LG Fuel Cell Systems Program and Technology Update

2015 SOFC Workshop, 14 July 2015

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Outline

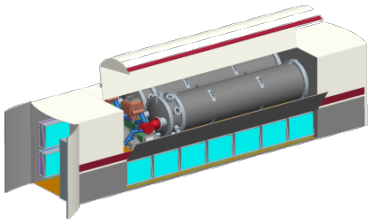
- 200kW scale demonstration test
- Cell degradation understanding and mitigation
  - Primary sources of degradation
  - Improvements for entrance-into-service (EIS) technology
    - Optimization of LSM-based cathode
    - Single layer anode
- Lower ASR cell technology
  - Broad changes of active layers and design for near-term product
  - Evaluating nickelate cathodes for longer-term objective

LG Fuel Cell System Inc.

Phases of the business:

Commercial Phase

EIS Phase



IST Phase

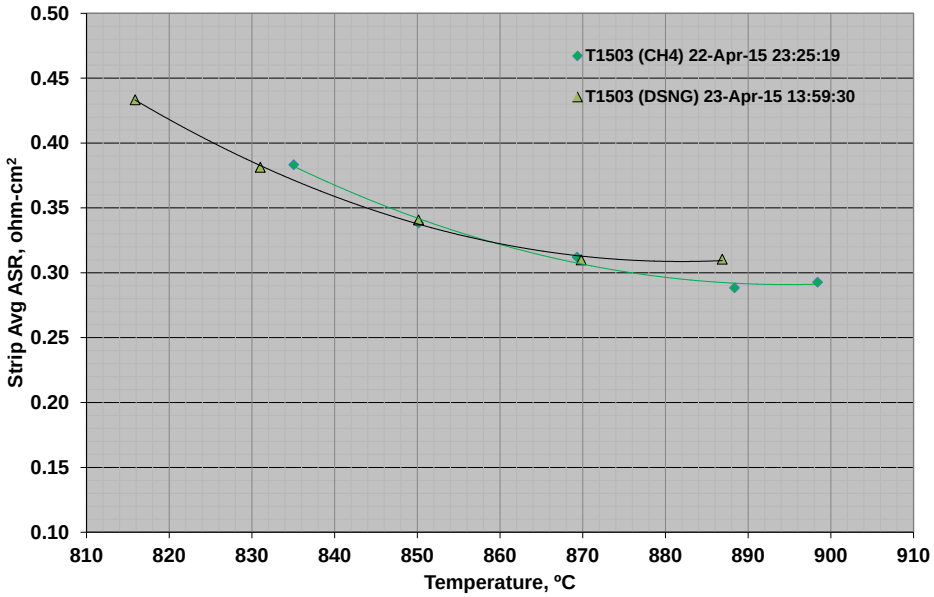
Building on a Solid Foundation

LGFCS Integrated String Test (IST)

- Testing began June 2015
- Pipeline natural gas to grid connection
- 200kW-class pressurized SOFC system
- Demonstrates functionality of integrated subsystems:
  - Fuel processing
  - Pressurized SOFC vessel
  - Turbogenerator assembly
  - Power electronics
  - Controls and safety system
- Utilizes cell technology developed under LGFCS DOE SECA programs

Block Performance Testing Prior to the IST

- UK test rig modified to test block design of IST
  - Rig accommodates 1 to 3 blocks
- Design point ASR of 0.32 ohm-cm^2 at block midpoint 860C demonstrated on DSNG
  - 62% anode loop efficiency
  - 78% fuel utilization
  - Block ΔT ~80C



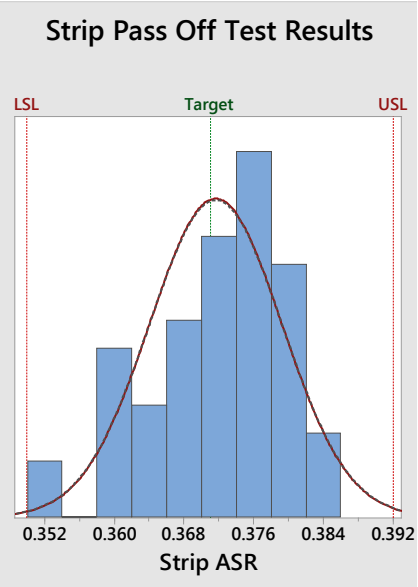
Performance of IST-stage (epsilon) Technology

- 60 Strips manufactured
  - Performance and/or OCV quality check of each strip
- IST block ASR matches single block and expectations from strip performance QA data
- LGFCS IP-SOFC ASR similar at scales ranging from penta cell, bundle, strip, multi-block (150,000x scale up)

Strip ASR (1 bar, 860ºC, half load)

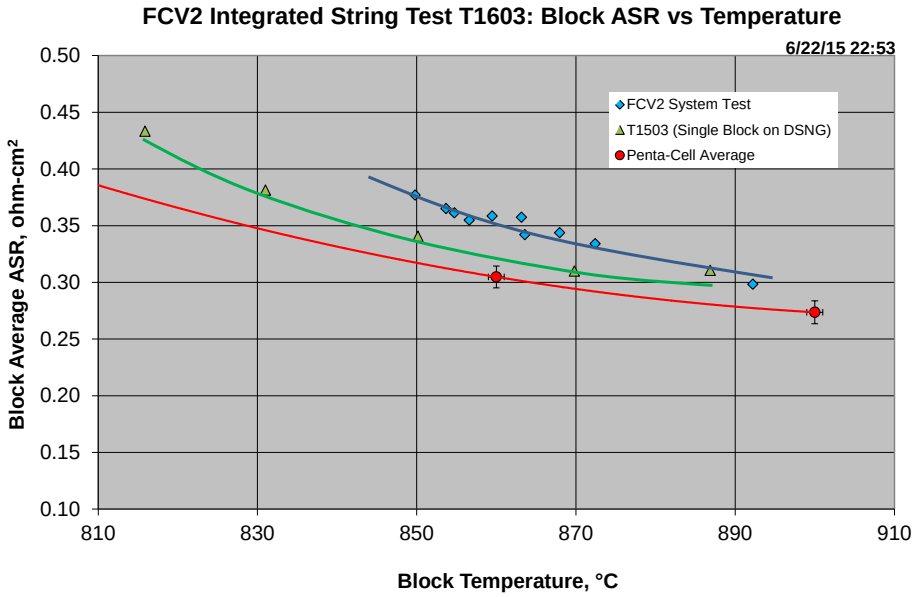
Average = 0.37 ohm-cm^2 @ 860ºC

Expected at IST conditions = 0.34 ohm-cm^2



Block ASR (IST conditions)

Average = 0.35 ohm-cm^2 @ 860ºC



Natural Gas Variability is Important Factor in System Design

North Canton Natural Gas Variability (October 2014 – May 2015)

Area	Methane	Ethane	Propane	C_4^+	Nitrogen	Carbon Dioxide	Specific Gravity	Wobbe Index (BTU/ft^3)	Gross HV (Dry), BTU/ft3
North Canton	89.6	7.97	0.53	0.28	0.889	0.720	0.615	1367.6	1072.2
US 2013*	95.3	2.79	0.29	0.08	0.582	0.864	0.586	1344.6	1030.7
US 1992*	93.0	3.21	0.66	0.32	1.803	0.845	0.599	1328.8	1027.9

*GTI Surveys

- High C_2^+ Hydrocarbons, v-%: 8.1 - 9.2
  - Increased risk for carbon fouling in fuel cell
- NG Contaminants
  - Total S, ppm-v: 0.3 - 1.5
  - Sulfur Species, Av. ppm-v: THT 0.32; Et_2S 0.14; EtMeS 0.05; Me_2S 0.19; Me_2S_2 0.04; t-BuSH 0.11
  - Moisture, ppm-v: 300-1000
- Selective catalytic sulfur oxidation (SCSO) not affected; passive sorbents impacted

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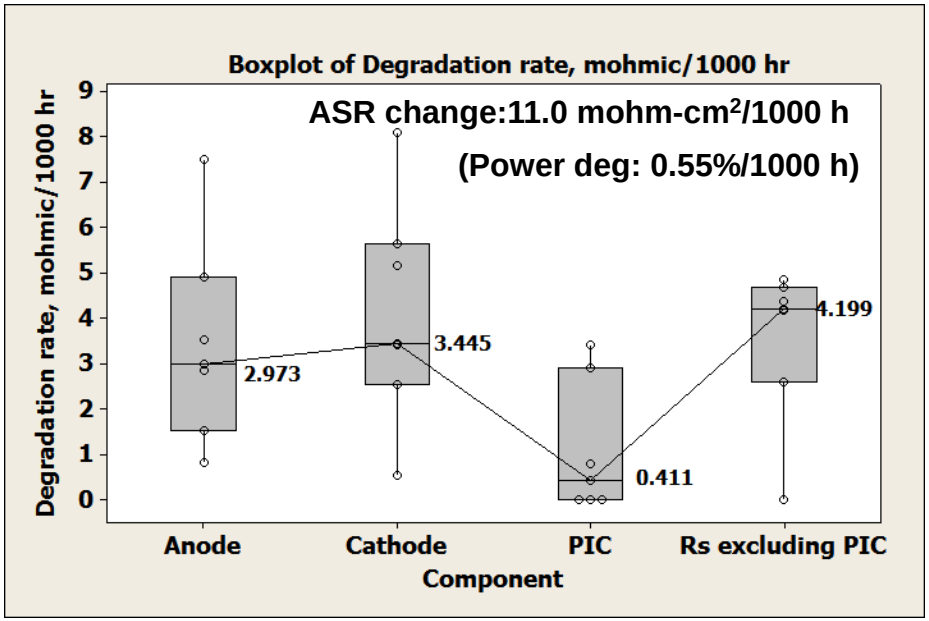
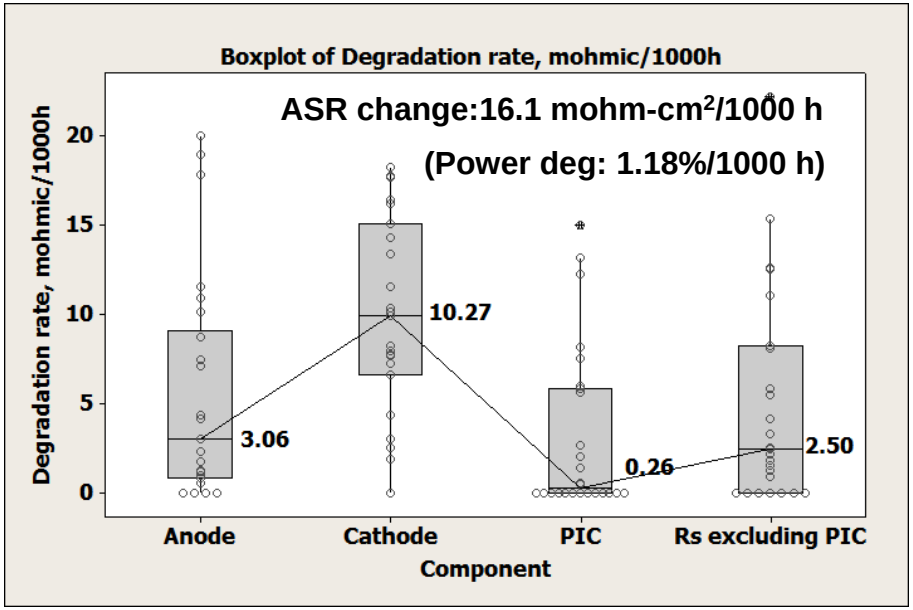
- **Cell degradation understanding and mitigation**
  - **Primary sources of degradation**
  - **Improvements for entrance-into-service (EIS) technology**
    - **Optimization of LSM-based cathode**
    - **Single layer anode**
- Lower ASR
  - Broad changes of active layers and design for near-term product
  - Evaluating nickelate cathodes for longer-term objective

Degradation Rate Deconvolution - Epsilon technology used in 200 kW IST Test

- Epsilon technology was frozen in 2012 for IST test
- Lower degradation at low end temperature of block operation
- Cathode degradation is dominant at high end temperature of block operation
- Current status: 13.5 mohm-cm^2/1000 hr across block temperatures



800C: 8,000 – 16,000 hrs



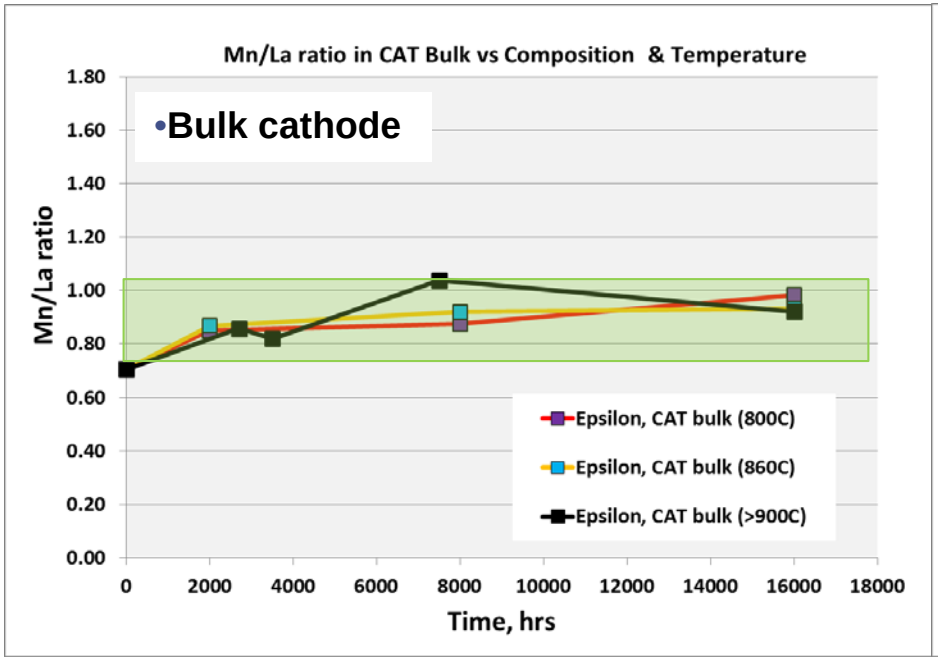
900-925C: 2,500 – 16,000 hrs

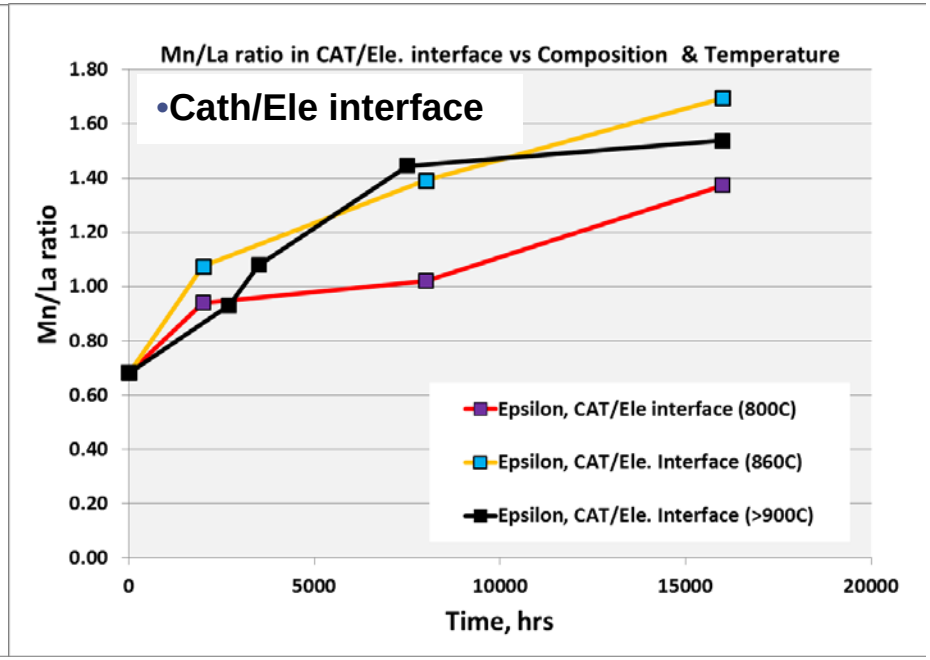
Key Degradation Mechanisms for Cathode

- Free MnOx formation and accumulation
- Cathode densification
- Chromium contamination
- Second phase formation was identified near electrolyte interface after high temperature operation
- Three revised LSM-based cathode formulations under evaluation for improved durability

Free MnOx distribution for Epsilon LSM cathodes

- Mn/La ratio in bulk cathode showed constant level as a function of operation time.
- Mn/La ratio at cathode/electrolyte interface increases with time.

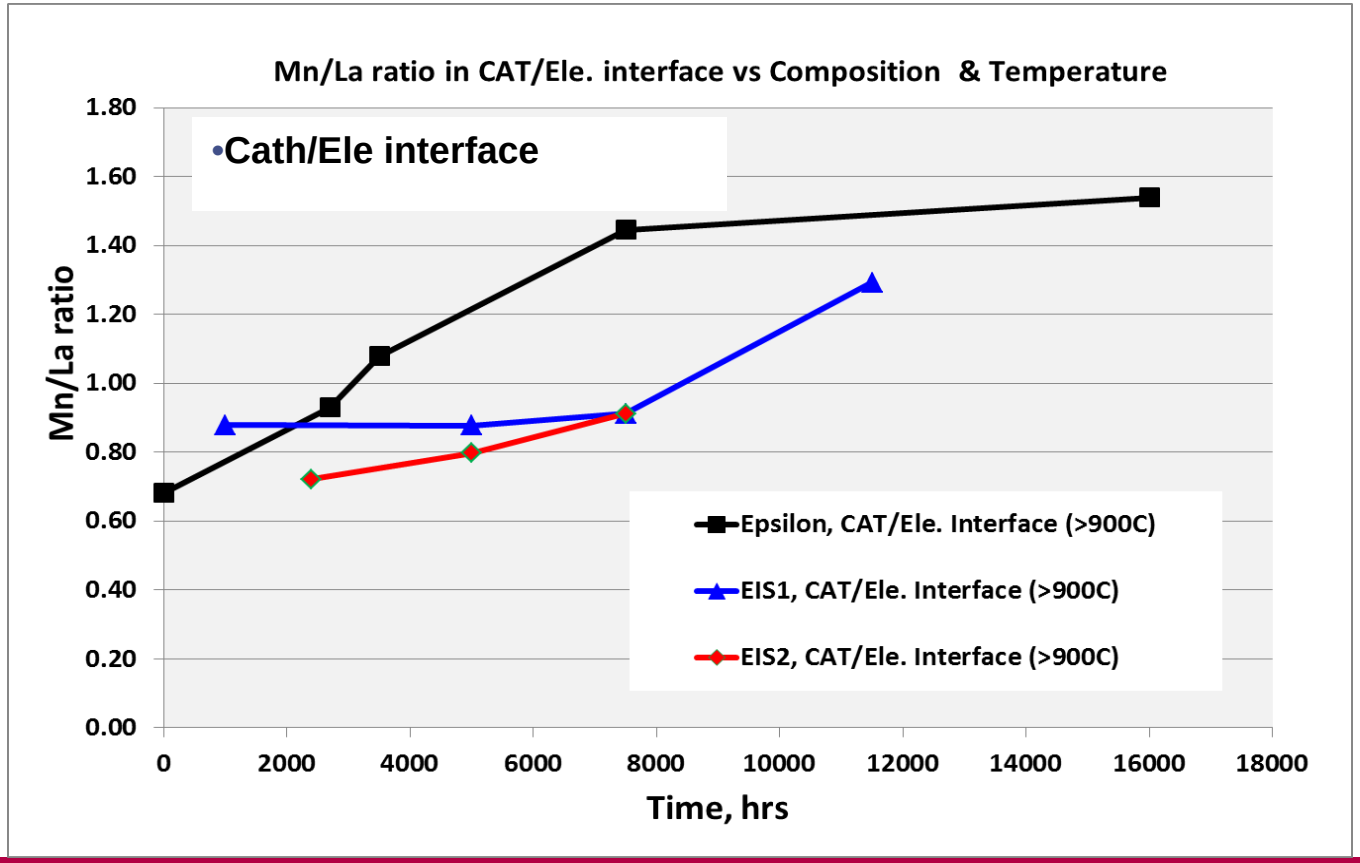




Mn/La ratio from EDS analysis

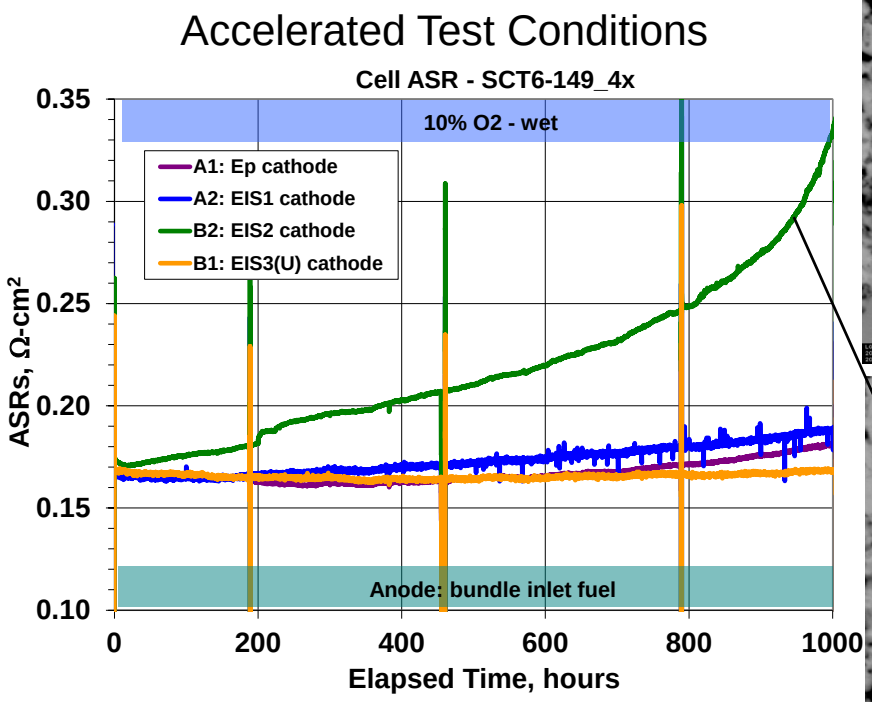
EIS Cathode Shows Less MnOx Rich Near Cathode/Electrolyte Interface

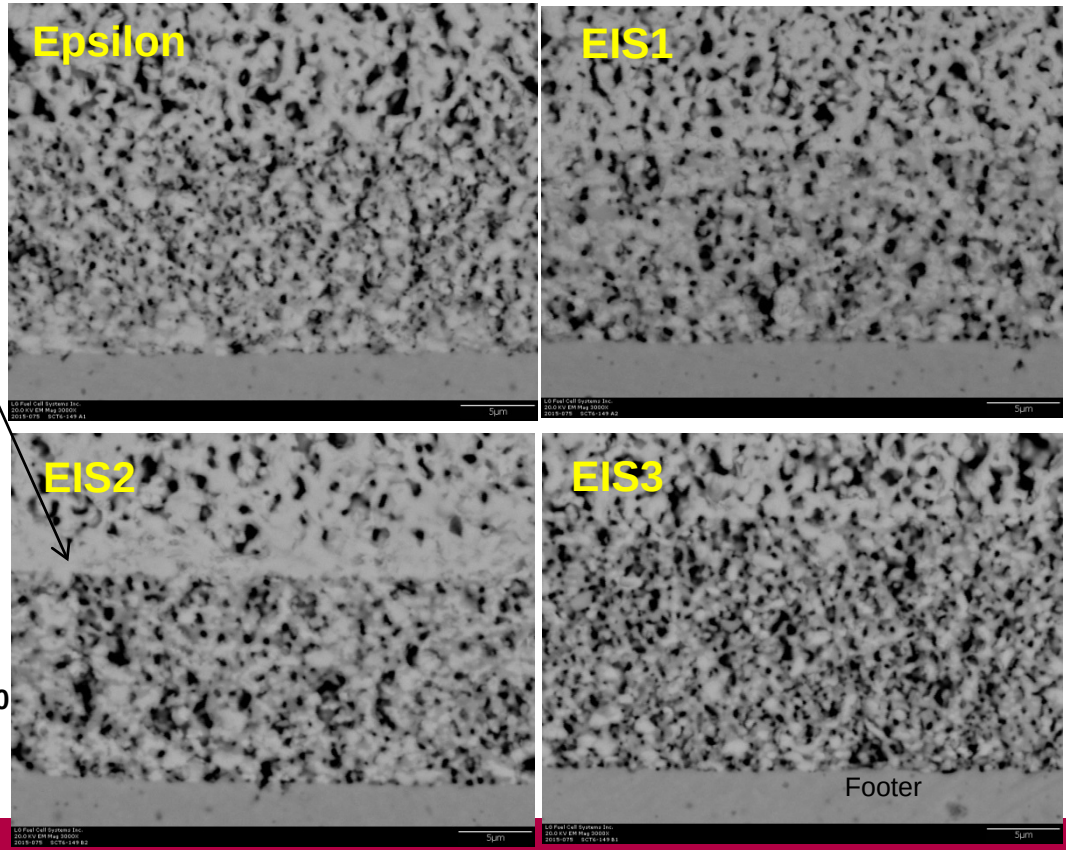
- EIS cathode has low and stable Mn content near cathode /electrolyte interface up to 8,000 hrs of operation



EIS Cathode Demonstrated Improved Resistance against Densification during Operation

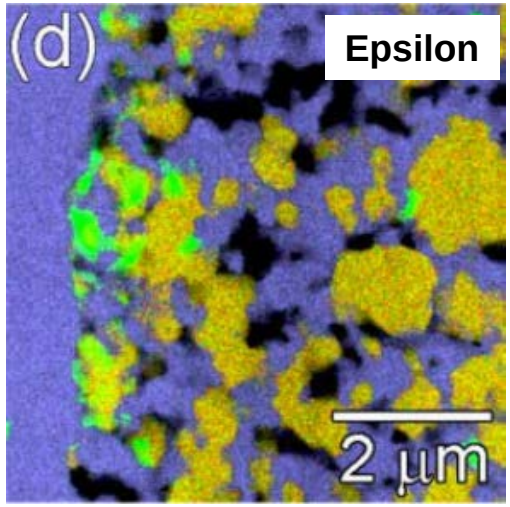
- At normal operating conditions, densification starts to show up at 8,000 hrs
- Under accelerated testing conditions, initial densification of epsilon cathode was observed at 500 hrs.
  - Selected EIS cathode shows more microstructural stability.



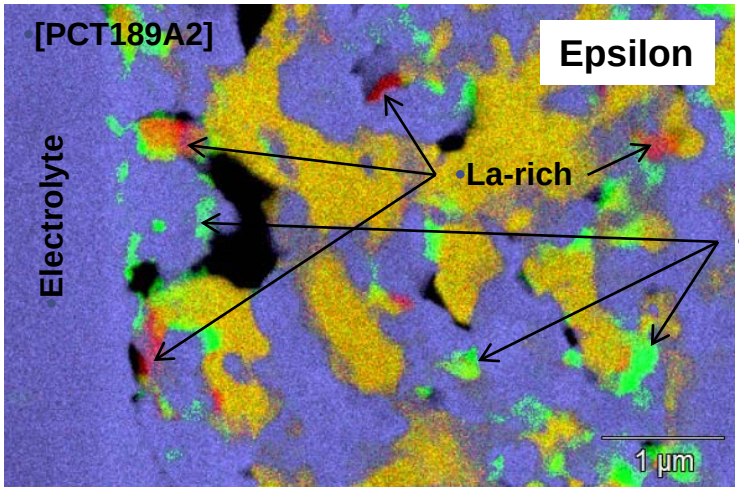


Second Phase Identified in LSM Cathodes Near Electrolyte Interface

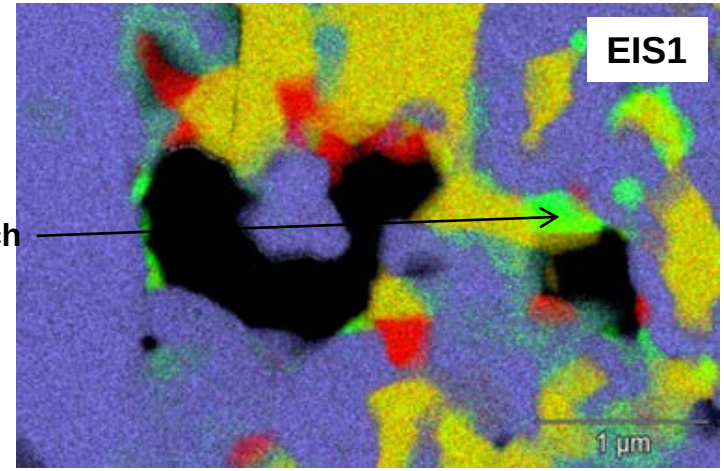
PCT89B:
800°C/16,000hr



- Second phase formed near cathode/electrolyte interface after long term operation at 925°C
  - La-Zr rich phase
- No La-rich phase at 800°C
- Maximum block temperature to be reduced with in-block reforming



PCT189A2: tested at 925°C for 16,000hr

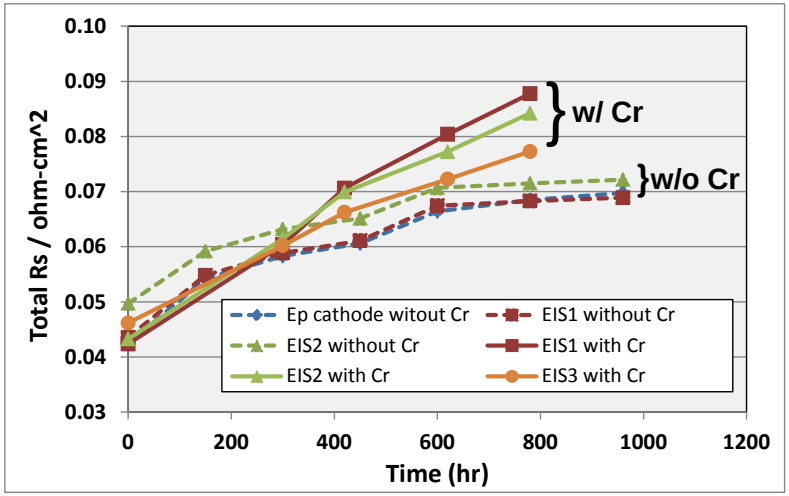


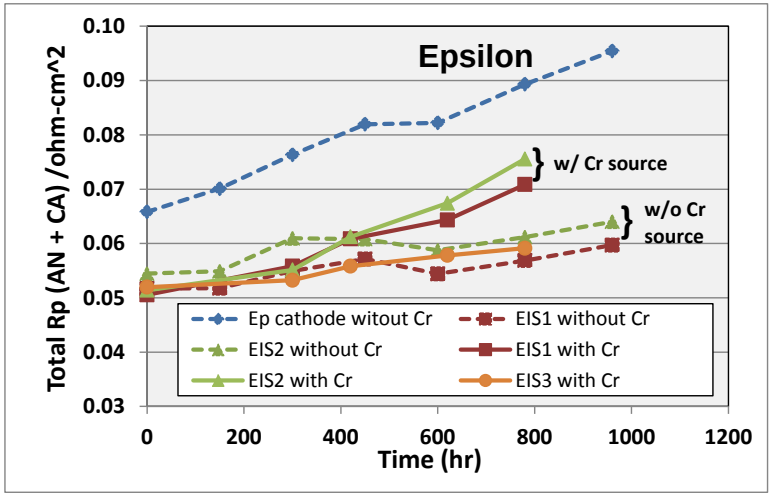
PCT208B2: tested at 925°C for 11,500hr

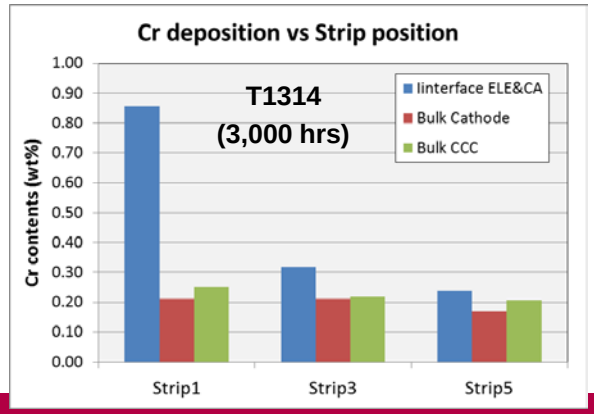
- La
- Mn
- LSM
- Zr

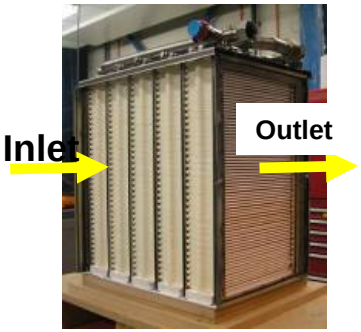
Understanding Cr Effect on Cathode Performance is One of Key Activities

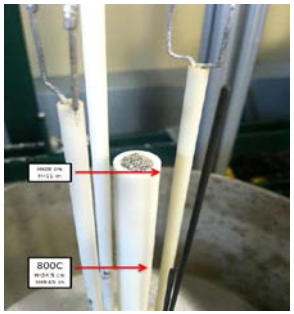
- More Cr deposition at cath/Ele interface in strip 1 (inlet) of block testing
- Cr deposition in bulk cathode and CCC shows no trend vs position
- Accelerated button cell test to understand Cr effect







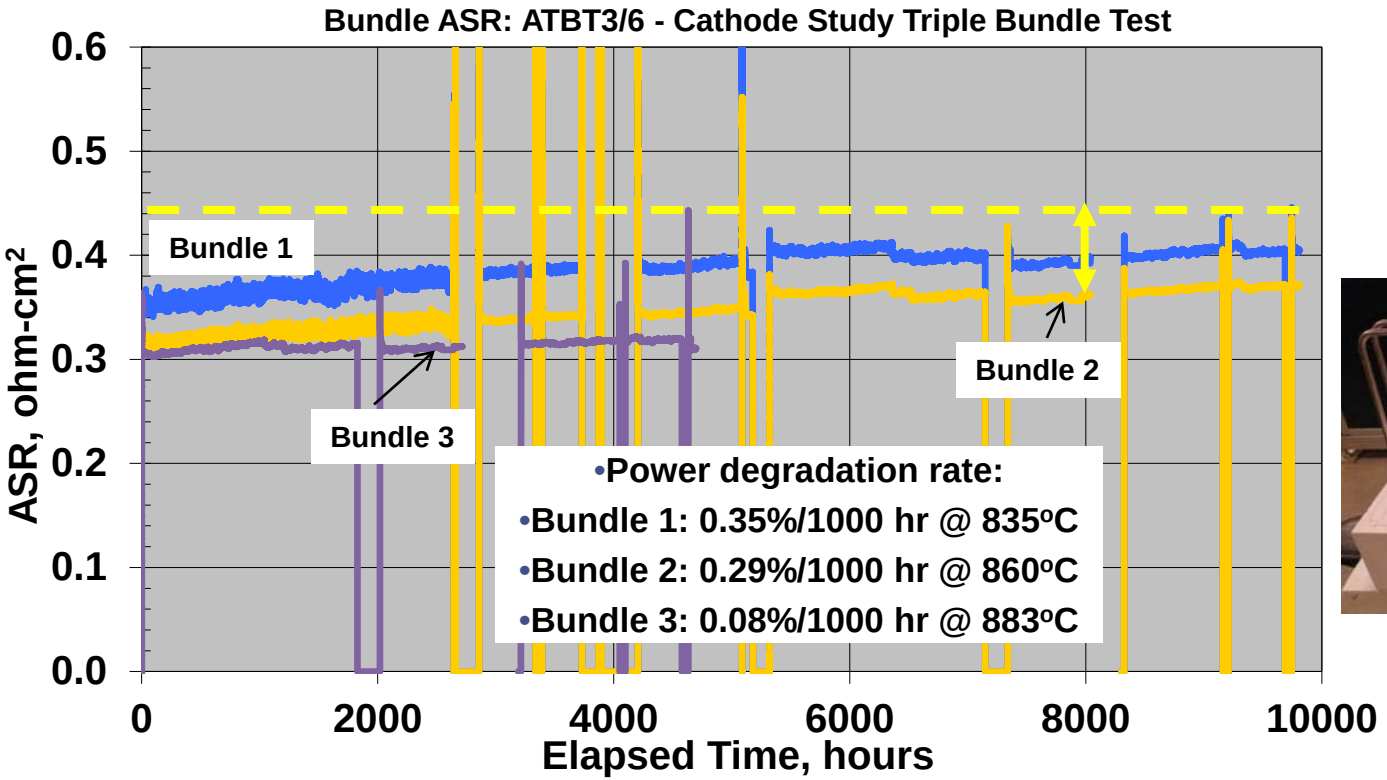




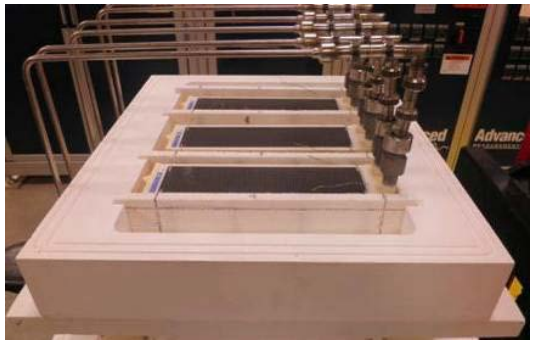
Button cell set-up for Cr test

Candidate EIS Cathode Projects ~3 Year Life

- Only change from epsilon cell technology was the cathode and PIC material
- Average bundle degradation rate at 860°C: 6.0 mohm-cm^2/1000 hrs
- Projects to a 3.0 year life across block temp.

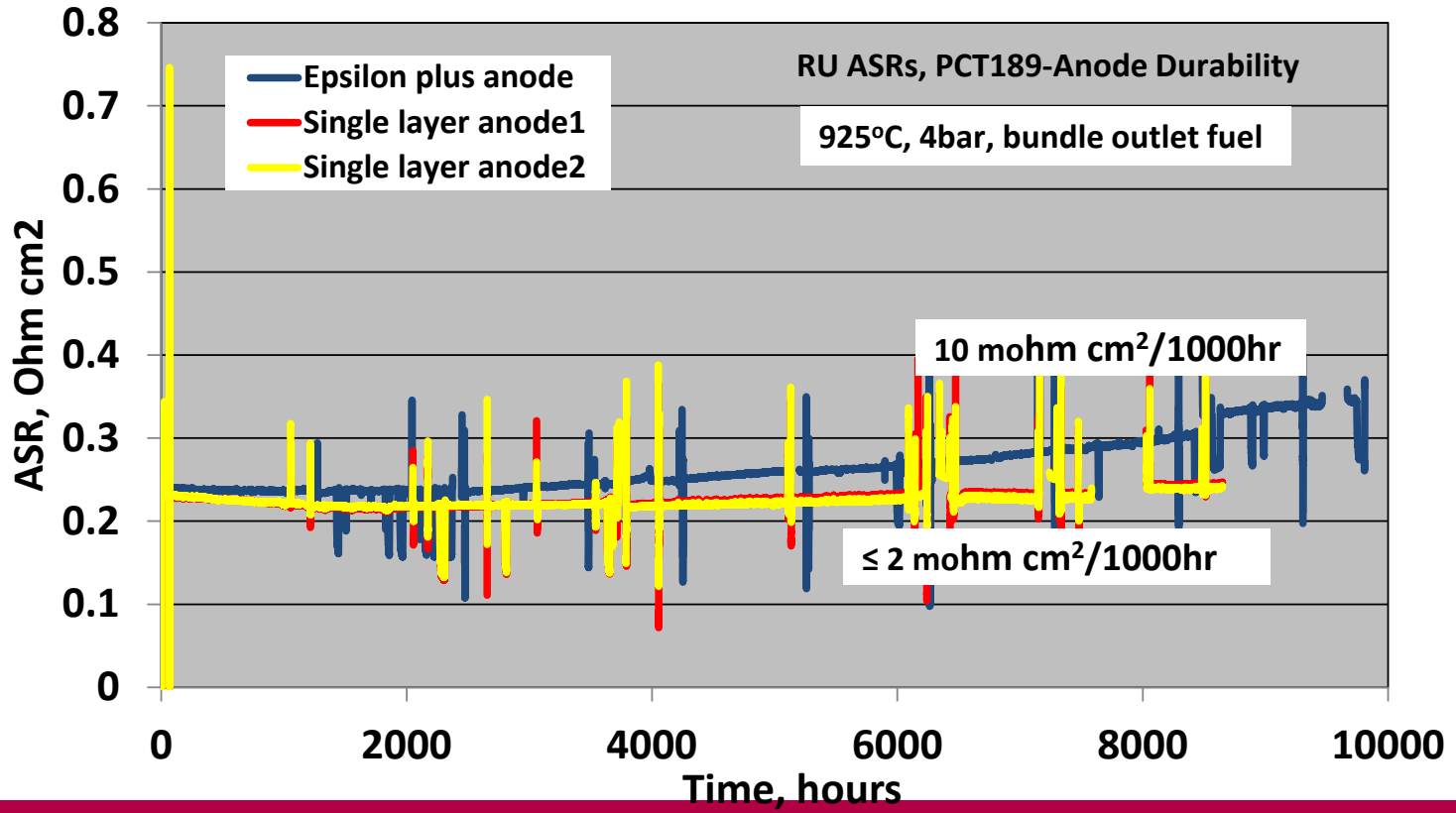


1-Bara, Low Cr, Dry air



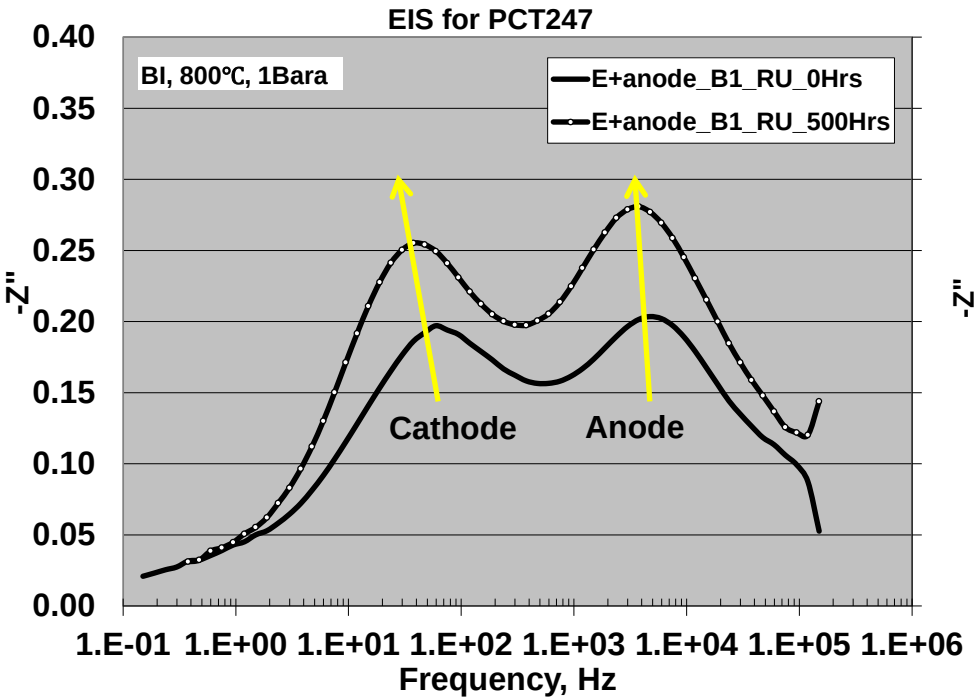
Single Layer Anode Continues to Show Lower Degradation Rate

- **Degradation rate**
  - Epsilon plus anode : 10 mohm cm^2/1000hr
  - Single layer anode: 1.5~2.0 mohm cm^2/1000hr

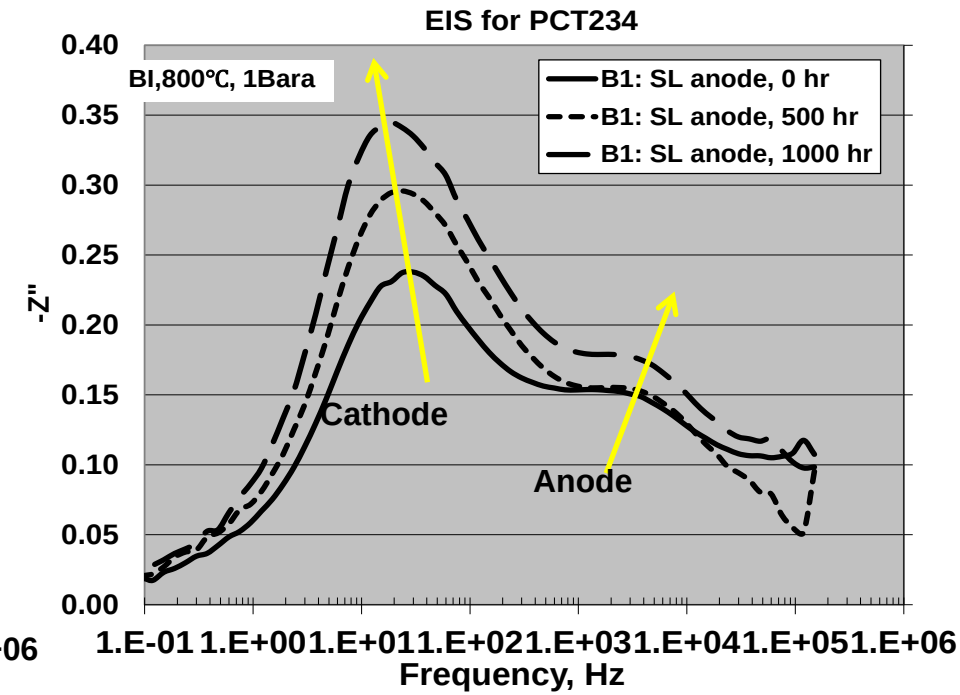


Accelerated Anode Testing Helps Database and Decision Making

- Current density, temperature, and fuel utilization
- Accelerated testing confirmed single layer anode is more stable than epsilon plus anode



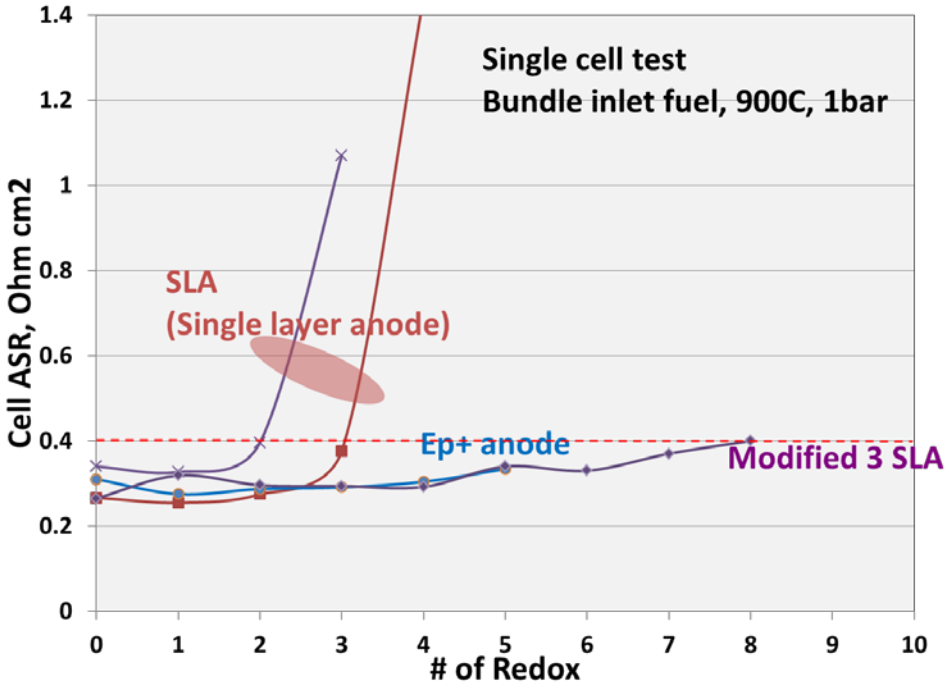
Epsilon plus anode

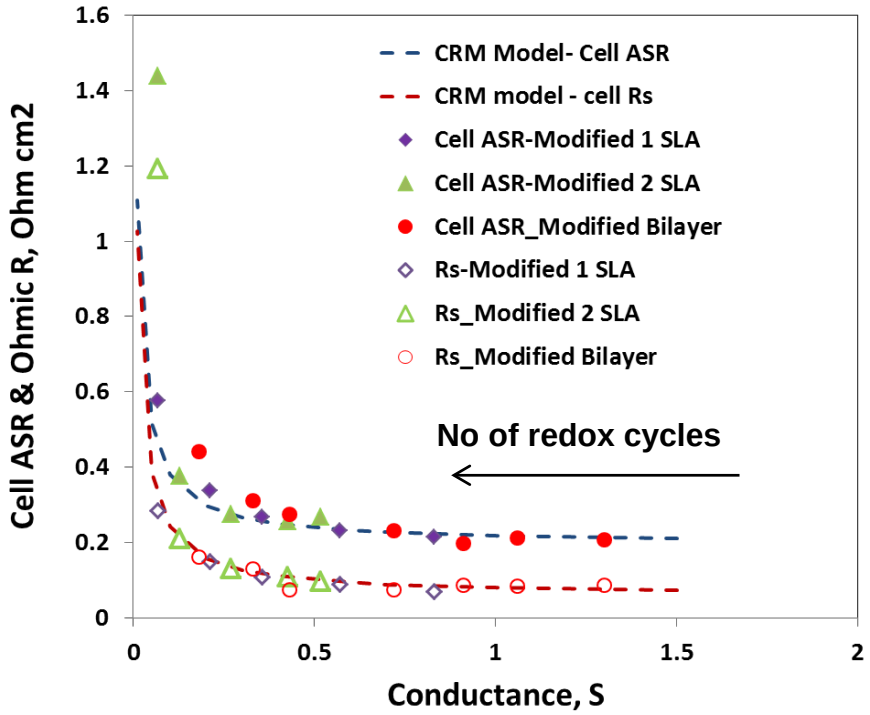


Single layer anode

Redox Tolerant Anode Benefits System Operation

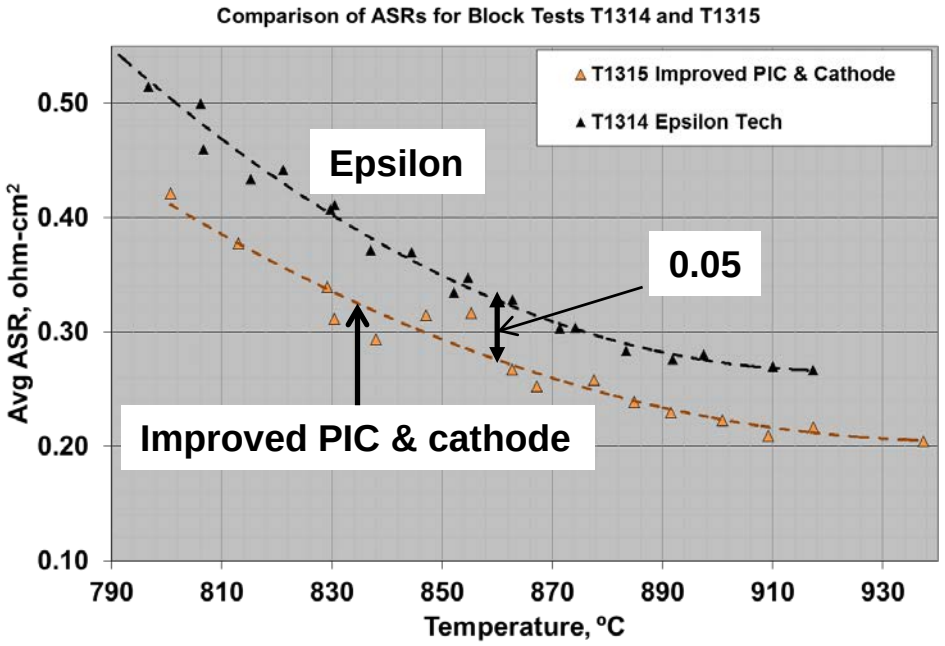
- Epsilon plus anode is able to tolerate 4-5 redox cycles
- Single layer anode being developed for improved redox tolerance
  - Equivalent or better than epsilon bi-layer structure
  - Able to tolerate more redox cycles without significant ASR change

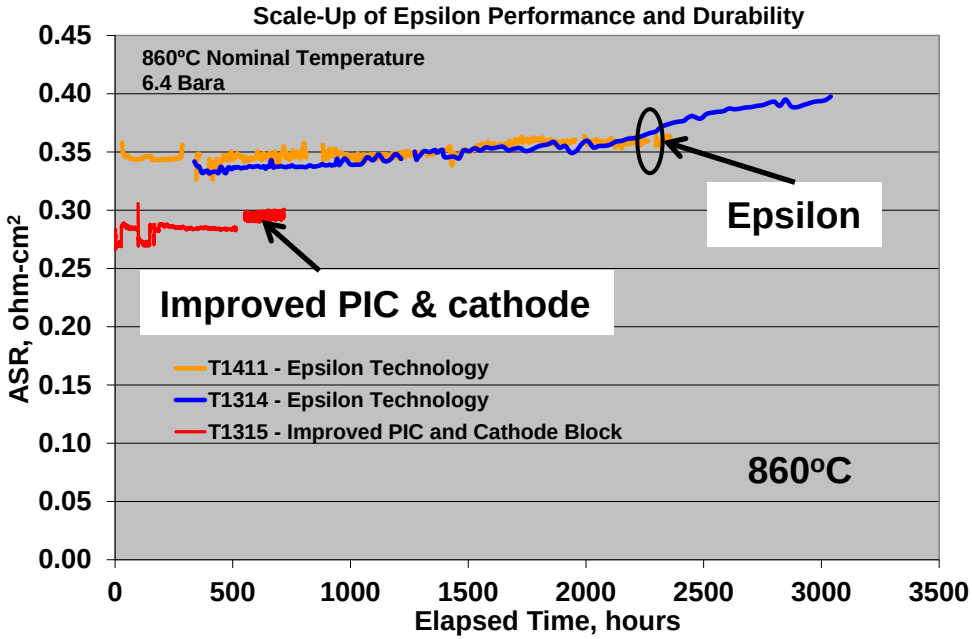




Lower ASR Technology was Demonstrated in Block Level

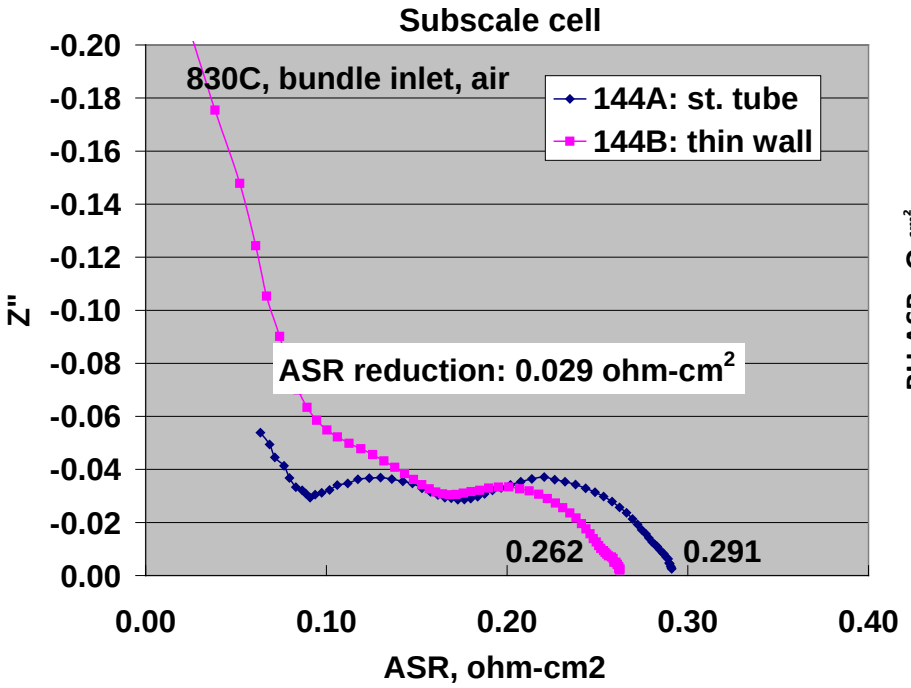
- High conductive interconnect plus EIS cathode
- Average block ASR: 0.28 ohm-cm^2 vs 0.35 ohm-cm^2 for epsilon technology
- Stable performance in 700 hrs of operation with 15.7 kW output

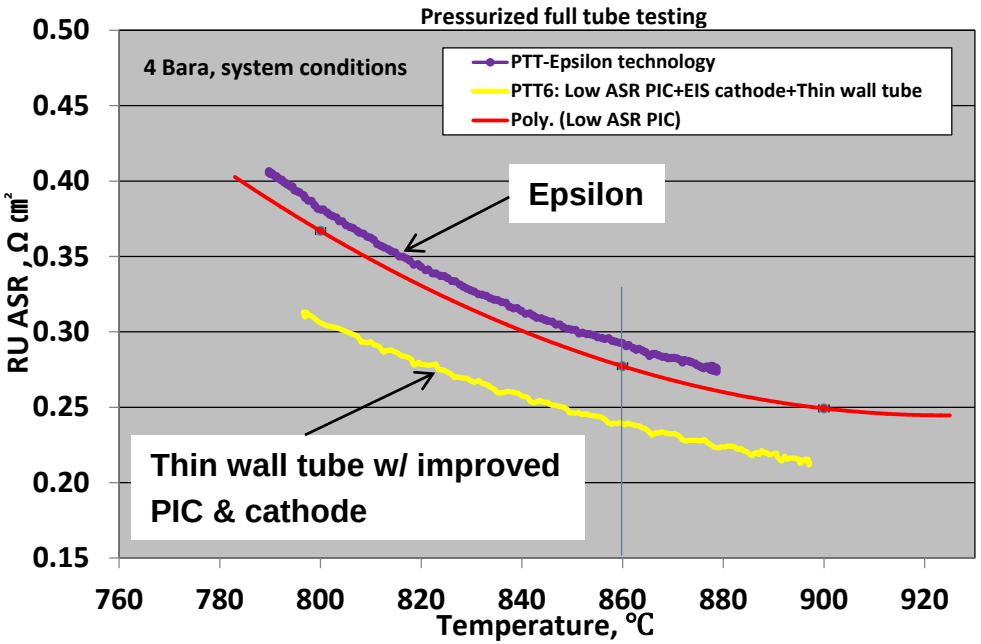




Further ASR Reduction - Thin Wall Tube

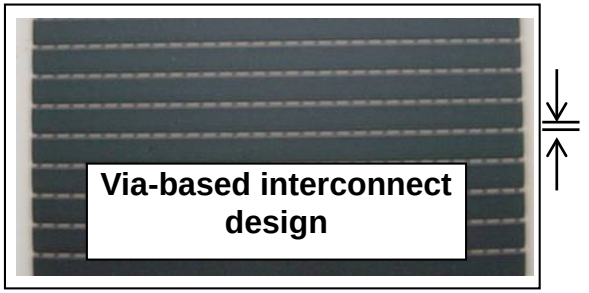
- Thin wall tube could reduce fuel diffusion resistance
  - ASR reduction 0.02 to 0.03 ohm-cm^2 by subscale cell
- Feasibility was demonstrated by pressurized full tube test

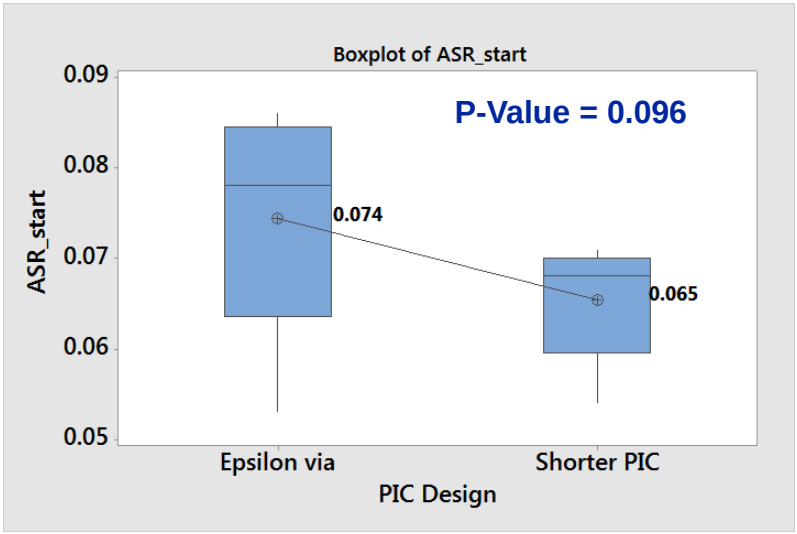


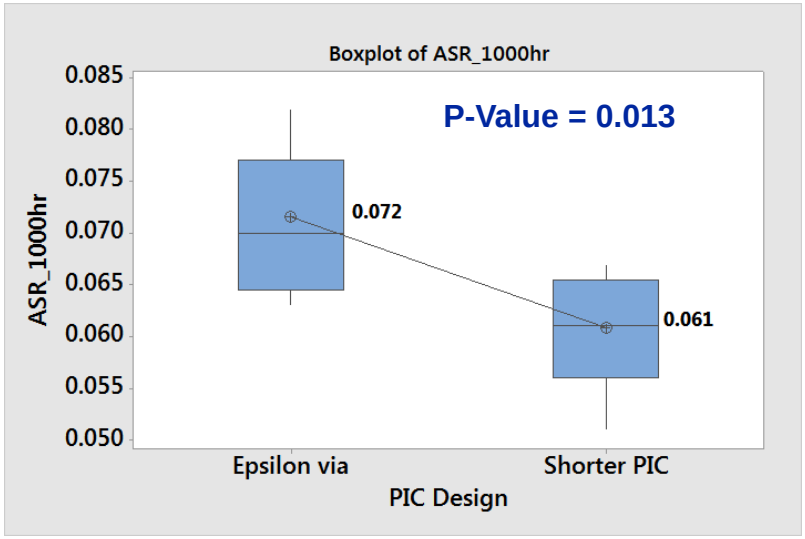


Shorter PIC for Further ASR Reduction

- Smaller PIC dimension has lower ASR contribution
- Shorter PIC will increase active cell area
- Model calculation indicates increase in power output up to 6%
- Shorter PIC was demonstrated by subscale cells
  - Meaningful lower ASR
  - Stable performance in test to 4,500 hrs

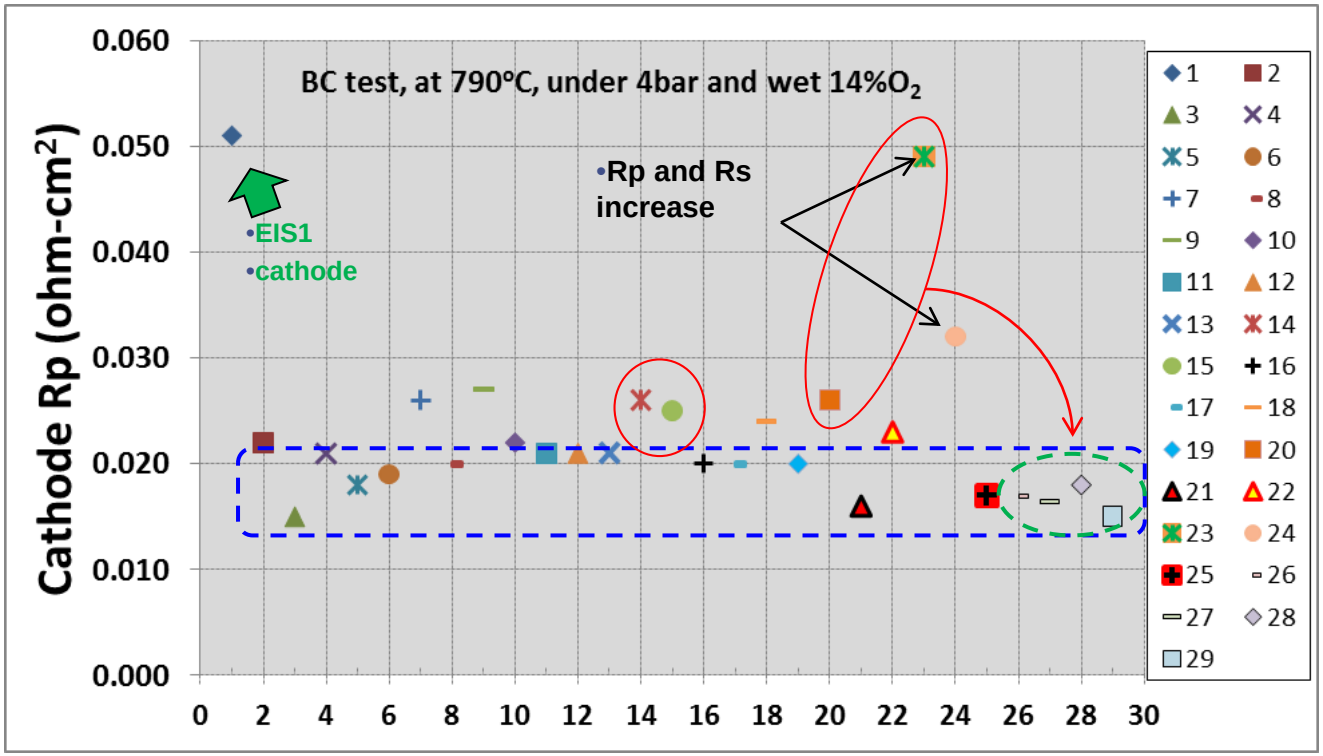






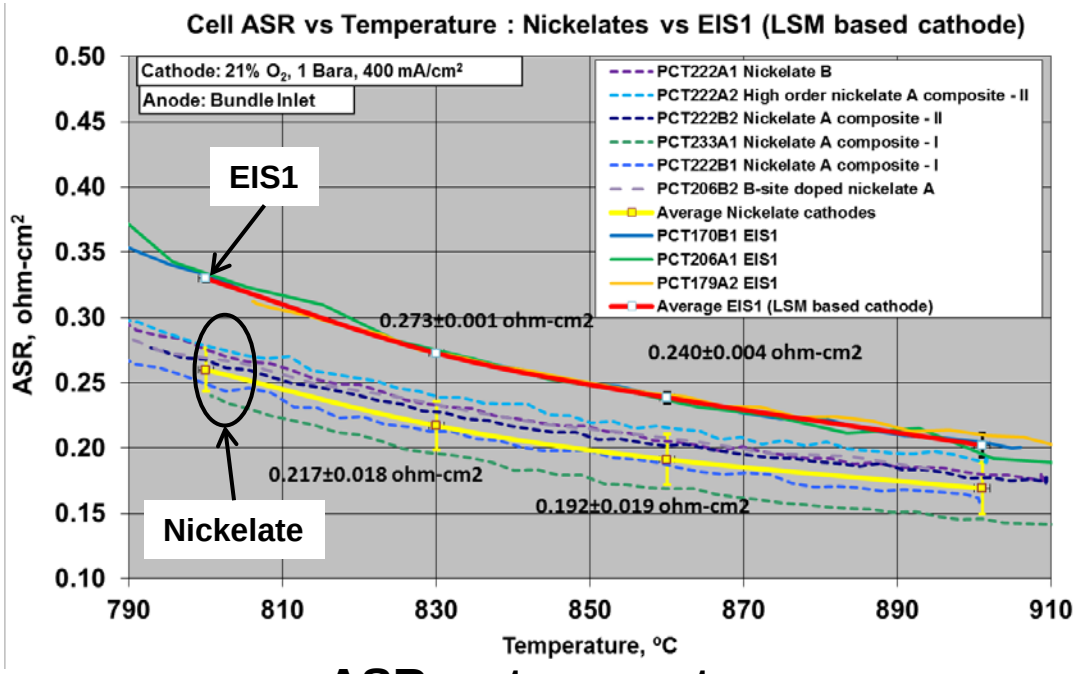
Significant Effort on Nickelate Cathode Screening

- Extensive composition matrix was evaluated using cathode symmetric cells
  - A site doped nickelate
  - B site doped nickelate
  - Composite nickelate
- Some compositions show much lower polarization than LSM-based cathode

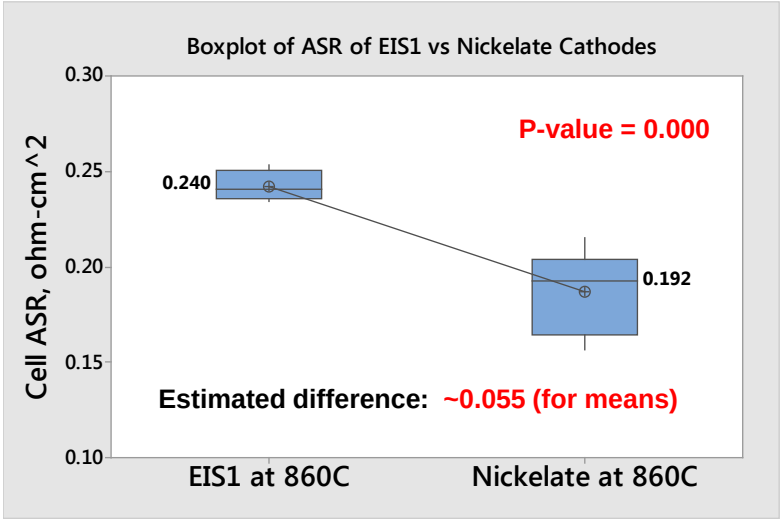


Nickelate Cathode Shows ASR benefits against LSM-Based Cathode Across Block Temperature Range

- Nickelate cathode has lower ASR than EIS LSM cathode
- Statistic data show the difference is meaningful



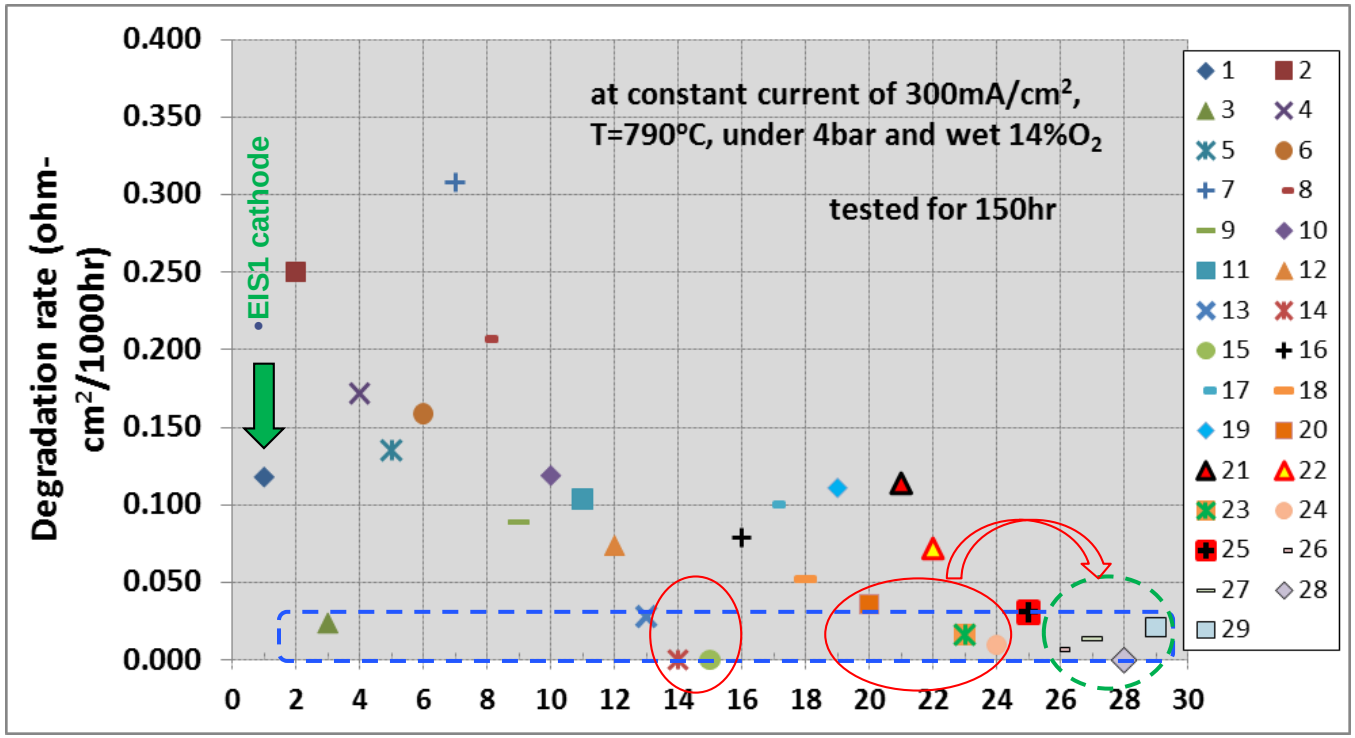
ASR vs temperature



Statistic analysis

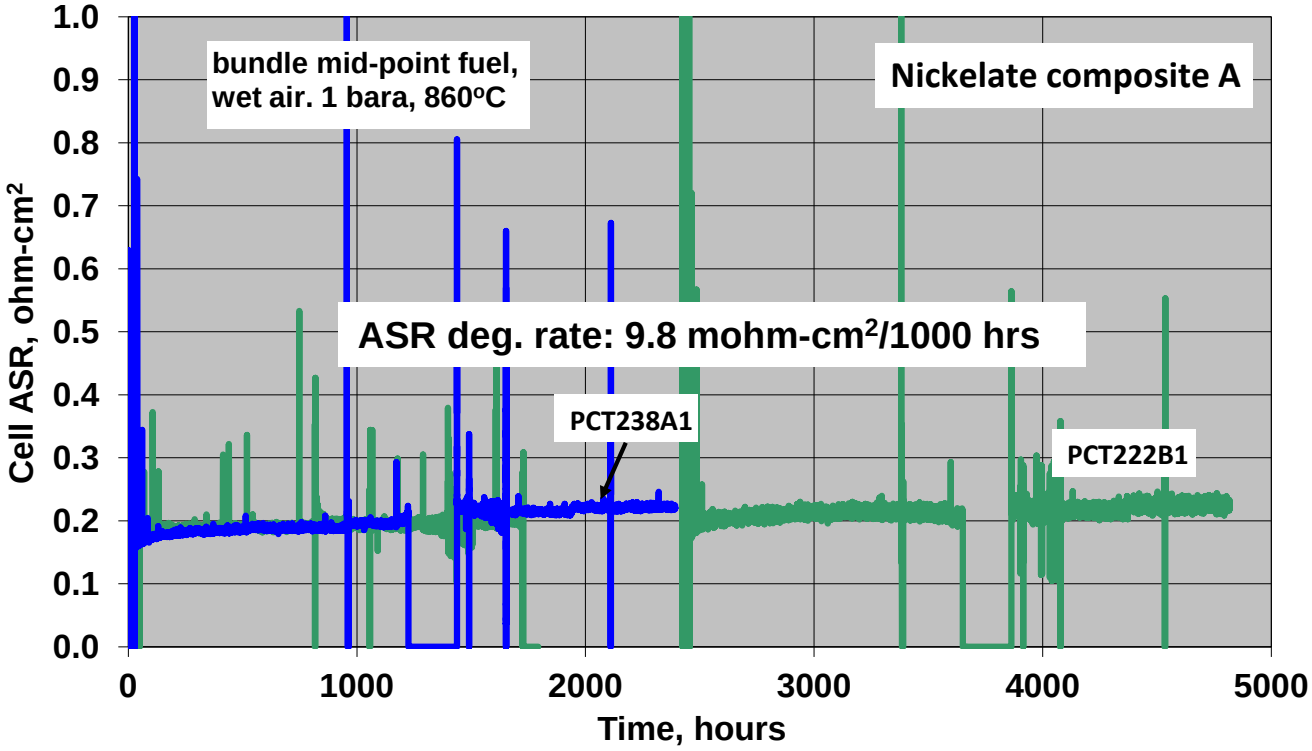
Lower Degradation Rate during Short-term durability Test

- High order nickelate cathodes showed lower degradation rate even though initial Rp is higher
- Some composite nickelate cathodes showed both lower ASR and degradation rate – chosen for subscale tube testing



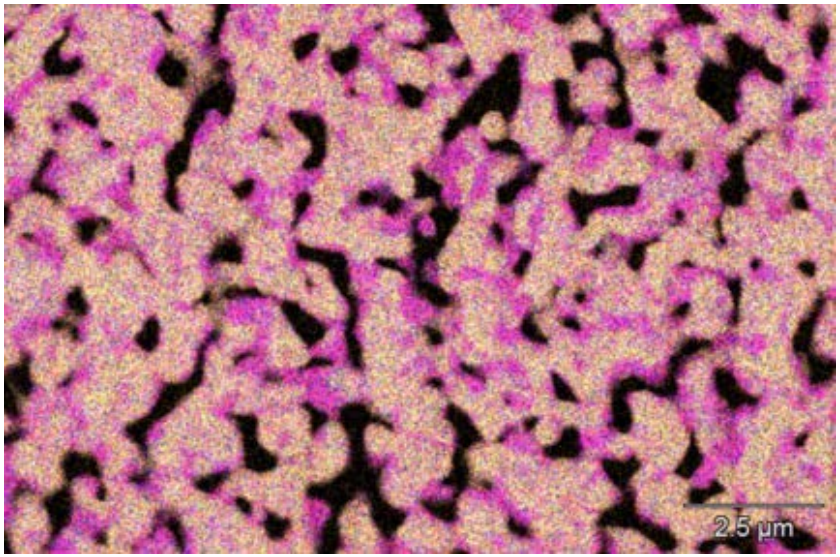
Long-term Durability of Nickelate Cathodes at 860°C is Promising

- Selected Nickelate cathode has low degradation rate, similar to LSM-based cathode
- Good repeatability
- Longer term durability is on-going

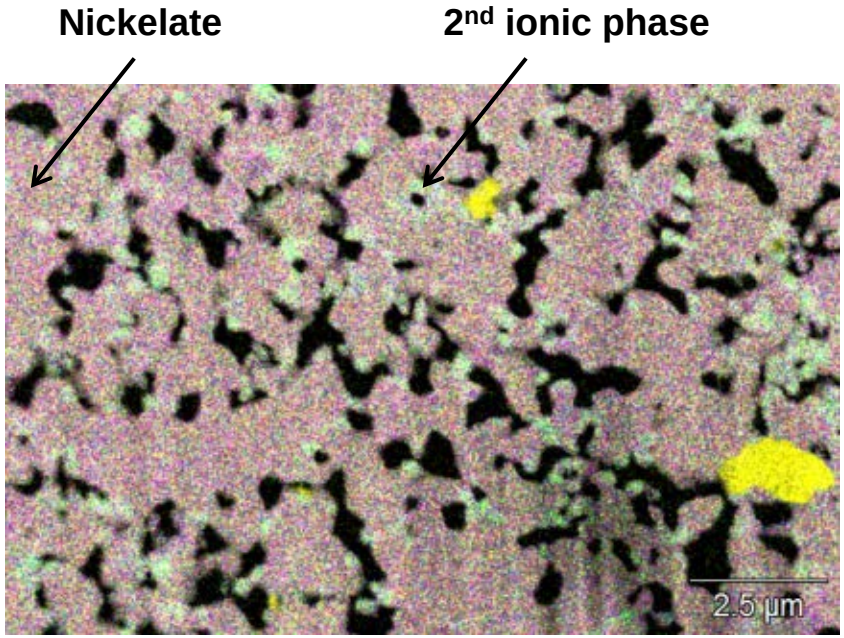


Phase Composition of Nickelate Cathode is Manageable

- **Composite nickelate cathode shows more uniform chemistry in nickelate phase after aging 870°C/500 hrs**



Pure Nickelate Cathode (n=1)
Ni-depleted phase on ageing



Nickelate Composite
Composite phases retained, some minor Ni dissolution

Summary

- 200 kW-scale system test performed
  - Pipeline natural gas to grid connection
  - Demonstrating product architecture for commercial systems
- Testing and analysis supporting cell technology showing an extension in service life
- Lower ASR technology in the pipeline for near-term and longer-term validation → cost and efficiency gains

Acknowledgements

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- University of South Carolina

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