10.9

Status of Redox Tolerance Improvement



Performance Curves Comparison at 750°C after 10 Thermal and 10 Redox Shutdown Cycles With 5 Hour Hot Holds (Fuel Pipes Disconnected)

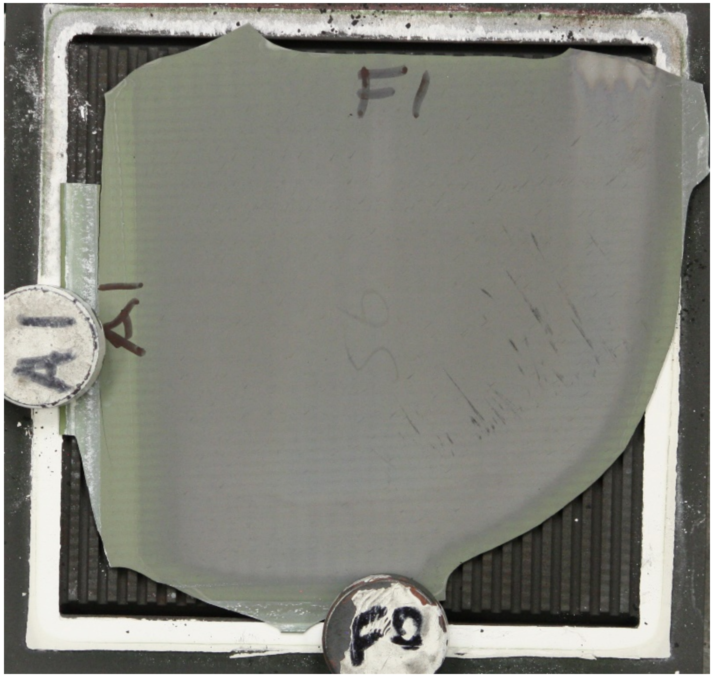
Status of Redox Tolerance Improvement



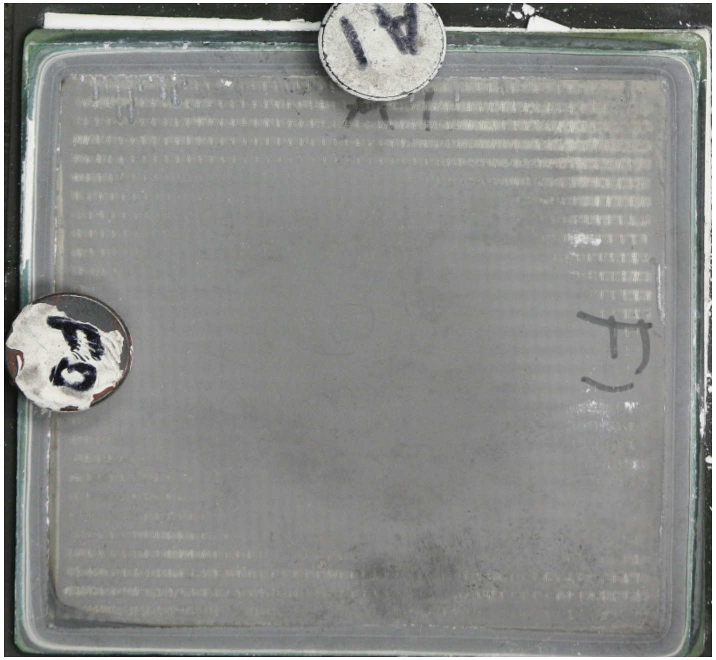
Steady State Hold Results at 750°C over 10 Thermal and 10 Redox Shutdown Cycles With 5 Hour Hot Holds (Fuel Pipes Disconnected)

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



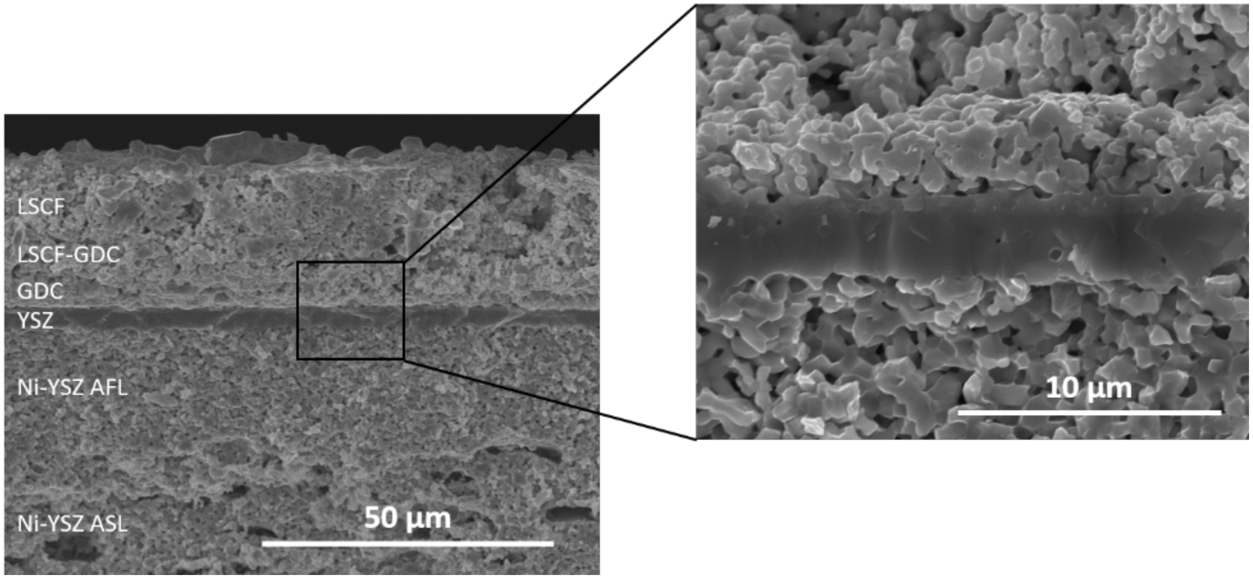
- Standard cell (left) failed after 5 redox cycles
- Autopsy shows cell failed catastrophically
- Broken cell with significant oxidation



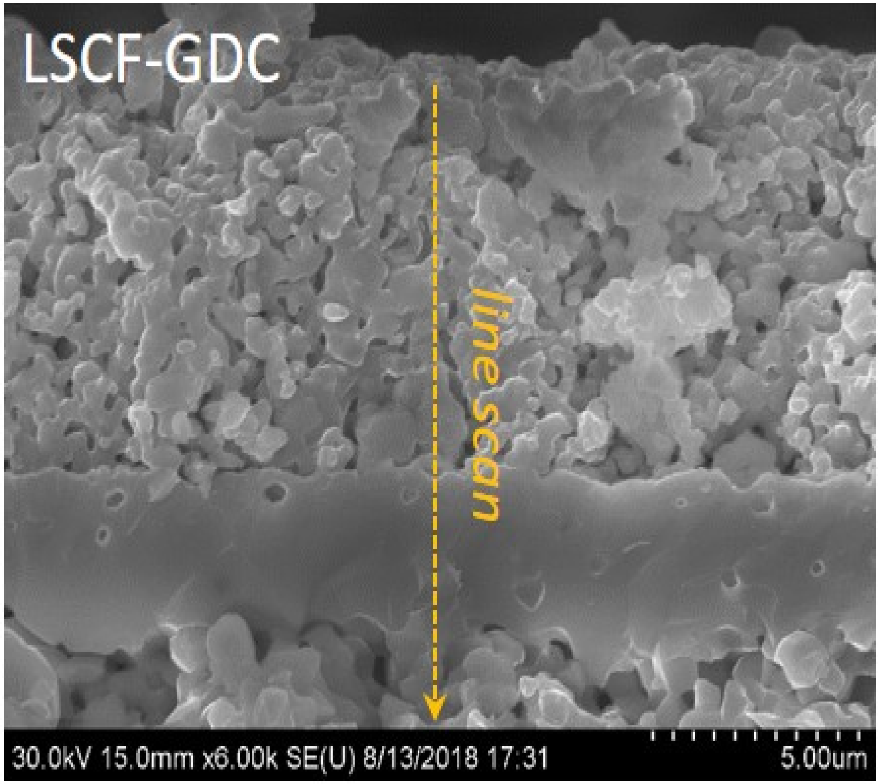
- Redox cell (right) fully in-tact
- Autopsy shows no signs of cracking
- No oxidation in active area
- Significant increase in robustness

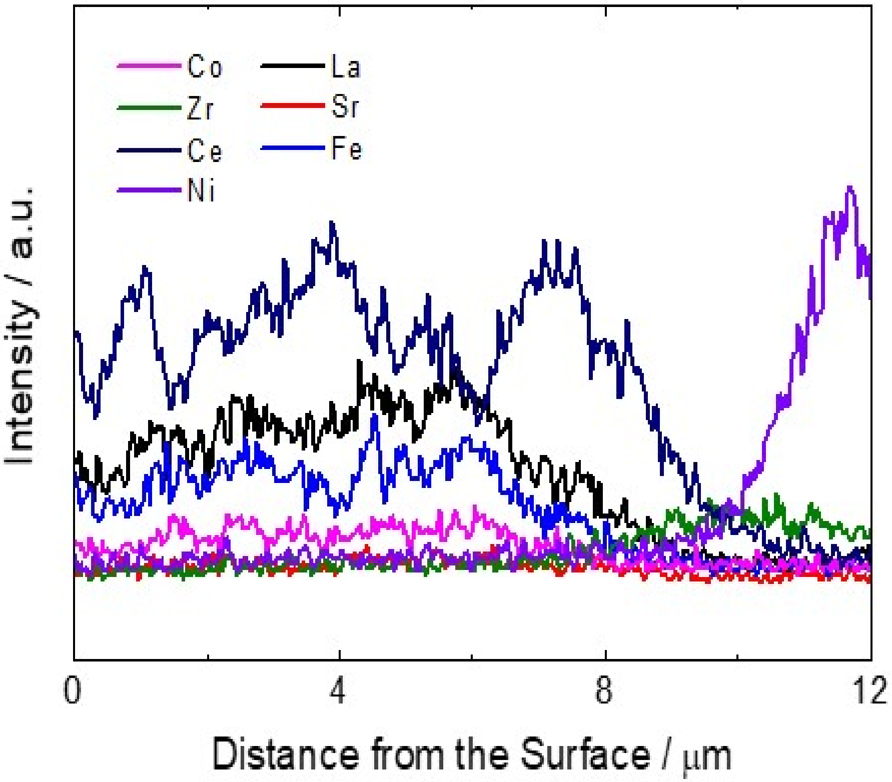
Cells With Ultra-Thin Electrolyte

- Methods were developed at Northwestern University to tape cast extremely thin (~ 2 micron) dense YSZ electrolyte layers
- The GDC layer was also 1 – 2 microns thick, either co-fired (dense) or separately fired (porous)
  - The images below show the basic cell architecture, for the case of a porous GDC layer
- Either method can yield high power density cells



Cells With Ultra-Thin Electrolyte

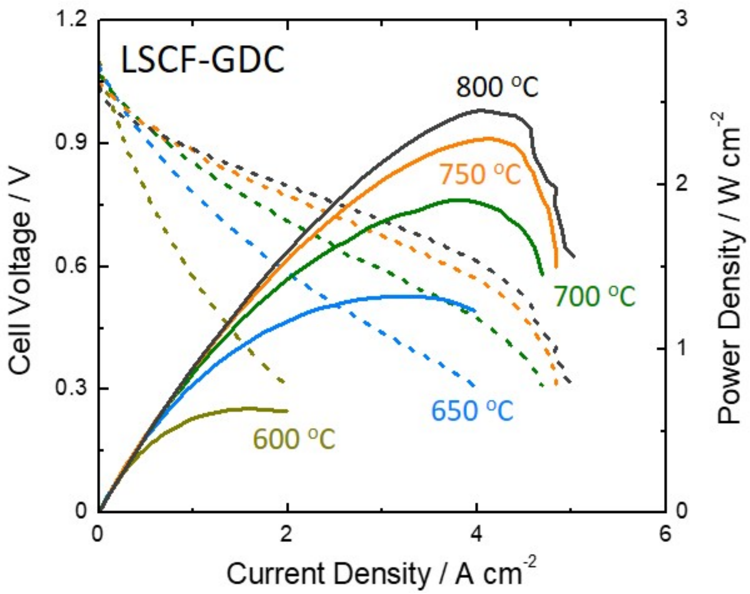


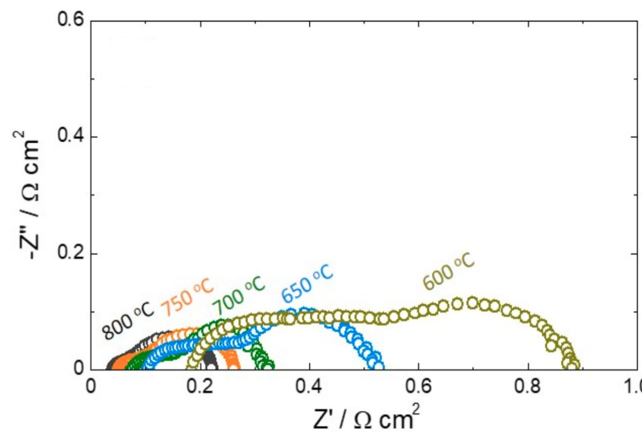


- Dense bi-layer electrolyte: ~ 1.7 µm YSZ, 1.0 µm GDC
- Note that reduced firing temperature (1250 °C) is essential to avoid complete inter-diffusion of YSZ and GDC

Cells With Ultra-Thin Electrolyte

- Results shown for cell with dense bi-layer electrolyte
- Excellent performance achieved down to 700 C
- Performance at 600 C lacking
  - Electrolyte resistance is acceptable
  - Polarization resistance is too large
- Low temperature performance could be improved with better electrodes, *e.g.* via infiltration





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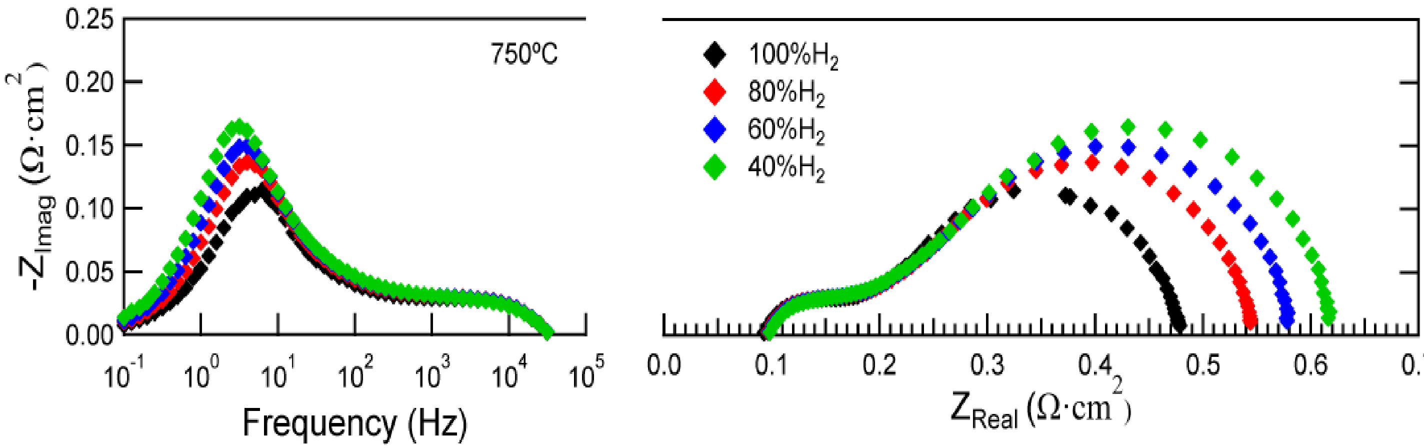
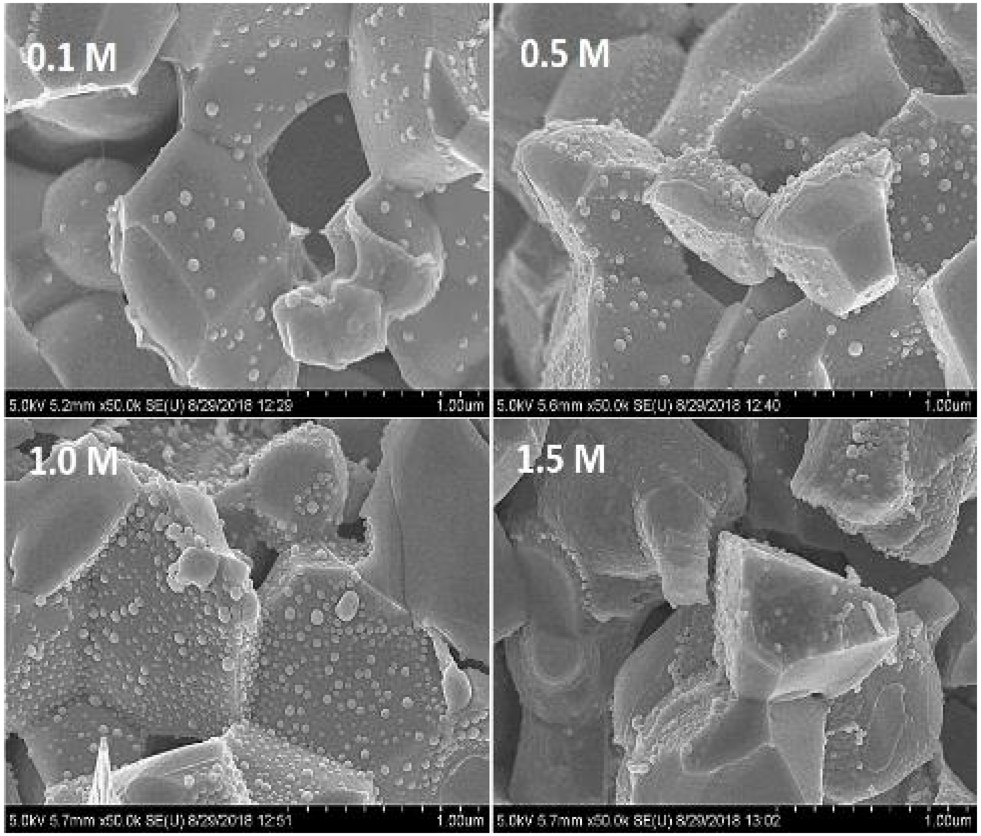
Cathode Infiltrated Cell: Diagnostics

- LSCF infiltrated into LSCF-GDC
- Variation of H_2 concentration shows that low frequency response is related to the anode
  - Since this is the main contribution to the polarization resistance, improved anodes are needed to make further improvements in cell performance



GDC-Infiltrated Ni-YSZ: Morphology

- infiltration of Gd-doped Ceria $Gd_{0.2}Ce_{0.8}O_2$ (GDC) into Ni-YSZ
  - GDC chosen due to its excellent catalytic and mixed ionic/electronic conducting properties
- Initial study done with Ni-YSZ / YSZ / Ni-YSZ symmetric cells
  - Reduced prior to infiltration
- Single-step infiltration of different concentrations (0.1 – 2.0 mol L^{-1})
  - $Gd(NO_3)_3 \cdot 6H_2O$ and $Ce(NO_3)_3 \cdot 6H_2O$ dissolved in distilled water
- SEM images show increasing density of GDC nanoparticles with increasing molarity
  - Surface appears to be fully covered for 1.5M



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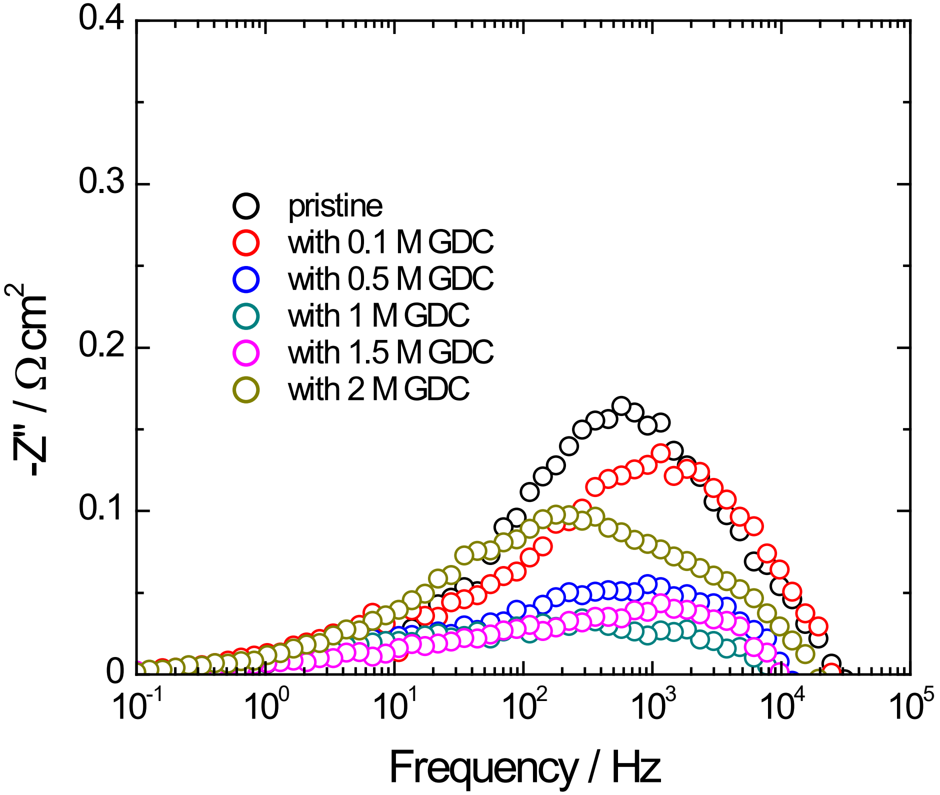
GDC-Infiltrated Ni-YSZ: Impedance Spectra

- EIS carried out at 600 C in humidified H_2
- Main response centered at ~ 1000 Hz decreases with increasing GDC amount to 1M, then increases
- Smaller response centered at 10 – 100 Hz also minimized using 1M GDC
- Similar improvements seen at 700 and 800 C



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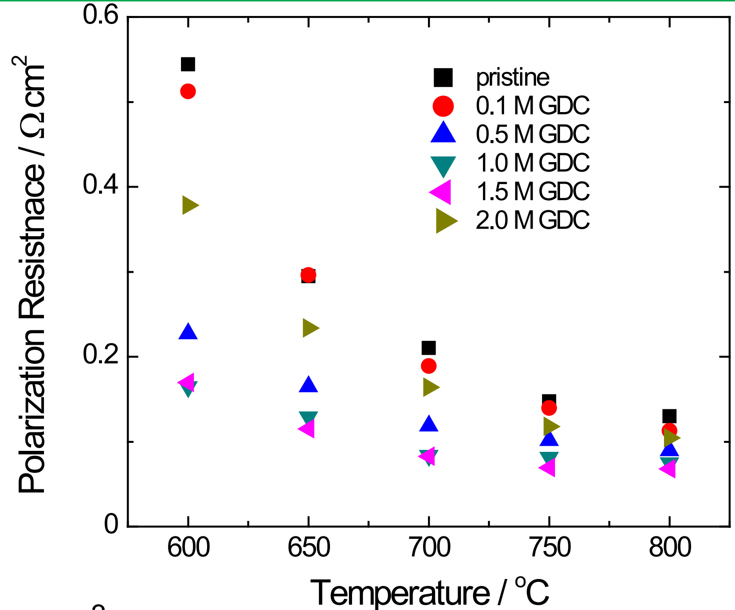
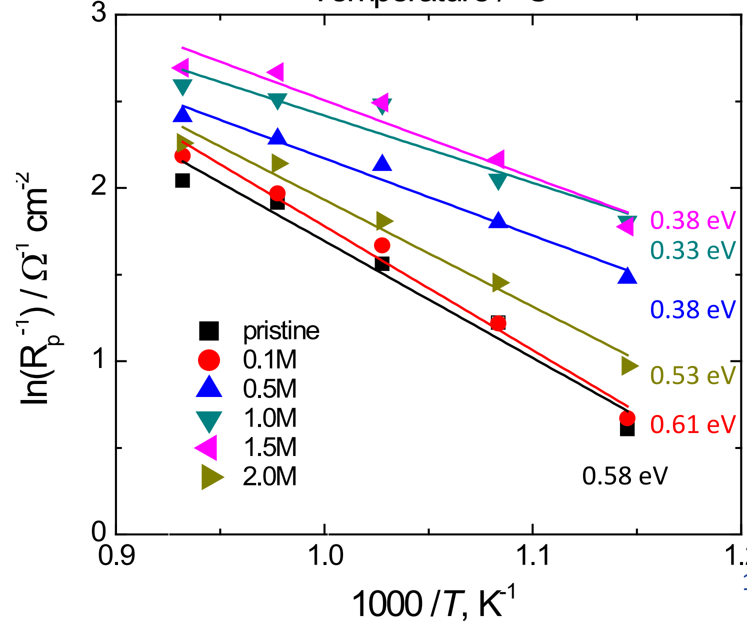
GDC Infiltrated Ni-YSZ: Polarization Resistance

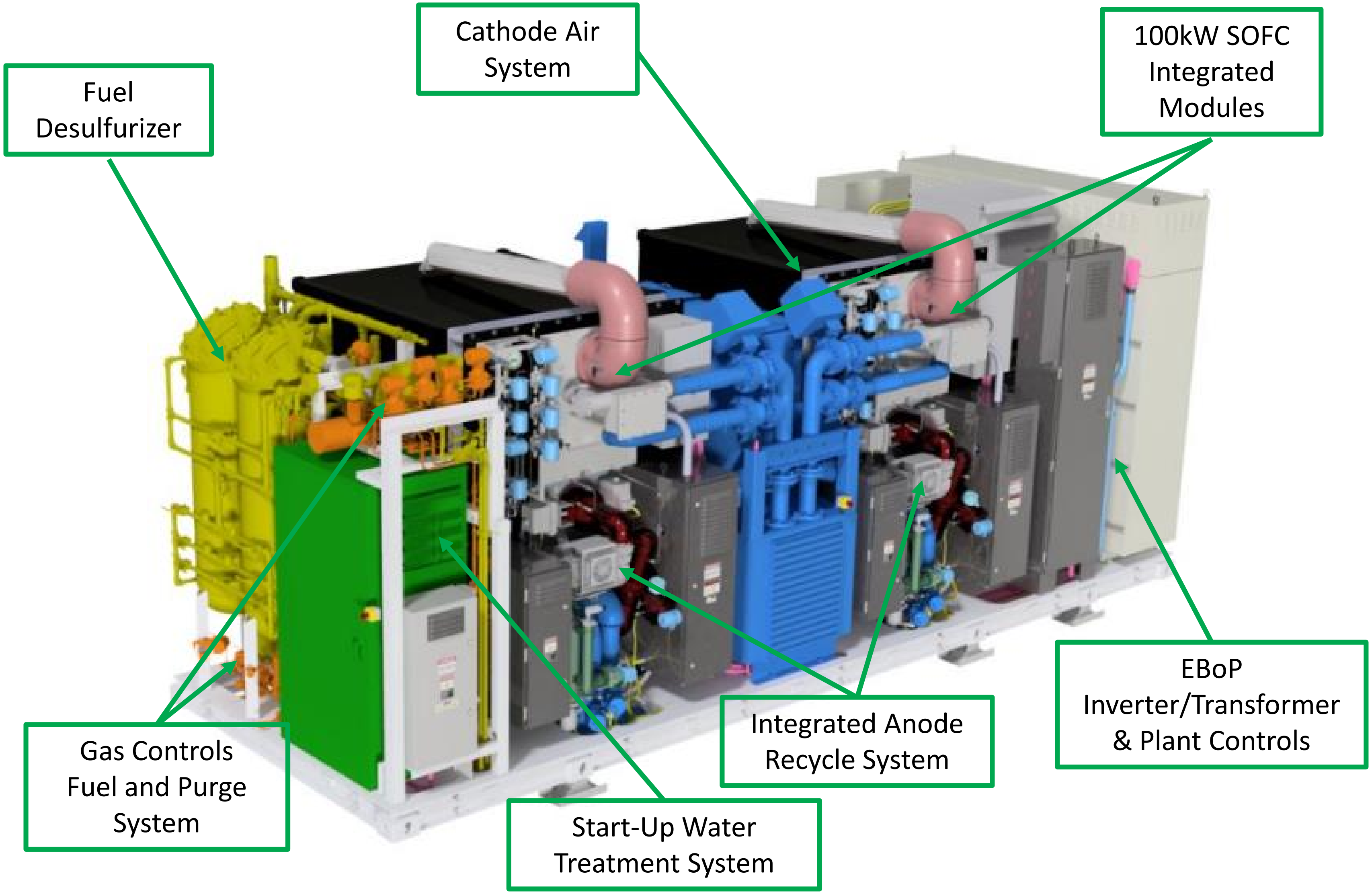
- Impedance spectroscopy carried out in humidified H_2
- Resistance and apparent activation energy decreases with increasing GDC molarity up to 1.0 M
- Most pronounced effect at lower temperature
  - At 600 C, decrease from > 0.5 to < 0.2 Ωcm^2
  - Viable for low-temperature SOFC!
- Preliminary life tests show good stability at 650 C
  - Challenging because Ni-YSZ must be reduced prior to infiltration





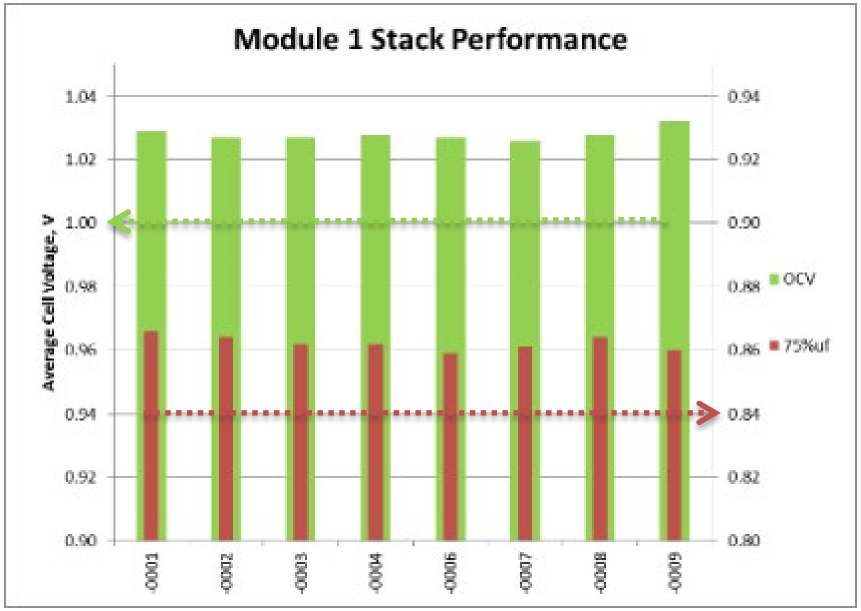
200 kW System Update

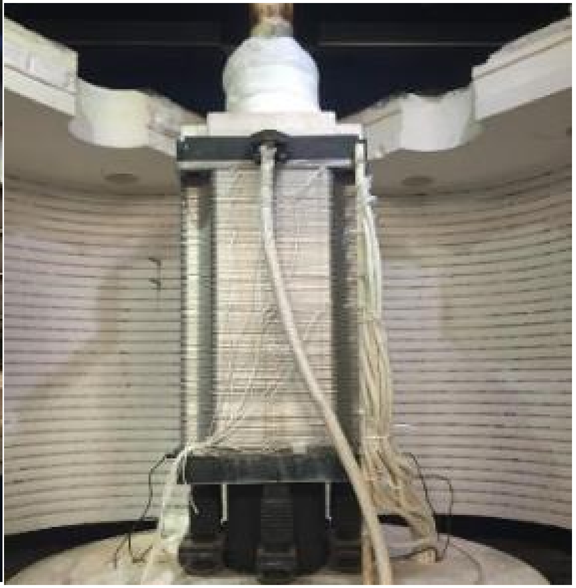
200kW SOFC Power System Overview

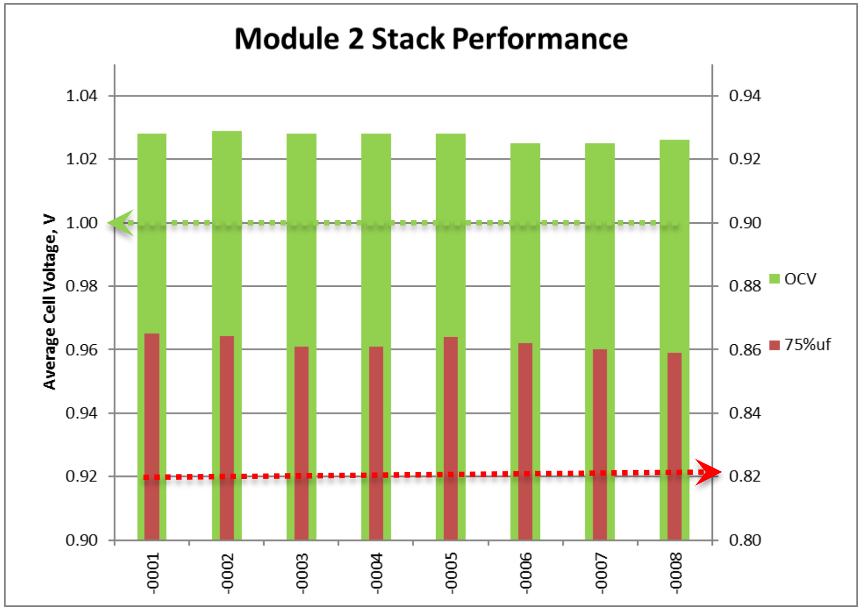


- Includes (2) 100kW SOFC stack modules designed to operate independently
- Factory assembled & shipped as a standard ISO 20' x 8' container

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

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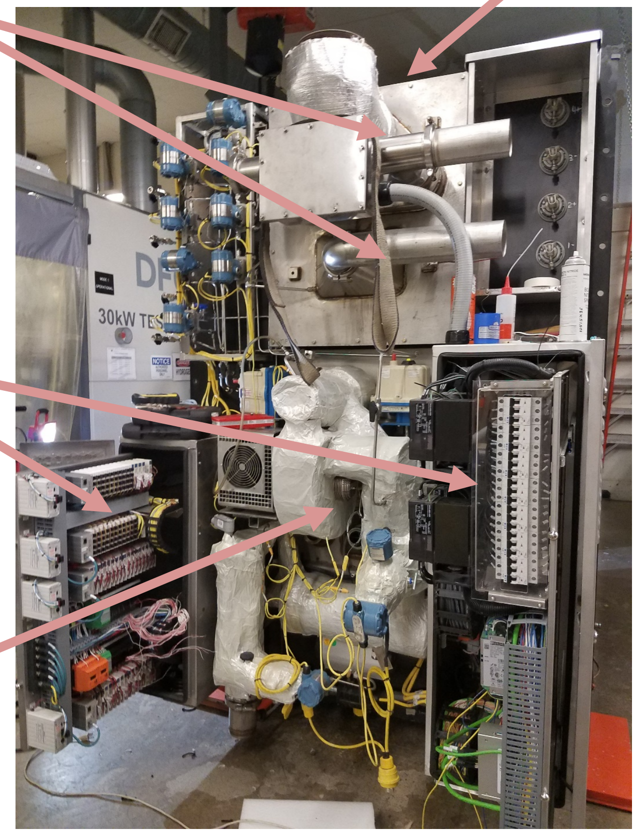
100 kW Module Design & Fabrication

Cathode Process Air Connections

Removable Vessel Shell

I&C Panels

Anode Recycle System



<u>100 kW Stack Module 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 SOFC System Factory Testing

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

Factory Acceptance Test Results at 100% Load

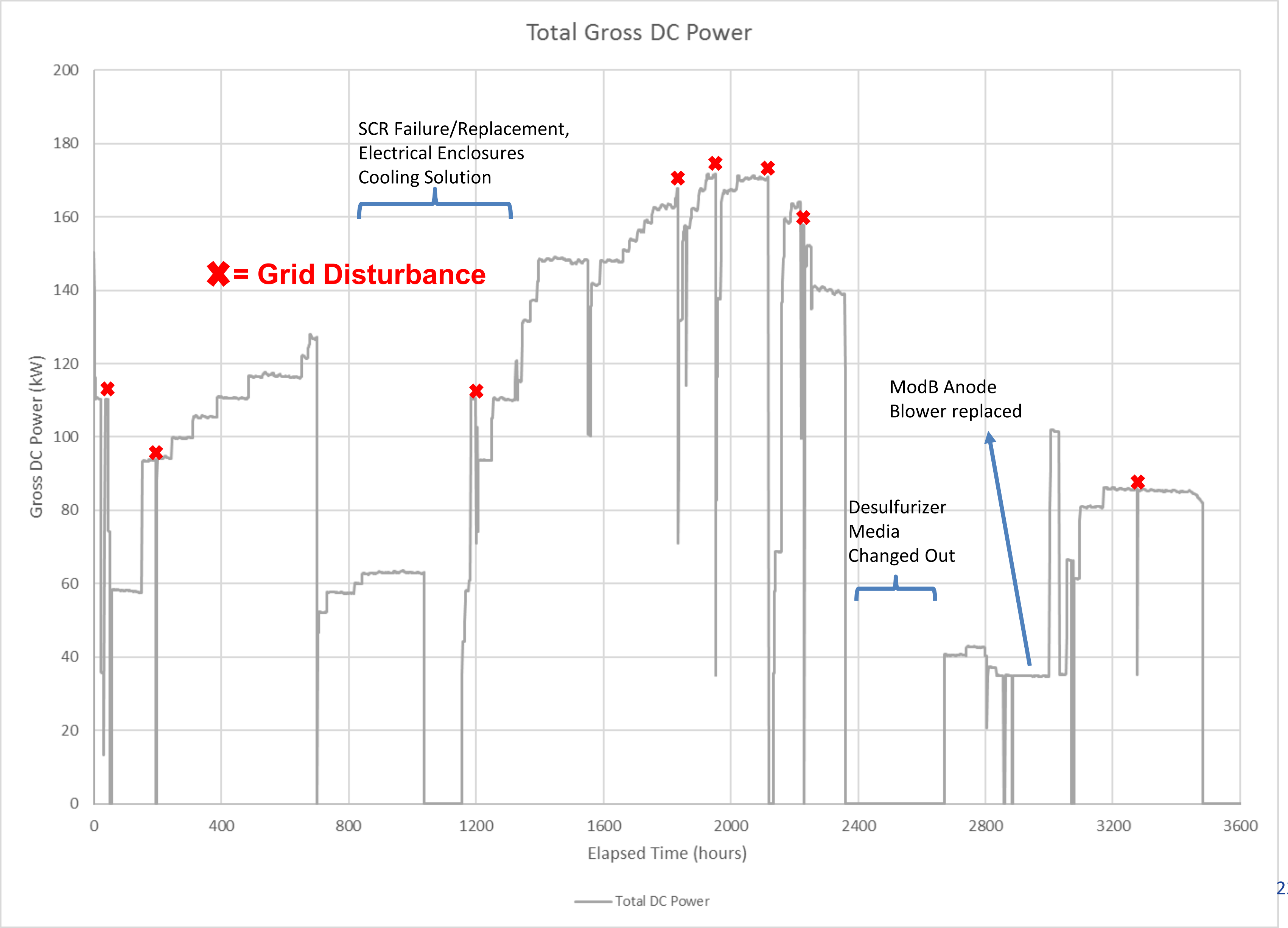
Module A Voltages

Module B Voltages

Installation at Demonstration Site

Energy Center Pittsburgh - Clearway Energy (Formerly NRG Yield)

Operation at Clearway Site



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Summary

- The system accumulated ~3500 hours of hot operation (includes FAT in Danbury and commissioning/demonstration test at Clearway)
- Anode Recycle Blower (ARB) on Module B failed after ~2000 hours of demonstration testing and was replaced with a spare unit
- Sulfur breakthrough starting after ~2000 hours of demonstration testing
  - Desulfurizer Media was replaced
  - Cause of sulfur breakthrough is NG supply far off specification, extreme high sulfur content and challenging mix of sulfur species.
  - Rapid breakthrough of replaced desulfurizer beds
- The system was shutdown and returned to FCE HQ (Danbury, CT) for further testing
- Module A was disassembled for post-test autopsy and diagnostic testing
- System has initiated operation using module B only, with >500 hours of operation as of 6/2/2020

Next Generation SOFC Stack Technology Development

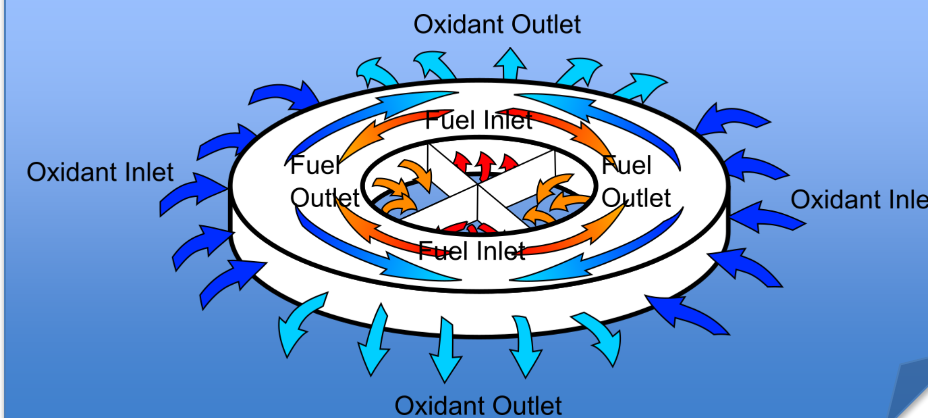
Compact SOFC Architecture (CSA) Platform

Integrated compression

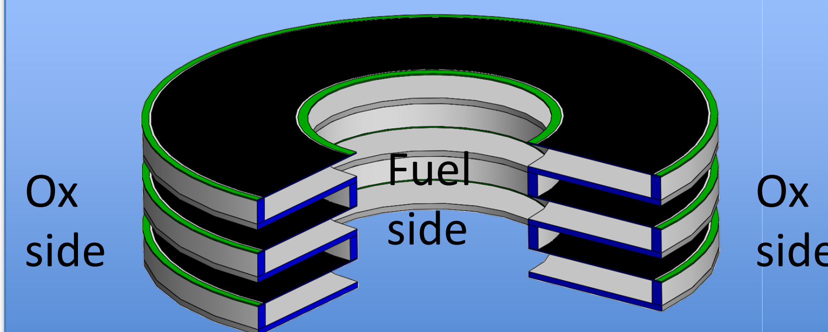
Oxidant outlet manifold

350 cells - 17” tall
~7 kW

Flow Geometry



Underlying Structure (expanded)



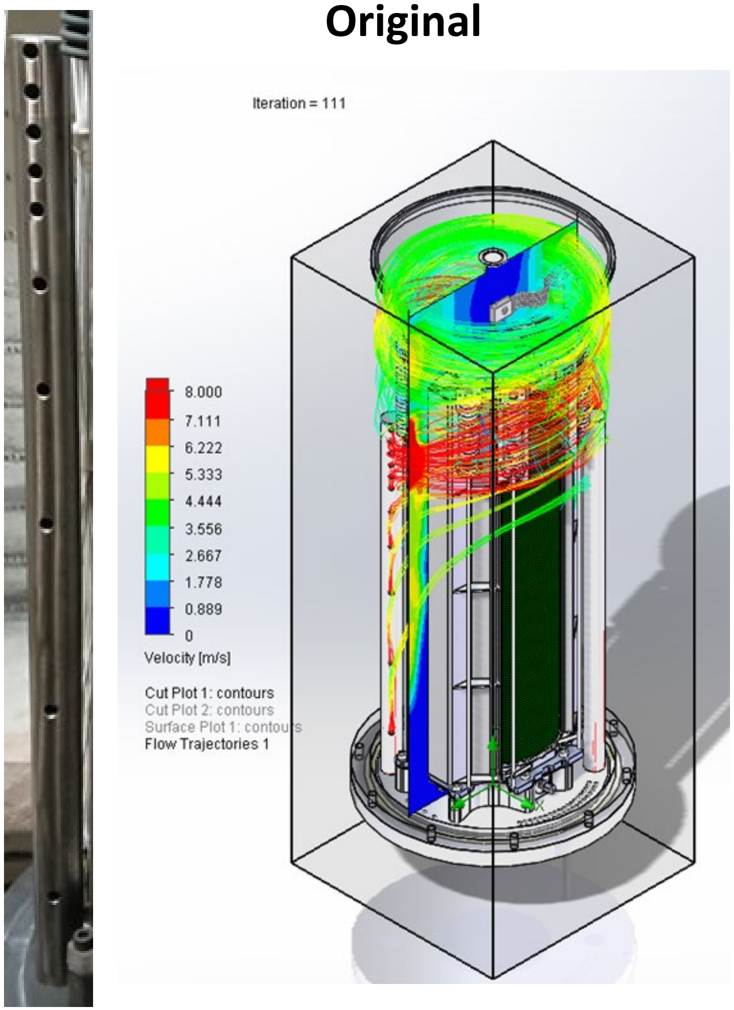
Bellows structure separates fuel and air and offers compliance and robustness

CSA Stack Family

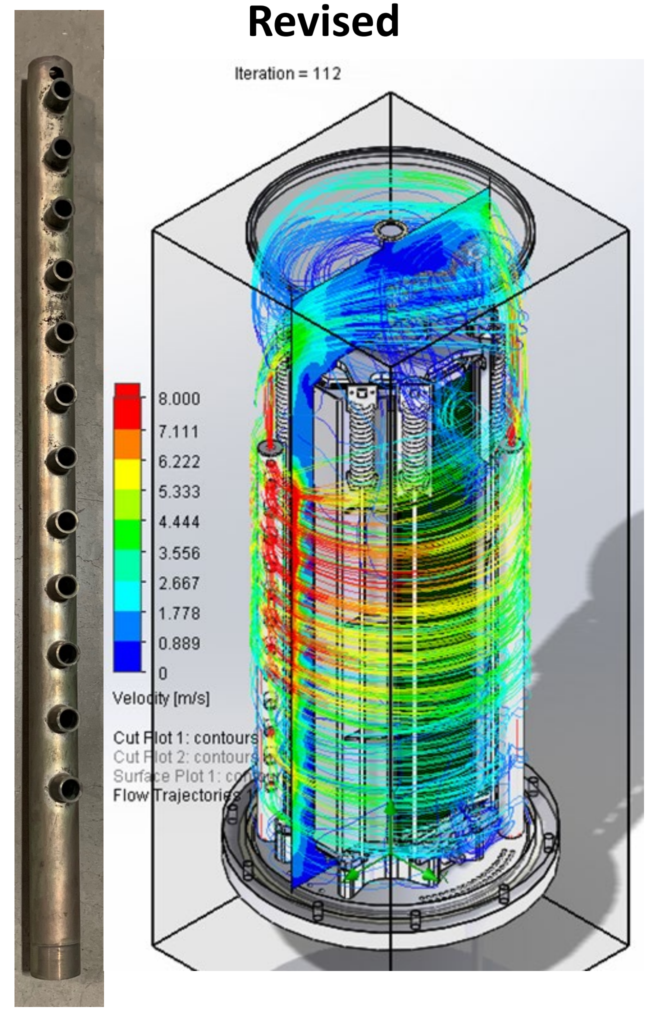
Property	Scale			Comments
	Short	Mid	**Full**	
Cell count	50	150	350	Nominal count
Operating Voltage, V	43	128	298	At 0.85 V/cell
Power, kW	0.9	3.0	7.0	At 0.29 A/cm^2
Height, mm (in)	91 (3.6)	211 (8.3)	440 (17.3)	

Recent Modification

Original



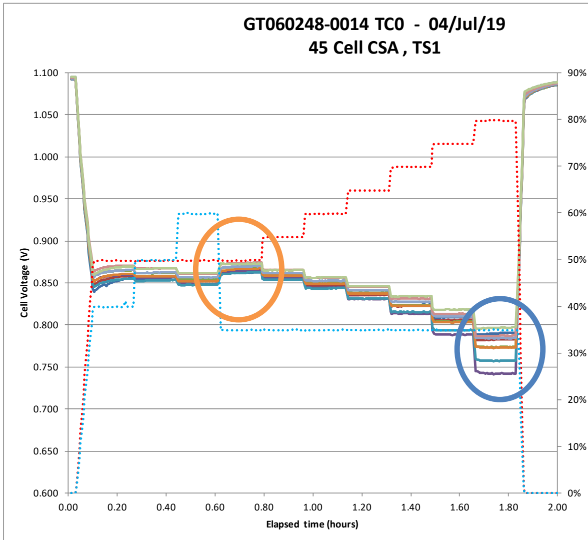
Revised



Test results suggested an air flow sensitivity. A re-examination of the air inlet distribution tubes showed a potential cause. Flow momentum at the higher flow rates was favoring air flow to the top. A revised air inlet was designed and built

Impact of Design Improvements

GT060248-0014



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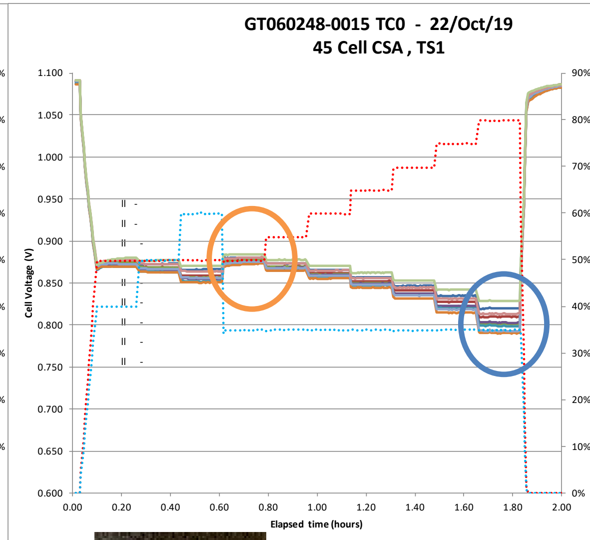

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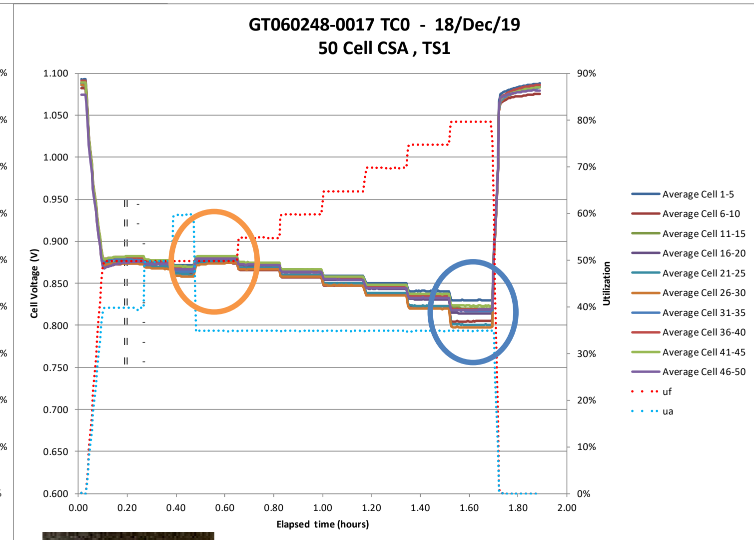
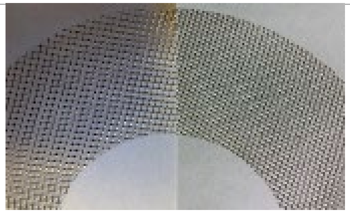




Base plate modification is yielding higher performance

Contact modification is yielding better uniformity

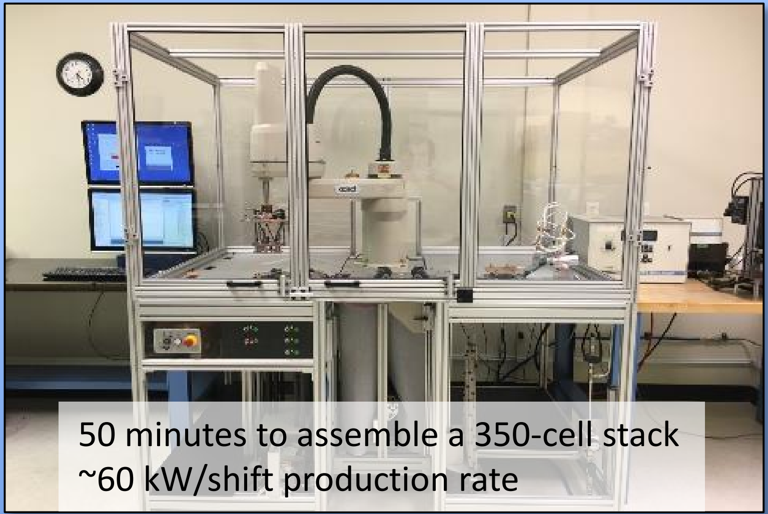
Design Freeze this configuration for project deliverables
Stack GT060248-0017 into fuel cell reformate hold for characterization

Automated production

The CSA stack achieves a 6x reduction in material content per stack compared to prior generation stacks, using smaller and lighter components.

Automated part handling, automated QC, and automated assembly are aided by these small lightweight parts, and deliver lower cost at higher quality than hand assembly.

Automated cell printing (in development)



Automated QC and stack build (fully deployed)

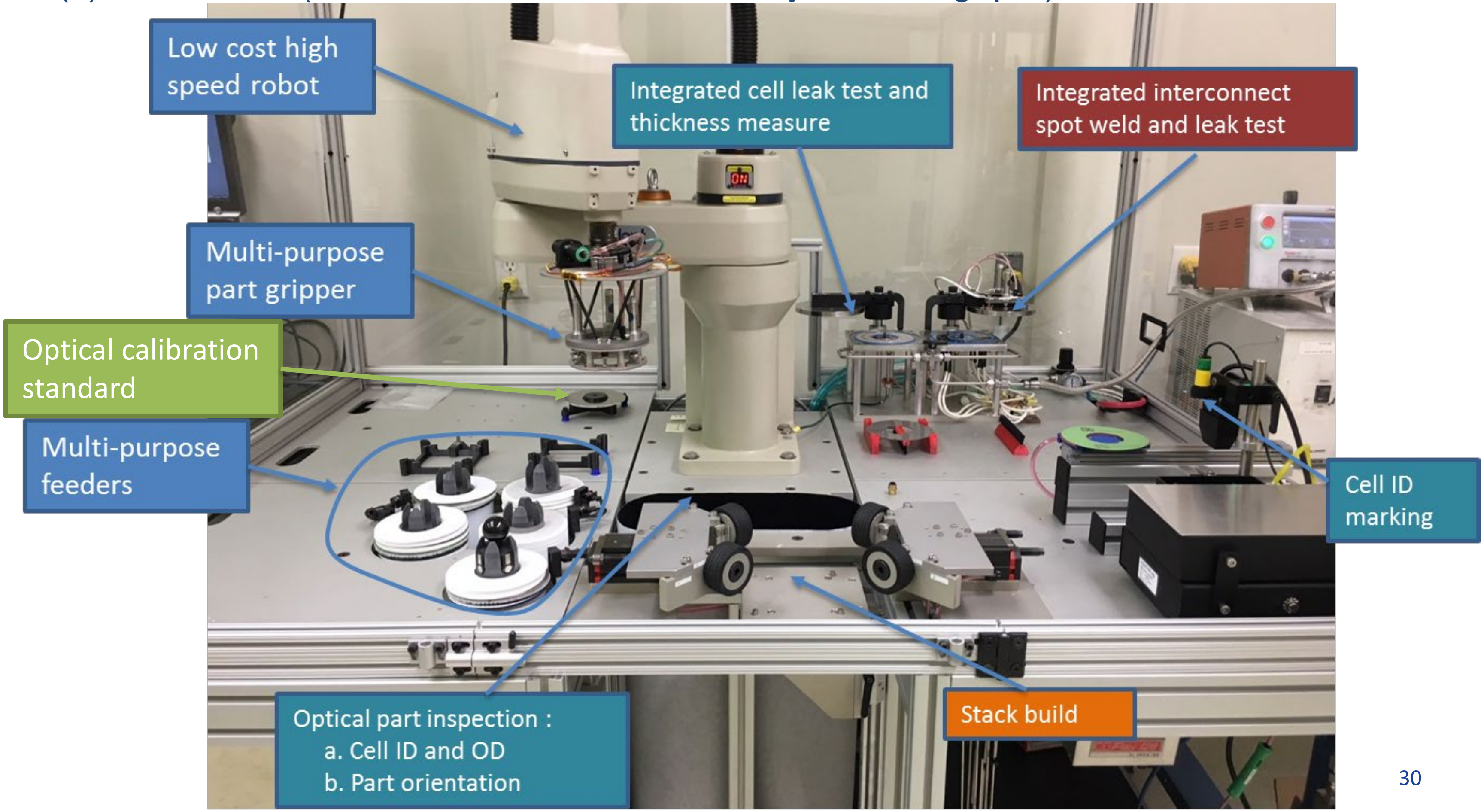
Automated Integrated Stacking &QC Station

Robotic work cell for:

(a) Cell QC - measure / leak test (Demonstrated >3 MW/shift/year throughput)

(b) Interconnect sub-assembly / QC (Demonstrated > 3 MW/shift/year throughput)

(c) Stack build (Demonstrated > 10 MW/shift/year throughput)



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- The progress in SOFC technology was supported by DOE/NETL Cooperative Agreements: DE-FE0023186, DE-FE0026199, DE-FE0026093, DE-FE0031639 and DE-FE0031648
- Guidance from NETL Management team: Shailesh Vora, Joseph Stoffa, and Patcharin Burke