Progress on Performance, Durability, and Reliability of LGFCS SOFC Technology

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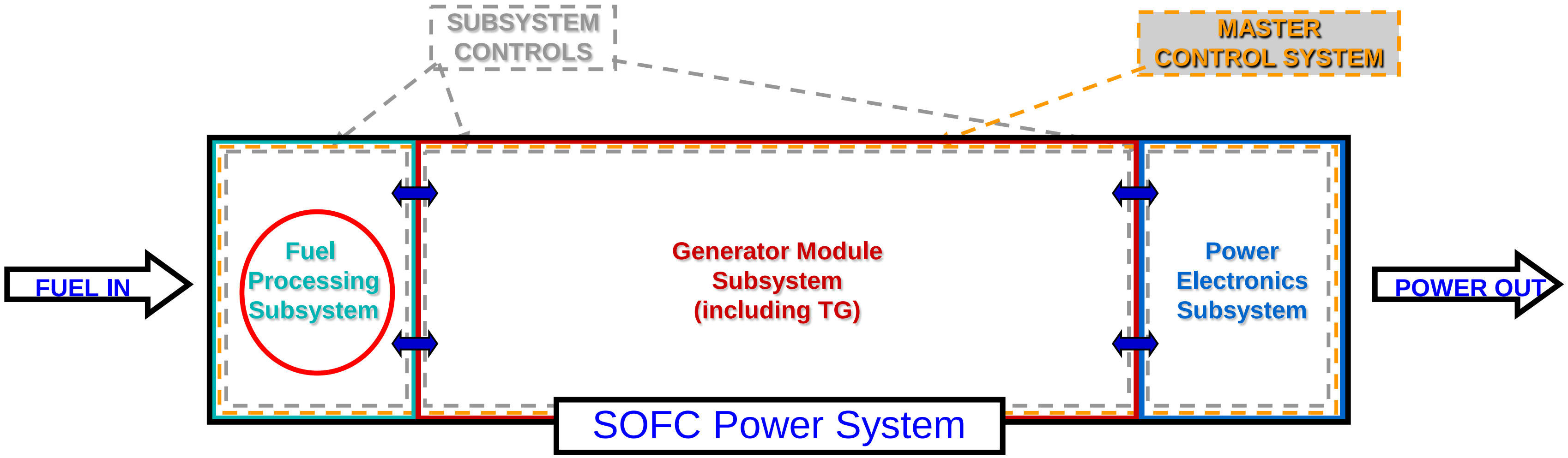
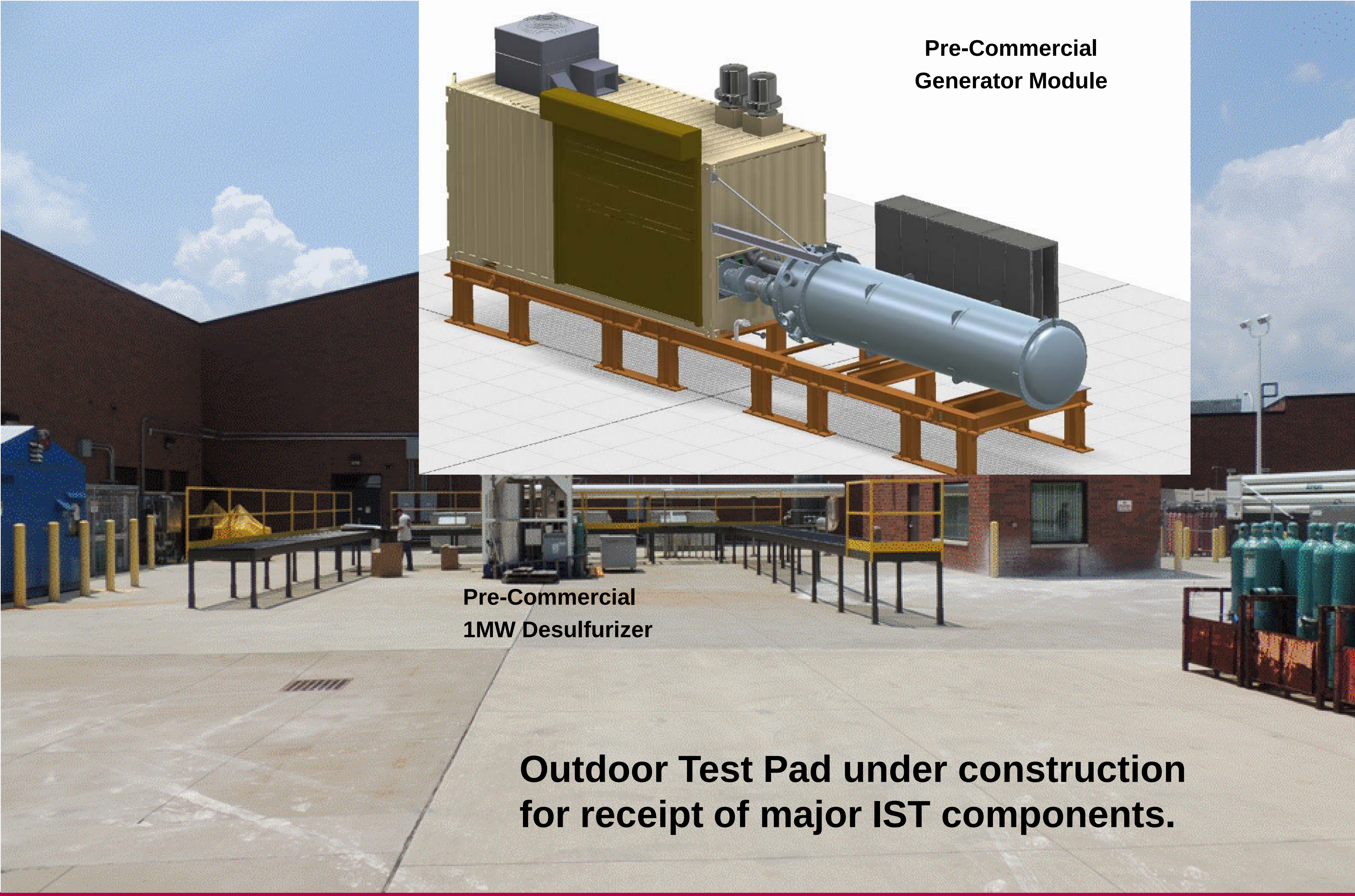
Outline

- LGFCS Program Overview
  - Manufacturing Automation
  - Integrated String Test
- Performance and Durability Testing
  - Block Scale Results
  - Subscale Results
- Cell technology status and optimization for commercial product
  - Primary Interconnect (PIC)
  - Anode Development
  - Cathode Development
  - Candidate materials for future cell technology
- Structural Reliability

LGFCS Integrated String Test Program

- Test of a 220 kW system demonstrator incorporating all key subsystems
  - Fuel Processing
  - Pressurized Generator Module including turbogenerator
  - Power Electronics
  - Pipeline natural gas and grid connection
  - 3Q-4Q 2014 commissioning/4Q testing
- SECA program supports further improvements in cell/stack lifetime up through Block-scale (19 kW) testing





Outdoor Test Pad under construction for receipt of major IST components.

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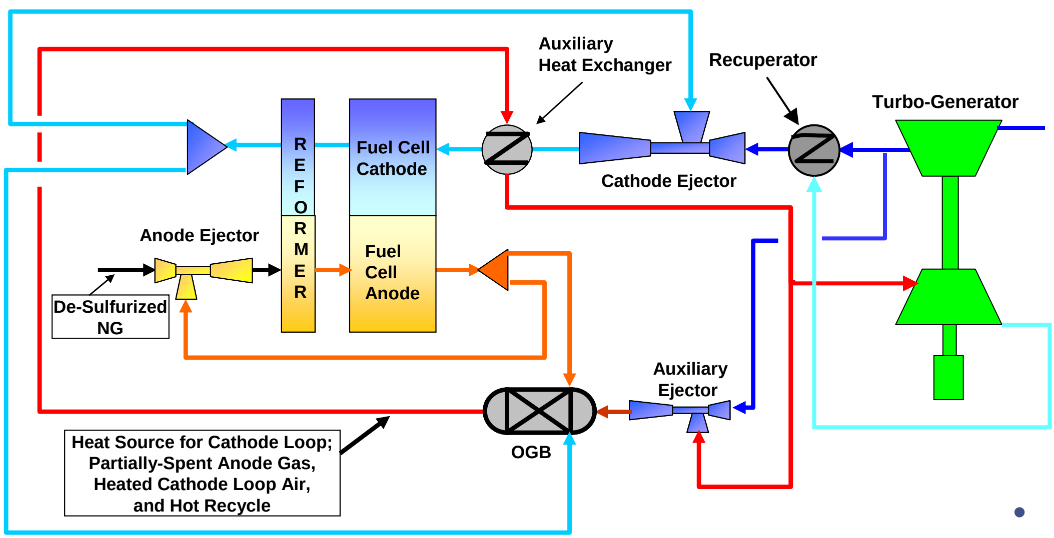
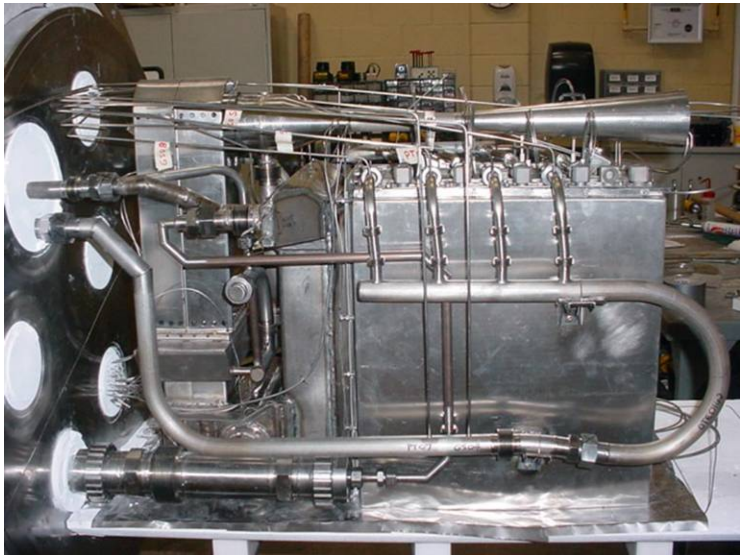
Block Test replicates Plant Configuration

- Block metric testing matches full system cycle, components (less TG and recuperator), operation and boundary conditions

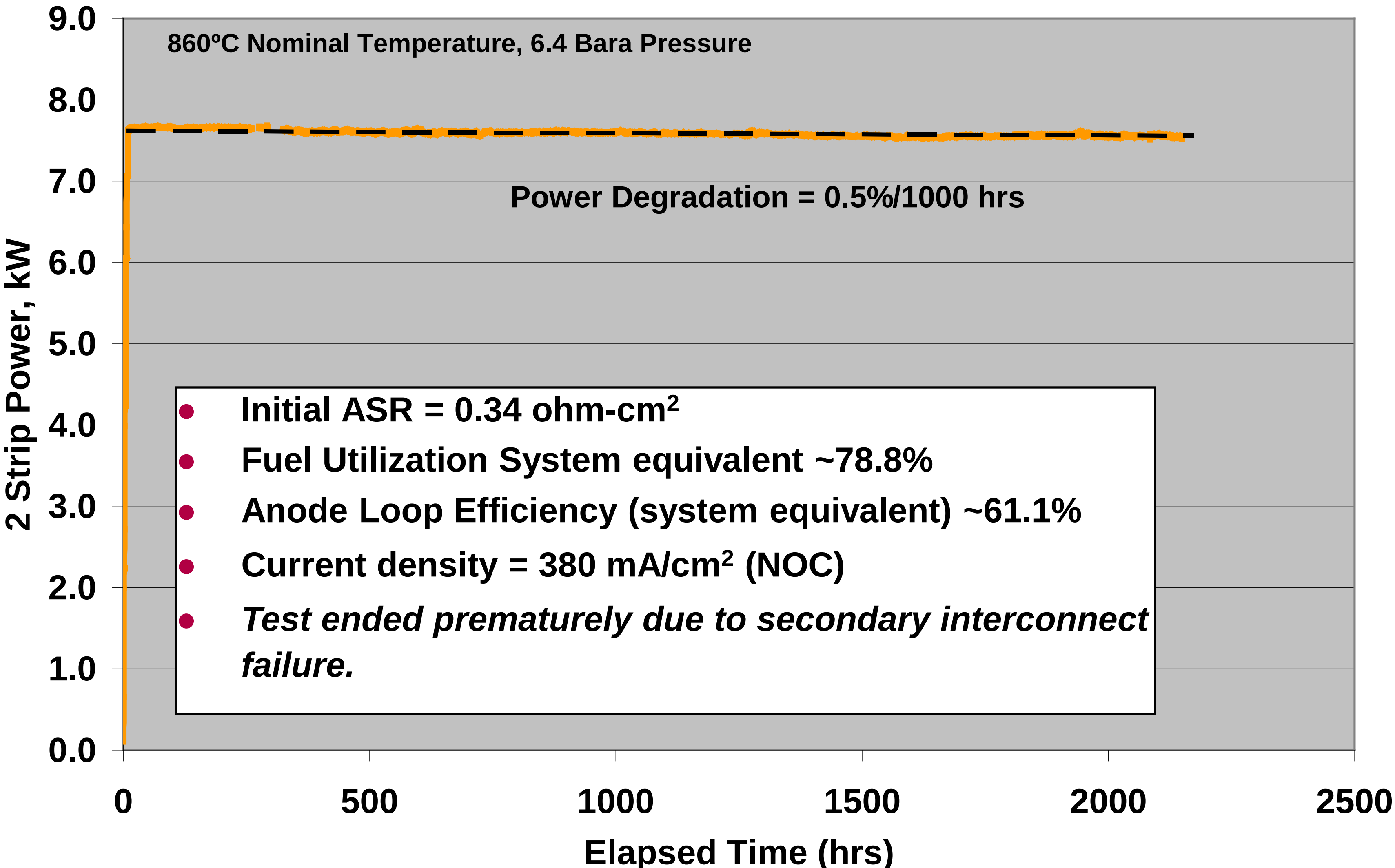
LGFCS NG "Dry Cycle" Configuration



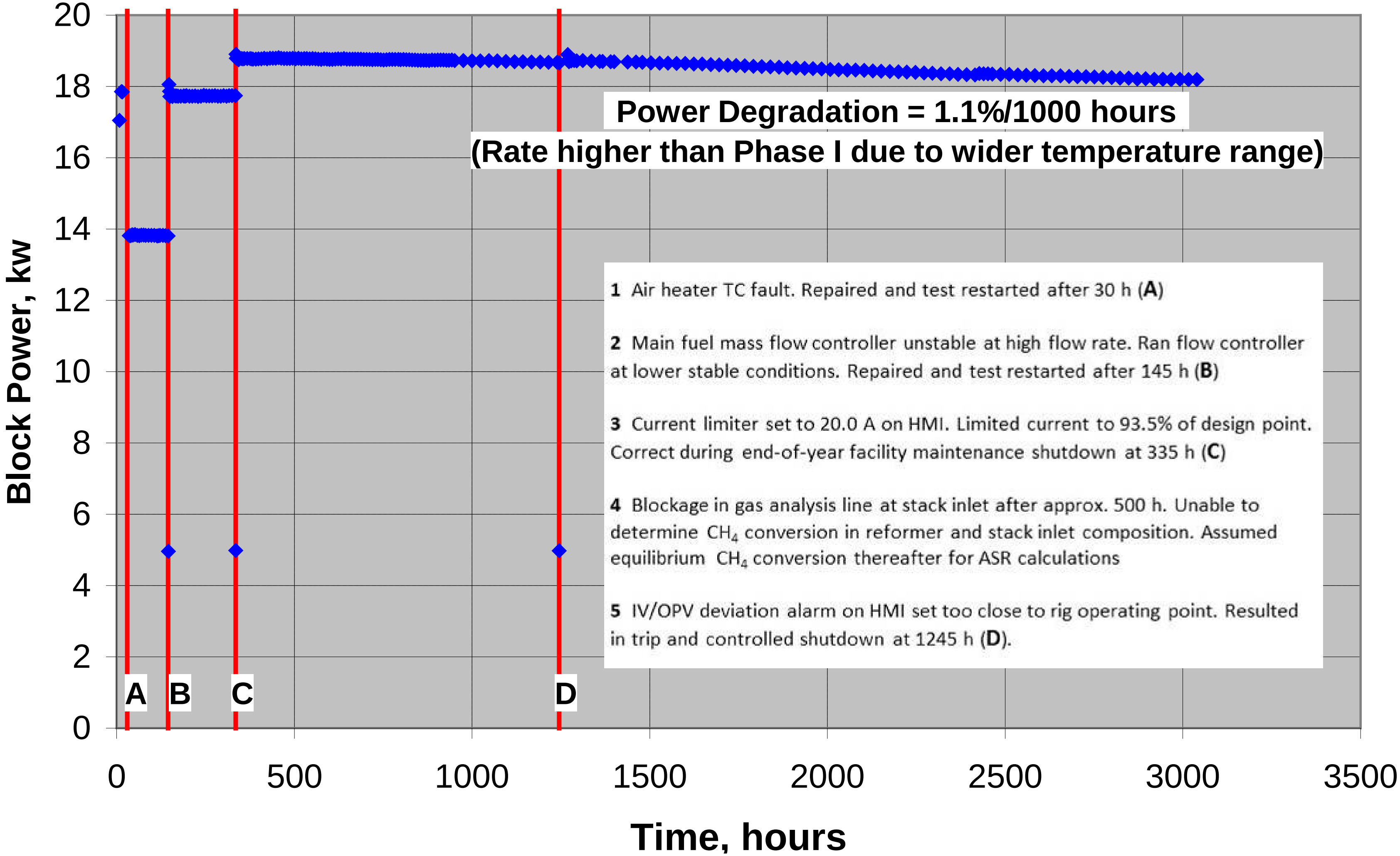


- Thermally self-sustaining insulation system
- Anode and cathode ejectors
- Reformers and heat exchangers
- Off-gas burners
- System control methodology

Phase 1 Test – Performance and Durability

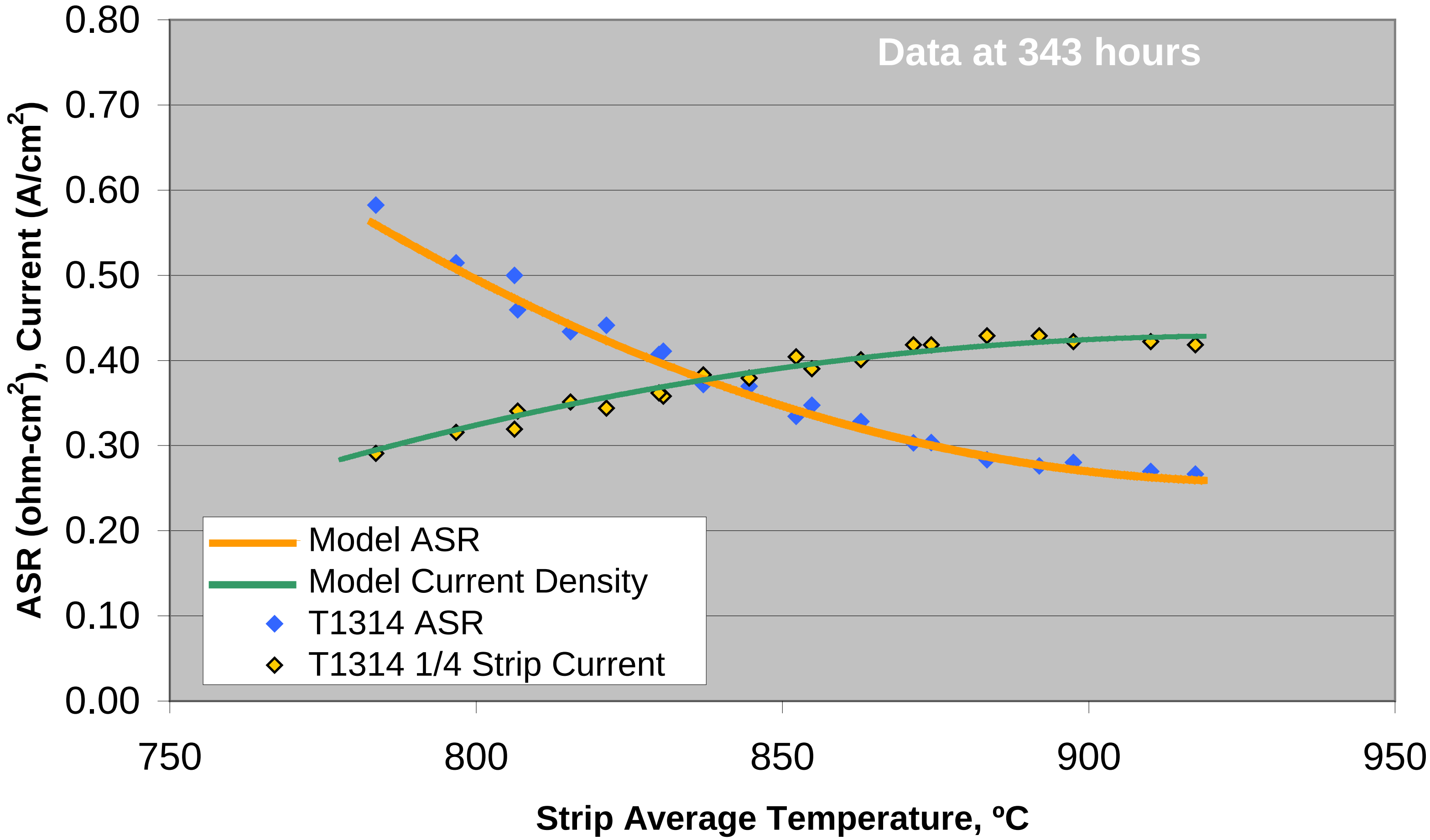


Phase II Test met SECA Target



Block Performance as Expected

(Current, fuel flow, and temperature drop forced to match data)



Phase II Block Testing Summary

- **Initial performance within expectations**
  - **18.8 kW output at design point current**
  - **ASR ~ 0.345 ohm-cm^2 for strips in design temperature range**
- **Power degradation 1.1%/1000 hours**
  - **Achieves SECA target of 1.5%/1000 hrs at 3000 hours**
- **Degradation higher than subscale and Phase I Test**
  - **Wider temperature range than for Phase I test. Parts of the block are outside of design temperature range.**
  - **Degradation observed due to printing defect which has since been addressed and correction validated**
  - **Degradation of strips near design average temperature was similar to Phase I test**

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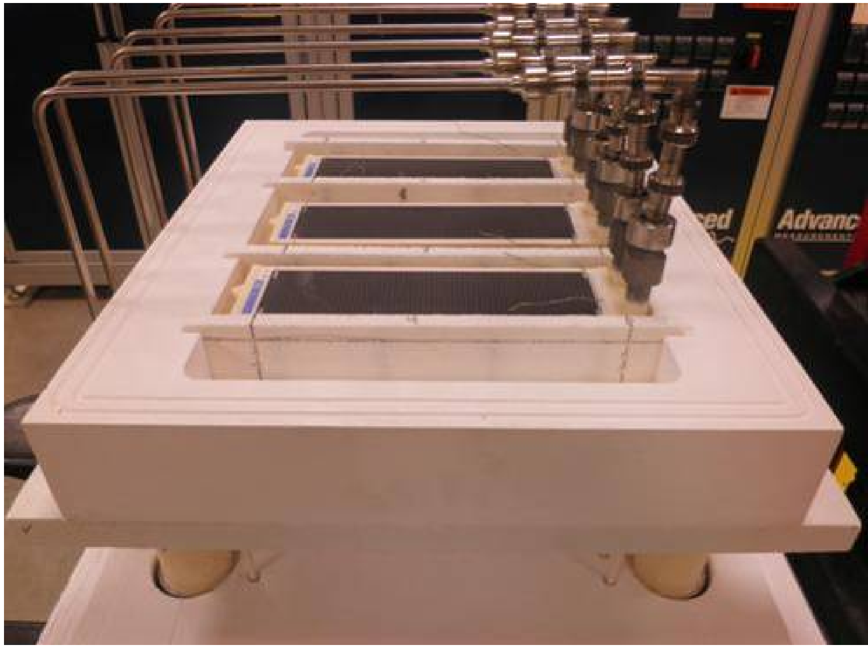
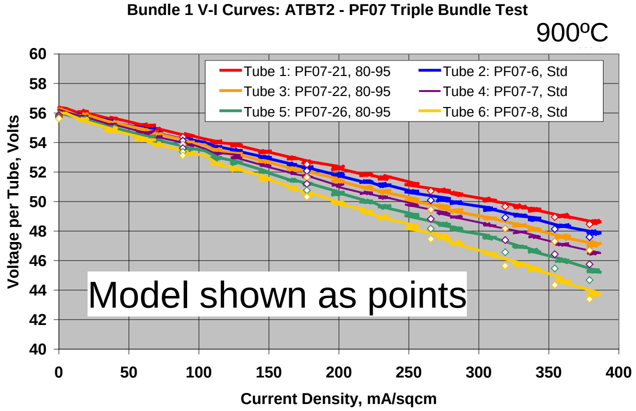
Bundle Testing Shows Consistent Performance

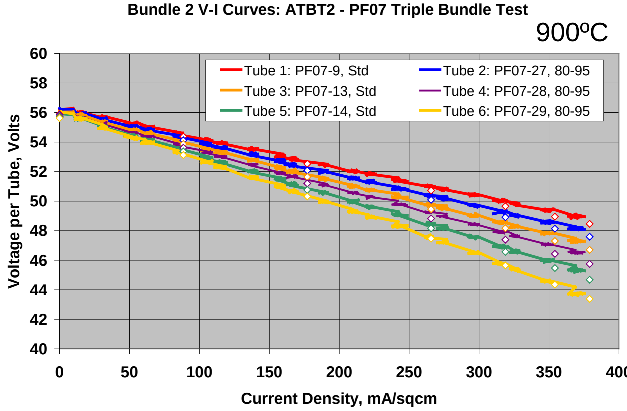
- Agrees well with model from pentacell data



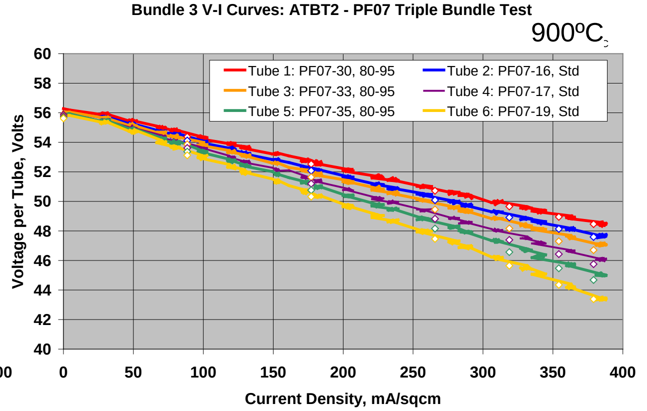
Bundle 1



Bundle 2

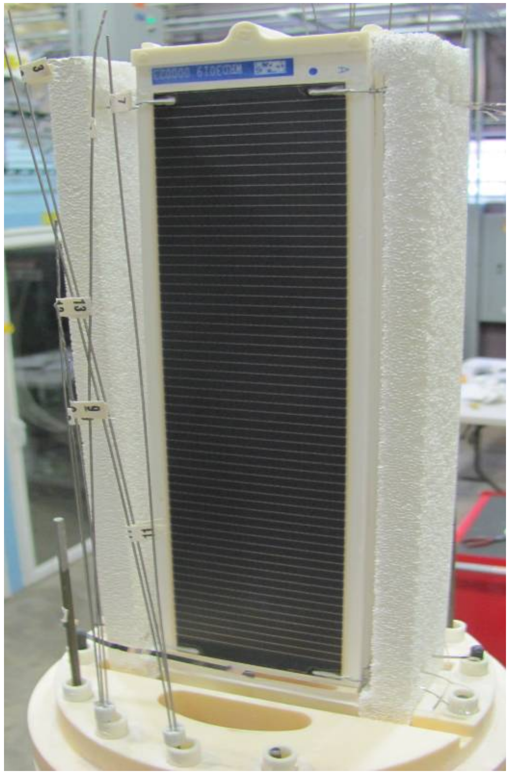


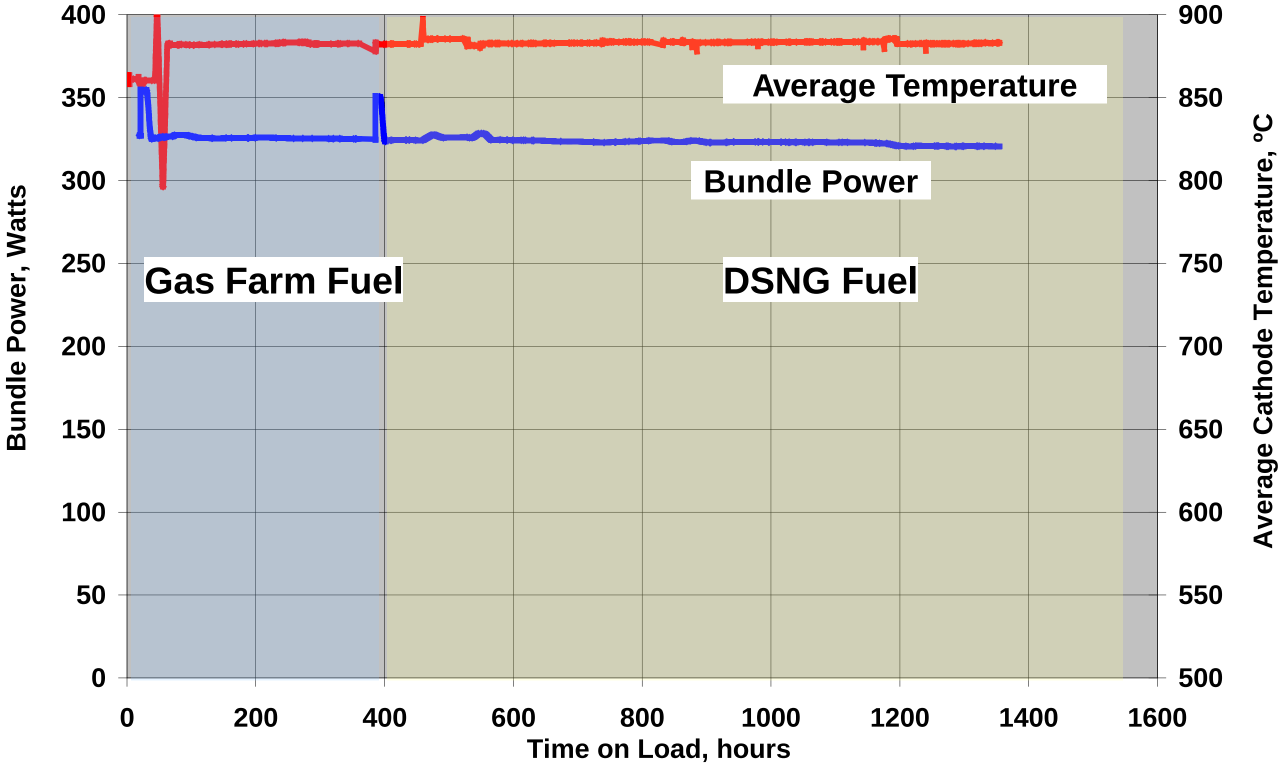
Bundle 3



Testing on desulfurized natural gas to confirm performance on real world fuel

- **Fueled from small scale SCSO* system using pipeline natural gas**
- **Initial performance and degradation are good**



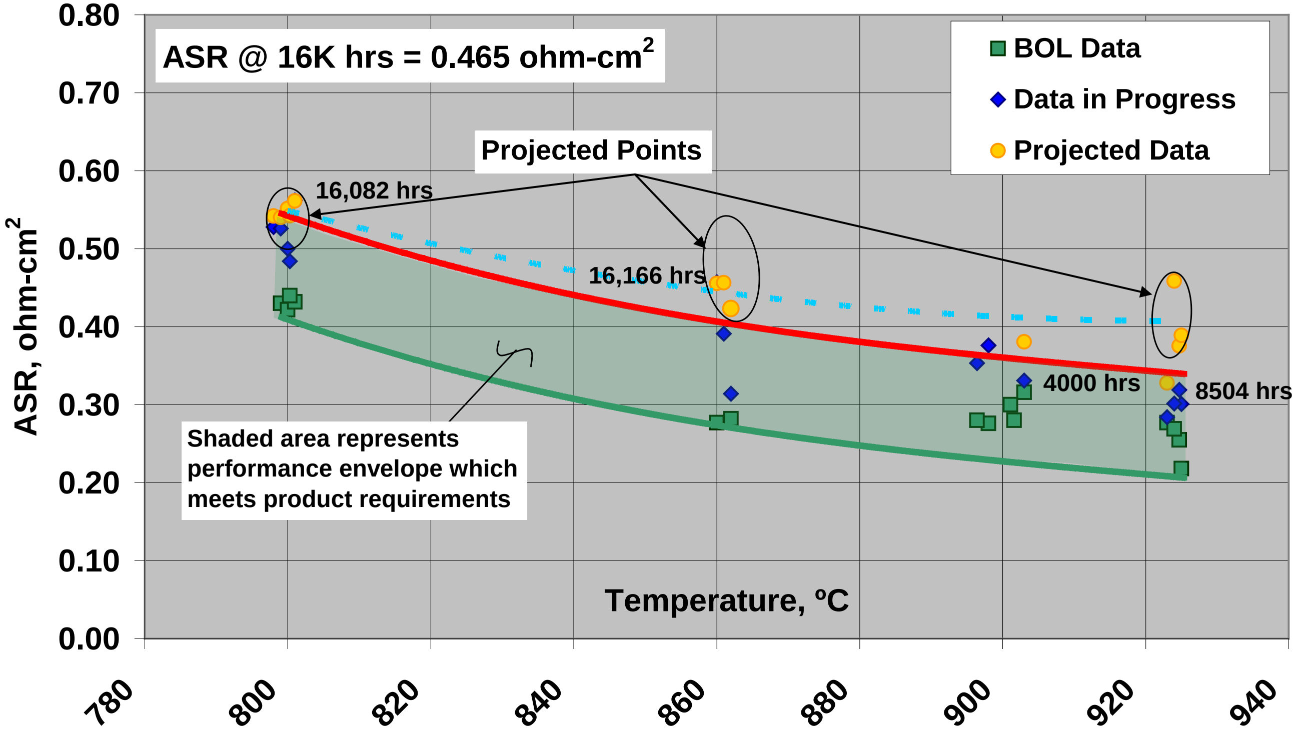


*SCSO = Selective Catalytic Sulfur Oxidation

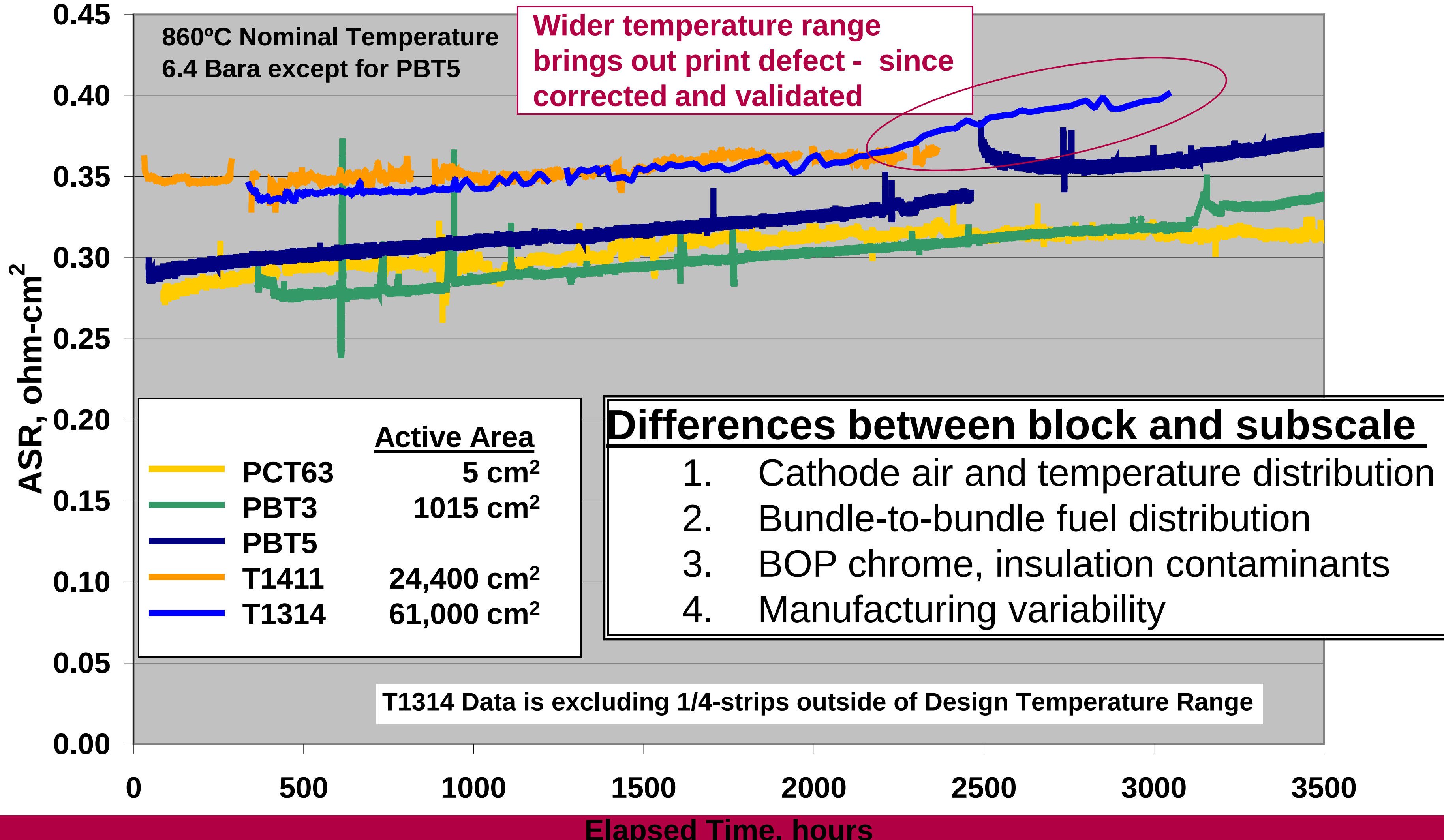
LG data

Subscale Durability Map Demonstrates Trends and Guides Cell Development

- Performance mapped over operating envelope
- Detailed performance separation achieved
- Durability performance confirmed at larger scales



Consistent performance across scales validates durability testing approach



Differences between block and subscale

1. Cathode air and temperature distribution
2. Bundle-to-bundle fuel distribution
3. BOP chrome, insulation contaminants
4. Manufacturing variability

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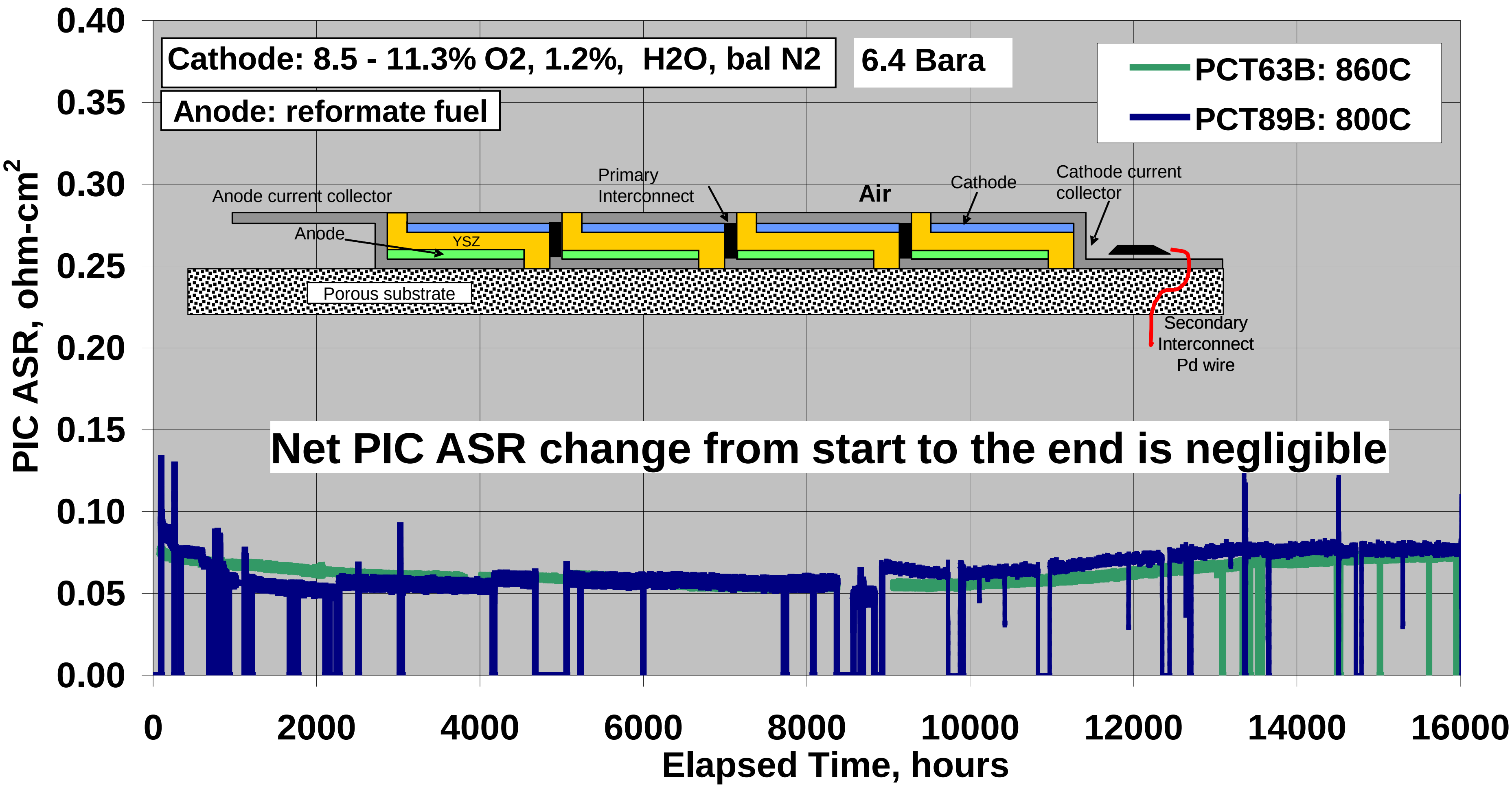
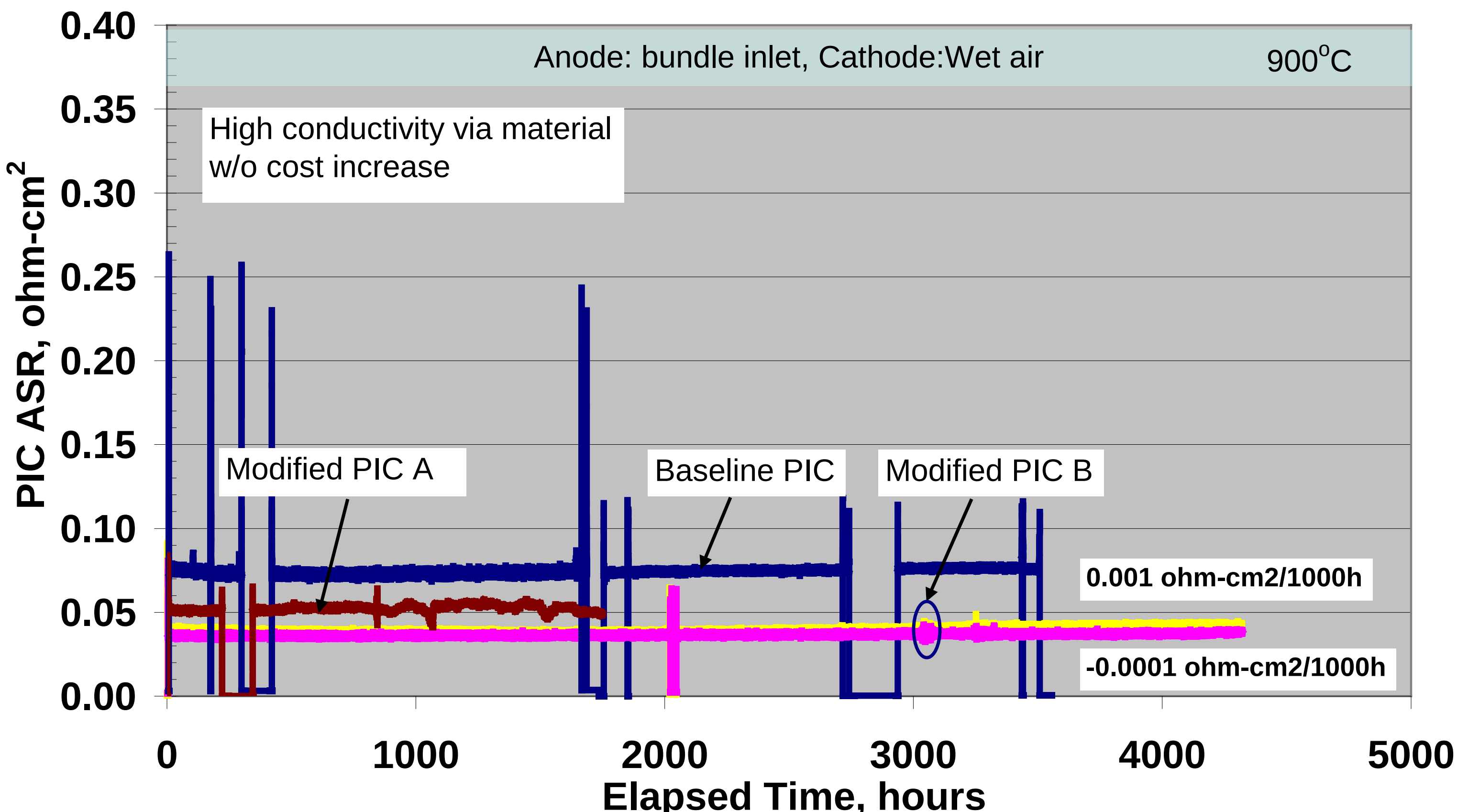
Two-Year Life was Demonstrated for Primary Interconnect (PIC) Design and Materials



Modified PIC Shows Improved Performance

- Further mitigate degradation mechanism for 3-5 year life
- Higher conductivity PIC materials and design modification
- PIC ASR is as low as 0.03 ohm-cm^2 and stable up to 4300 hrs



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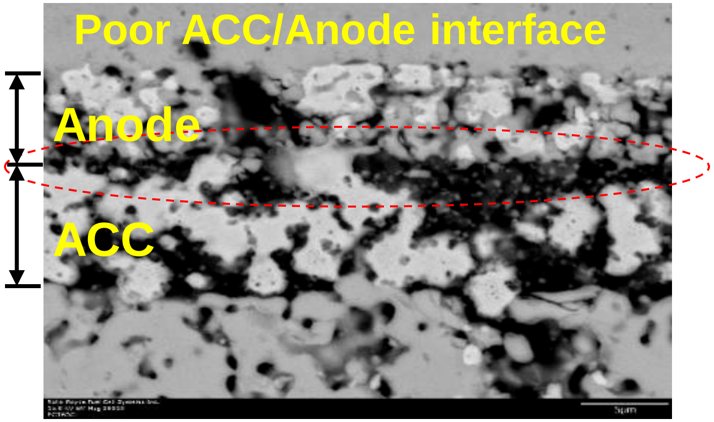
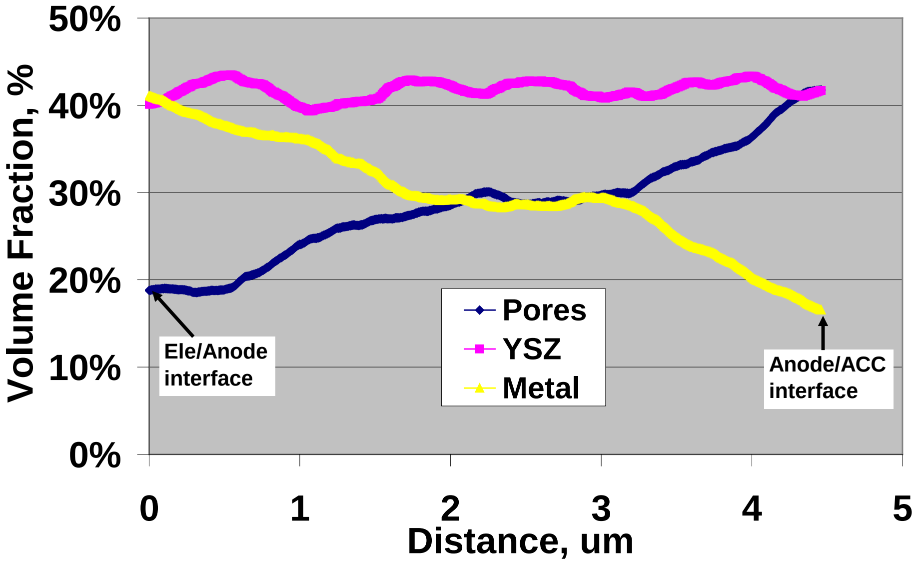
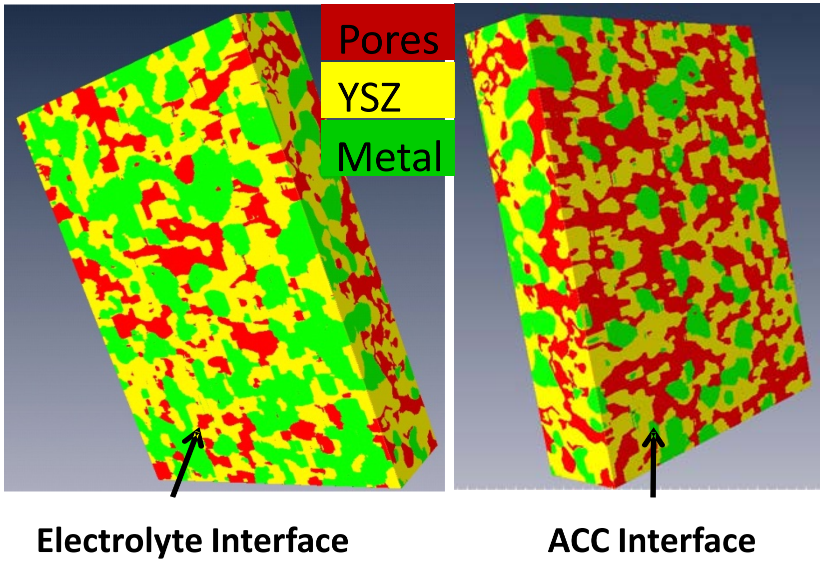
Baseline Anode Microstructural Change (ODOD*)

- Baseline anode (Ni-YSZ) tested at 925°C for 4000 hrs
- Significant microstructure change
  - Porosity increases and metal phase depletion at anode/ACC interface





PCT 65C



* This work is supported by Ohio Department of Development

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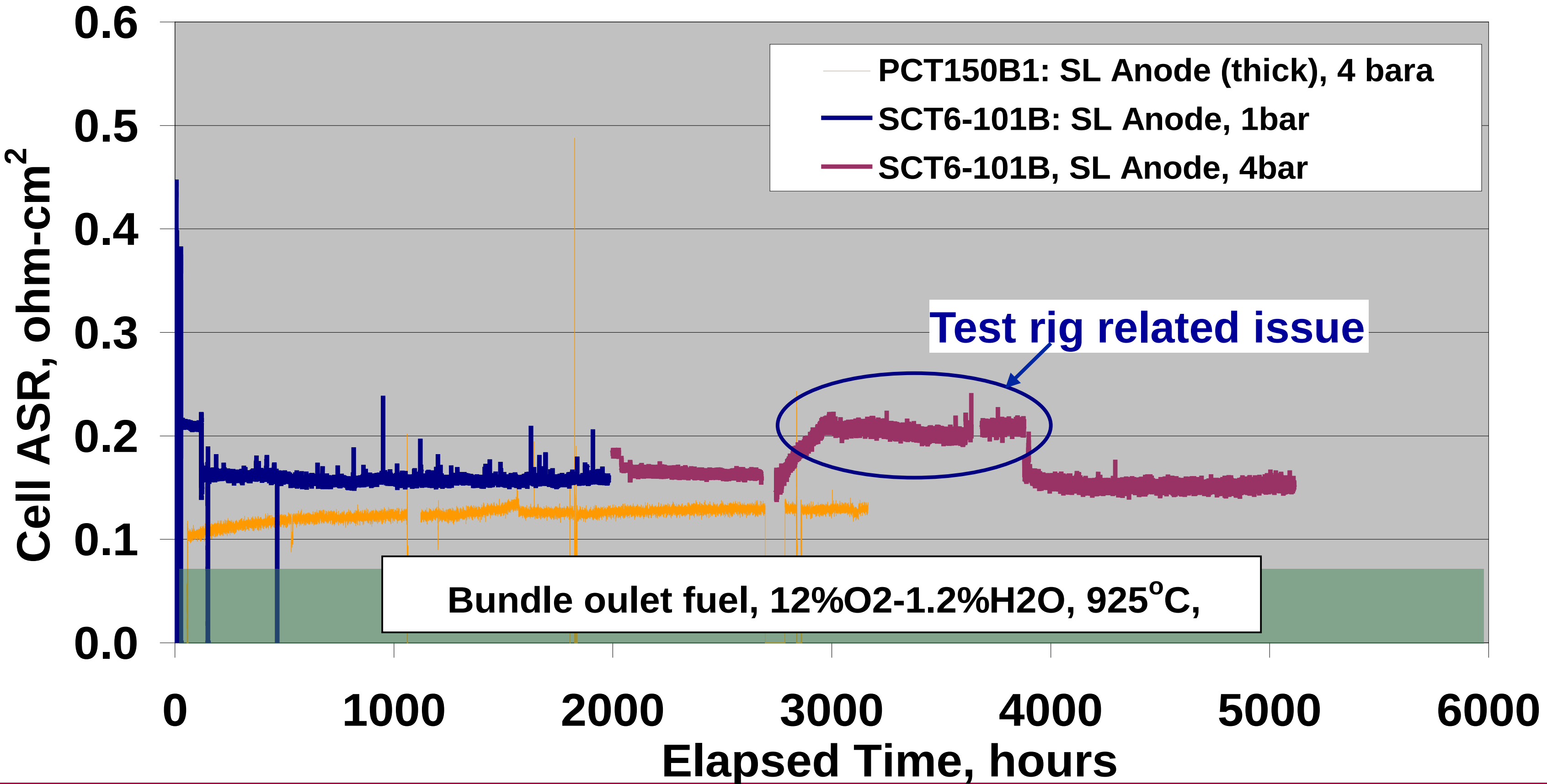
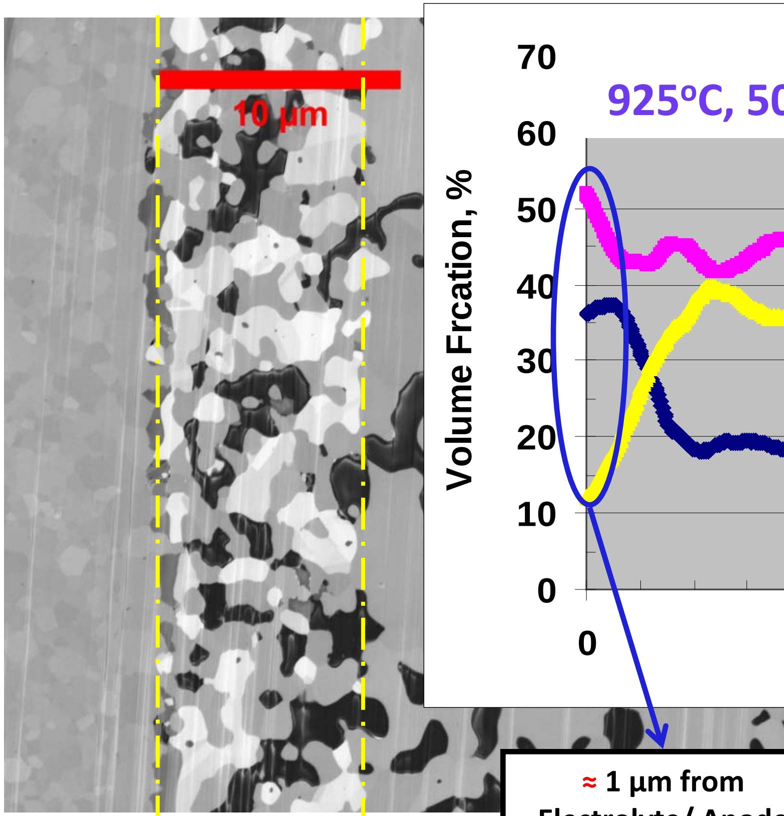
Single Layer Anode for Improved Durability

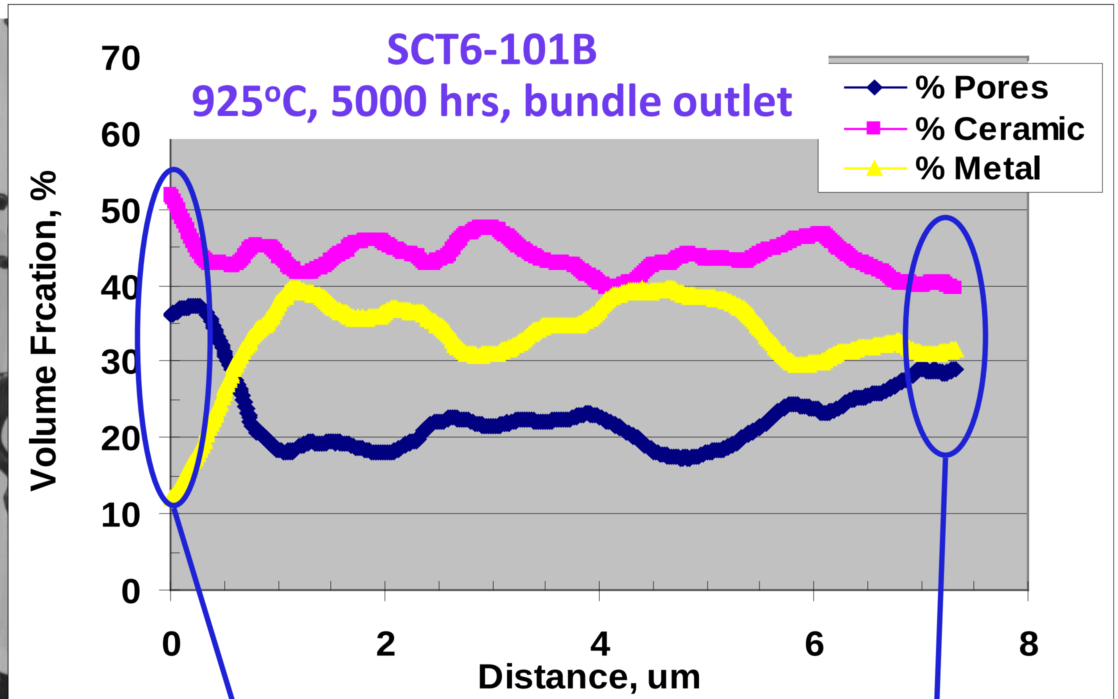
- 1980hrs in ambient + 3006 hrs in simulated system conditions

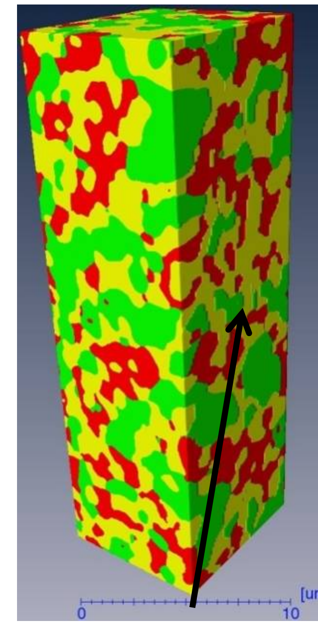


Detailed Microstructural Analysis of Single Layer Anode by 3D Reconstruction (ODOD*)

- Metal phase generally is uniform across the anode







Anode/substrate Interface

≈ 1 µm from Electrolyte/ Anode interface

≈ 1 µm from Anode/substrate interface

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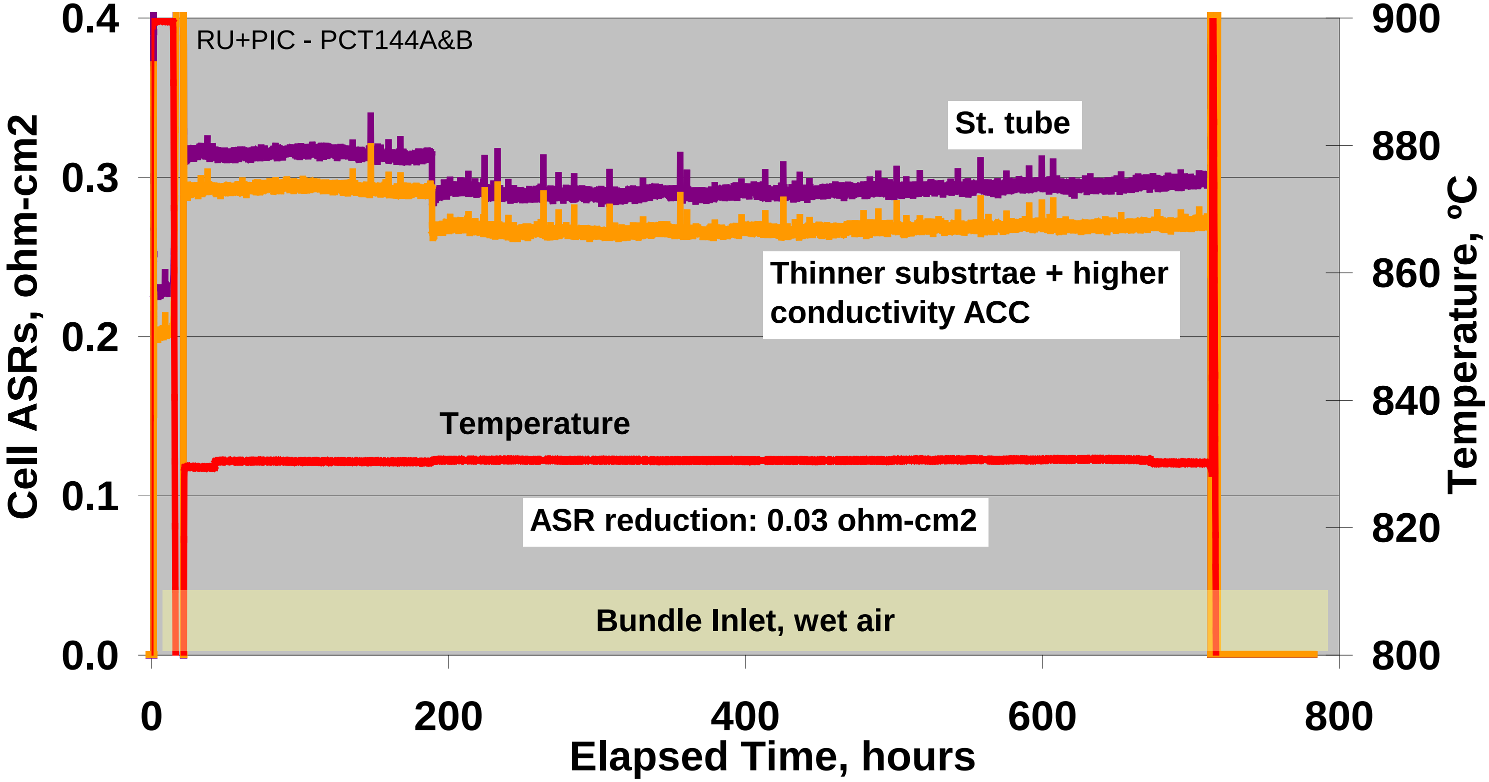
Lower Anode ASR Demonstrated for Future Cell Technology

- **High thermal expansion substrate allows use of higher conductivity anode current collecting material**
- **Thinner substrate reduces fuel diffusion resistance**



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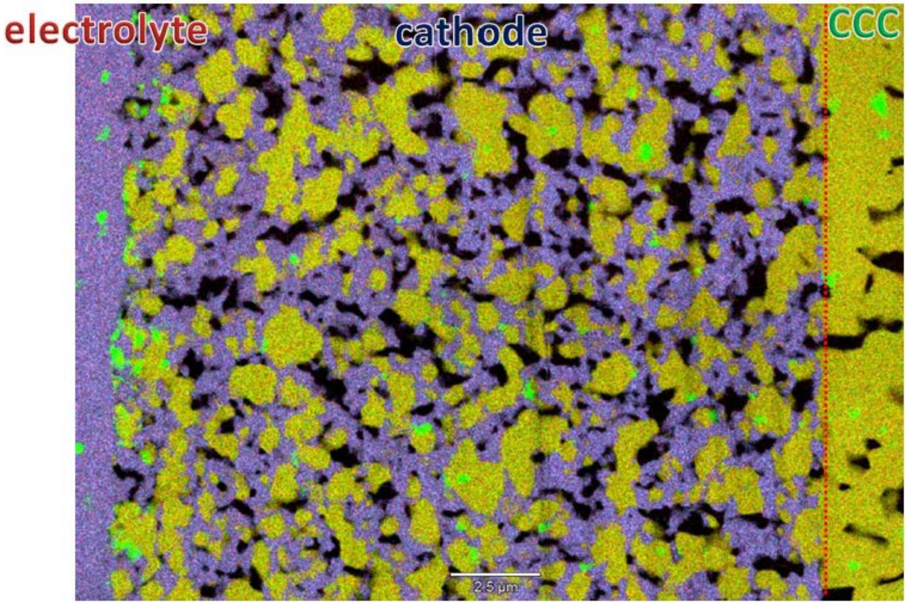
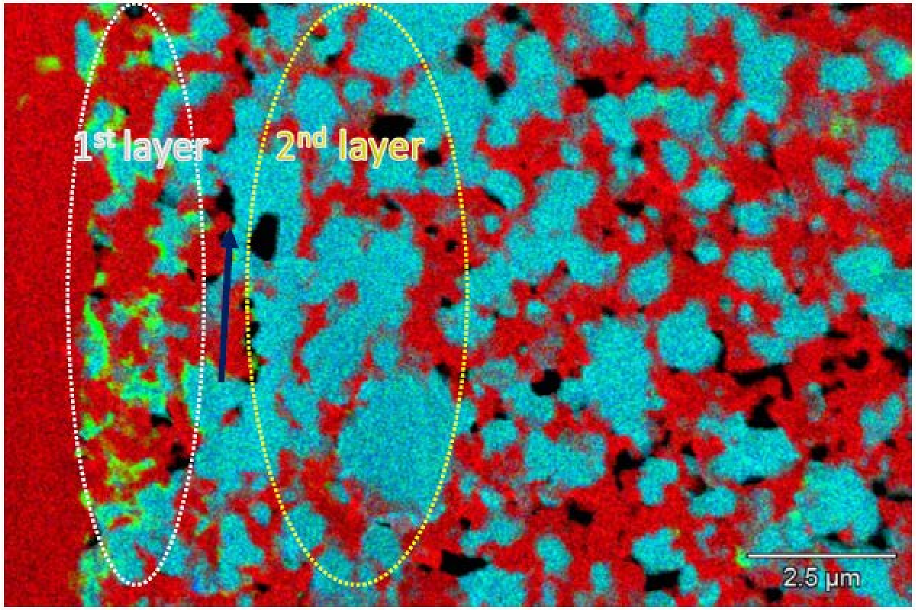
Cathode Microstructural Change after 16,000 hrs

- **Accumulated free MnOx at electrolyte interface at 800°C**
- **At 860°C also see densification**



Mn LSM Zr

PCT89B: 800C/16,000 hrs



Mn LSM Zr

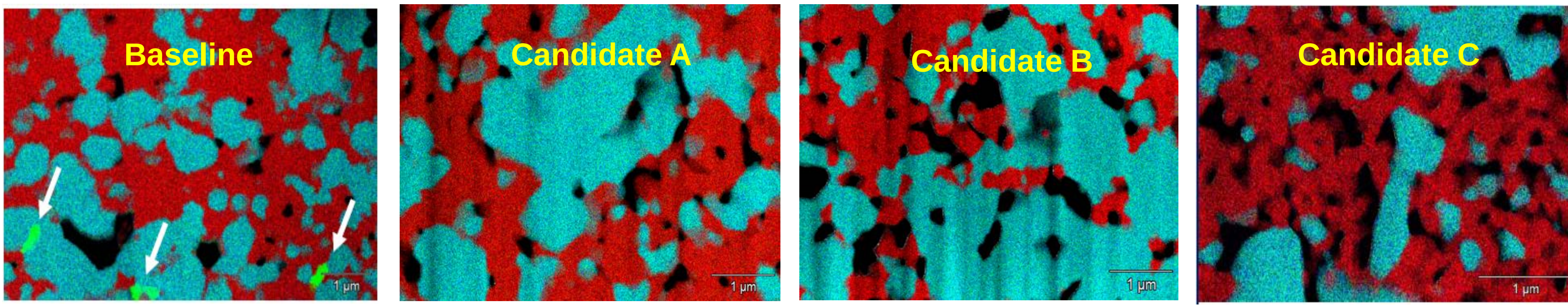
PCT63B: 860C/16,000 hrs

Approaches for LSM-Based Cathode Optimization

- **Evaluation of different cathode compositions – LSM and ionic phase**
  - **Thermodynamic consideration**
  - **Second phase/impurities**
- **Doped LM/LSM for microstructural stability at high temperatures**

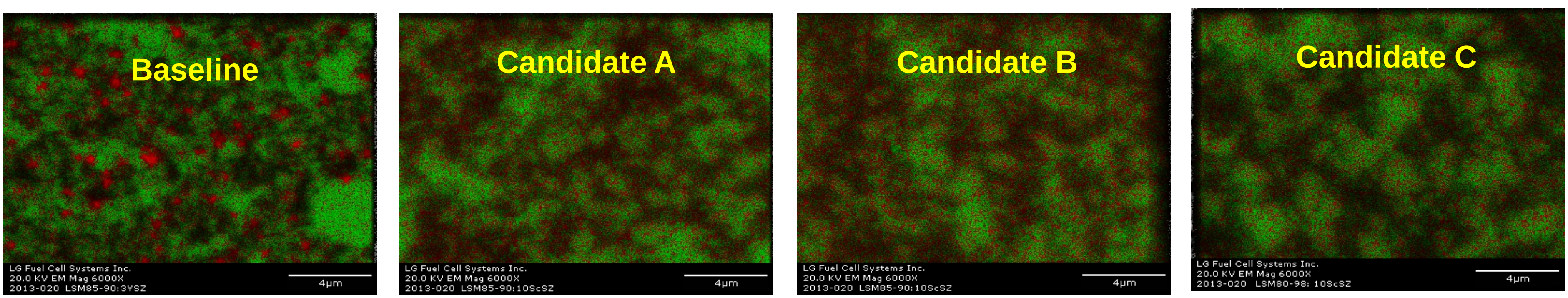
Cathode Optimization to Eliminate Free MnOx

- **Free MnOx was identified only in baseline cathode pellet**



Mn LSM Zr

As-fired cathode pellets

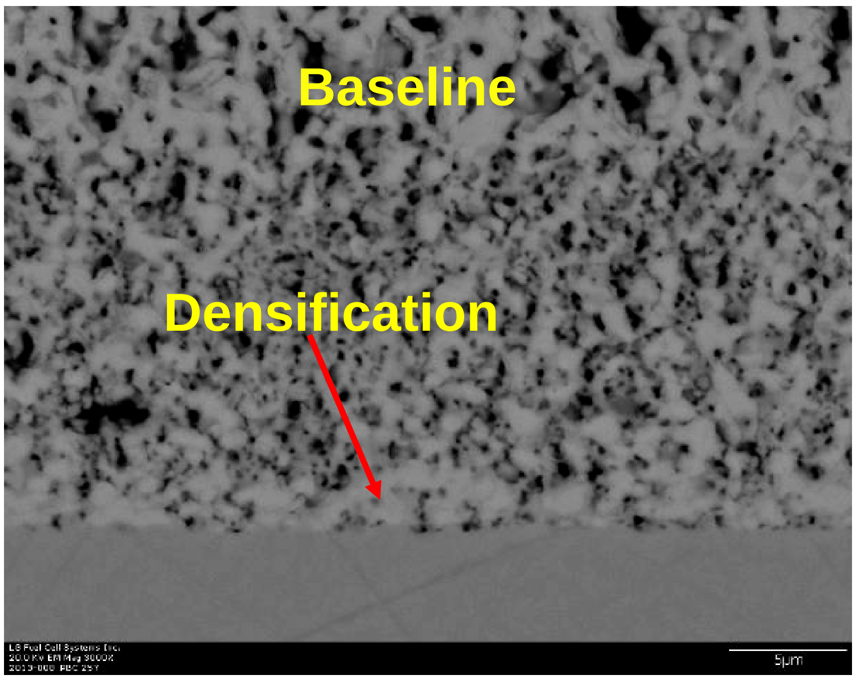


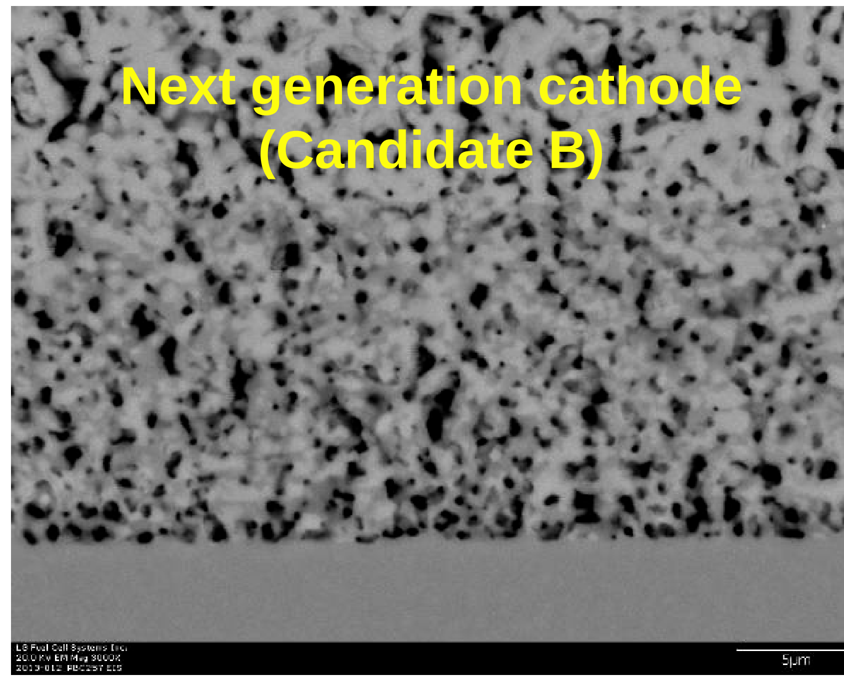
Mn

Cathode pellets aged for 1000 hours at high temperature

Accelerated Testing Method Developed for Cathode Screening

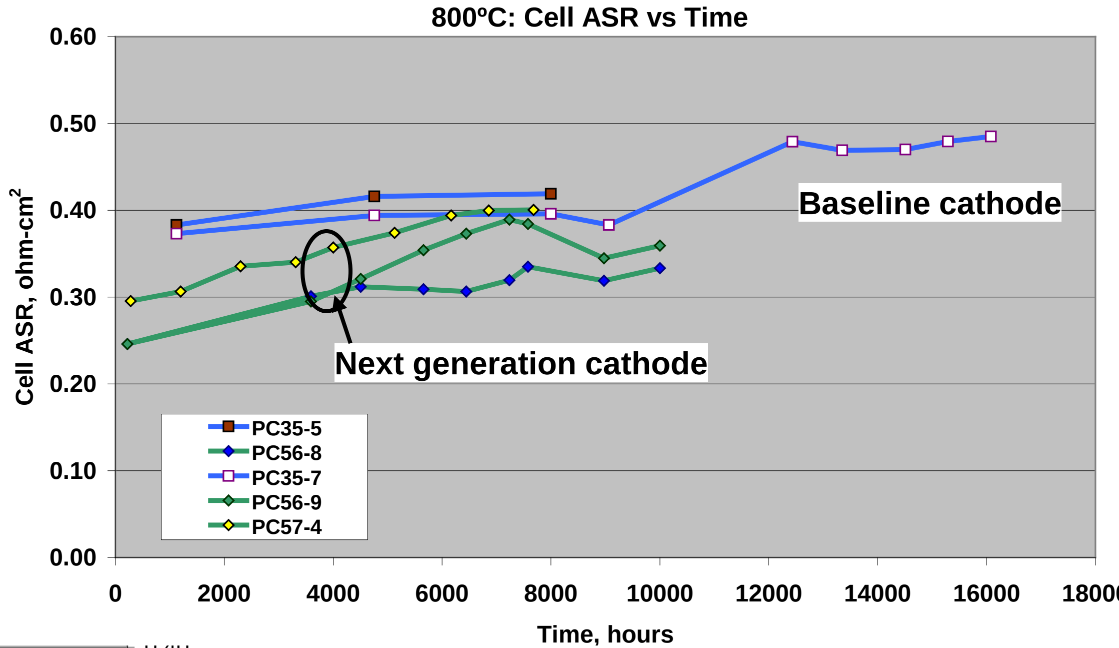
- **Allows screening of cathodes in 500 hrs**
- **Accelerated testing indicates next generation cathode is more stable**
- **Results repeated for both baseline and next generation cathodes**

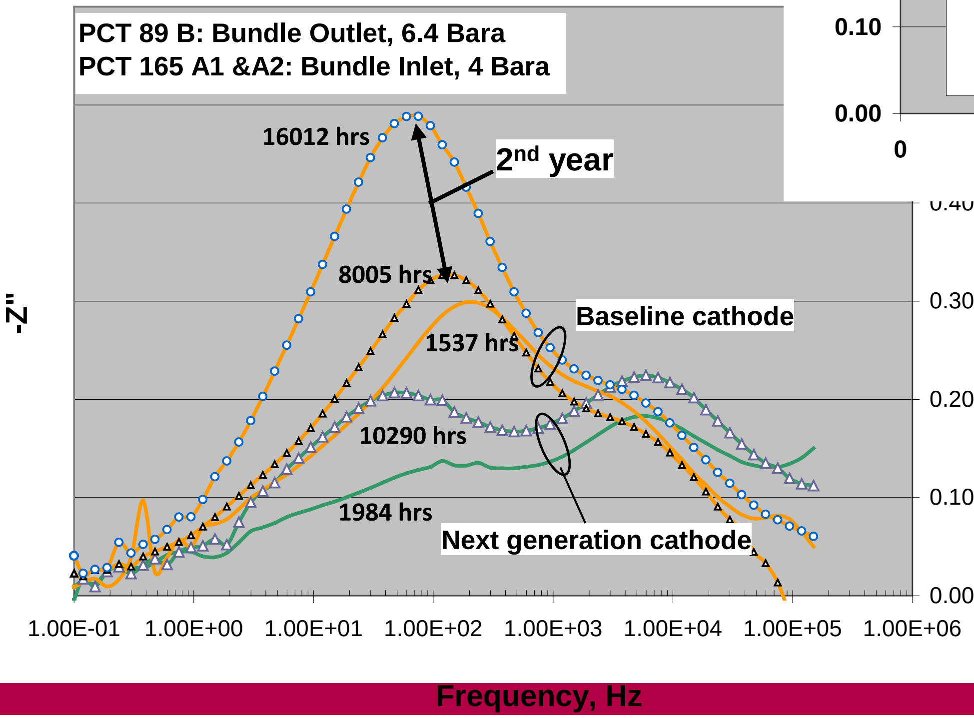




500 hrs at accelerated testing conditions

Next Generation Cathodes Show Improved Durability (800ºC)

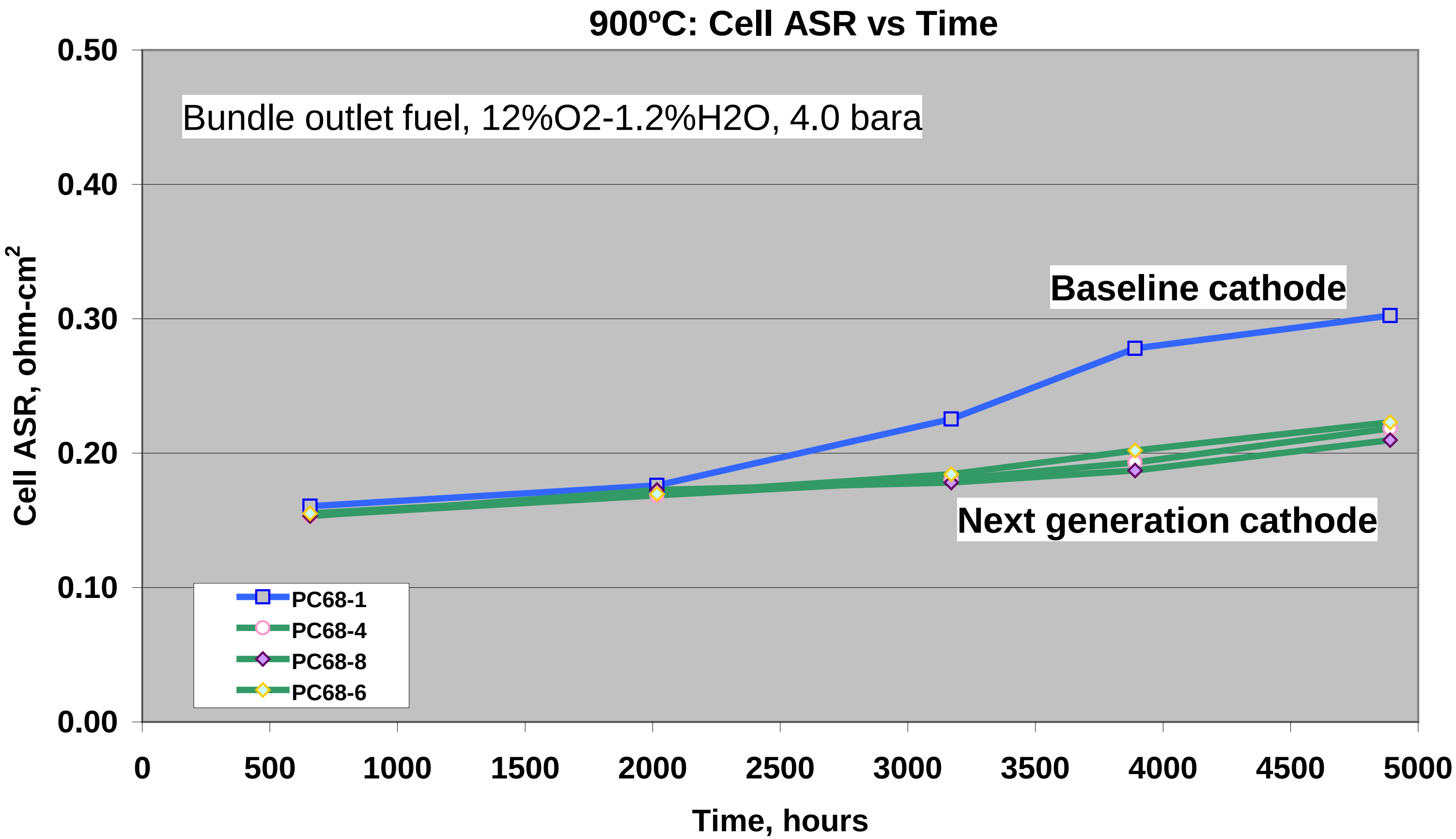




- For baseline degradation in 2nd year attributed to cathode (process at ~100 Hz)
- The change in the AC impedance peak not clearly linked to electrode microstructure change

Next Generation Cathodes Show Improved Durability (900ºC)

- **Tests at higher temperature show potentially better performance for next generation cathodes compared to baseline**



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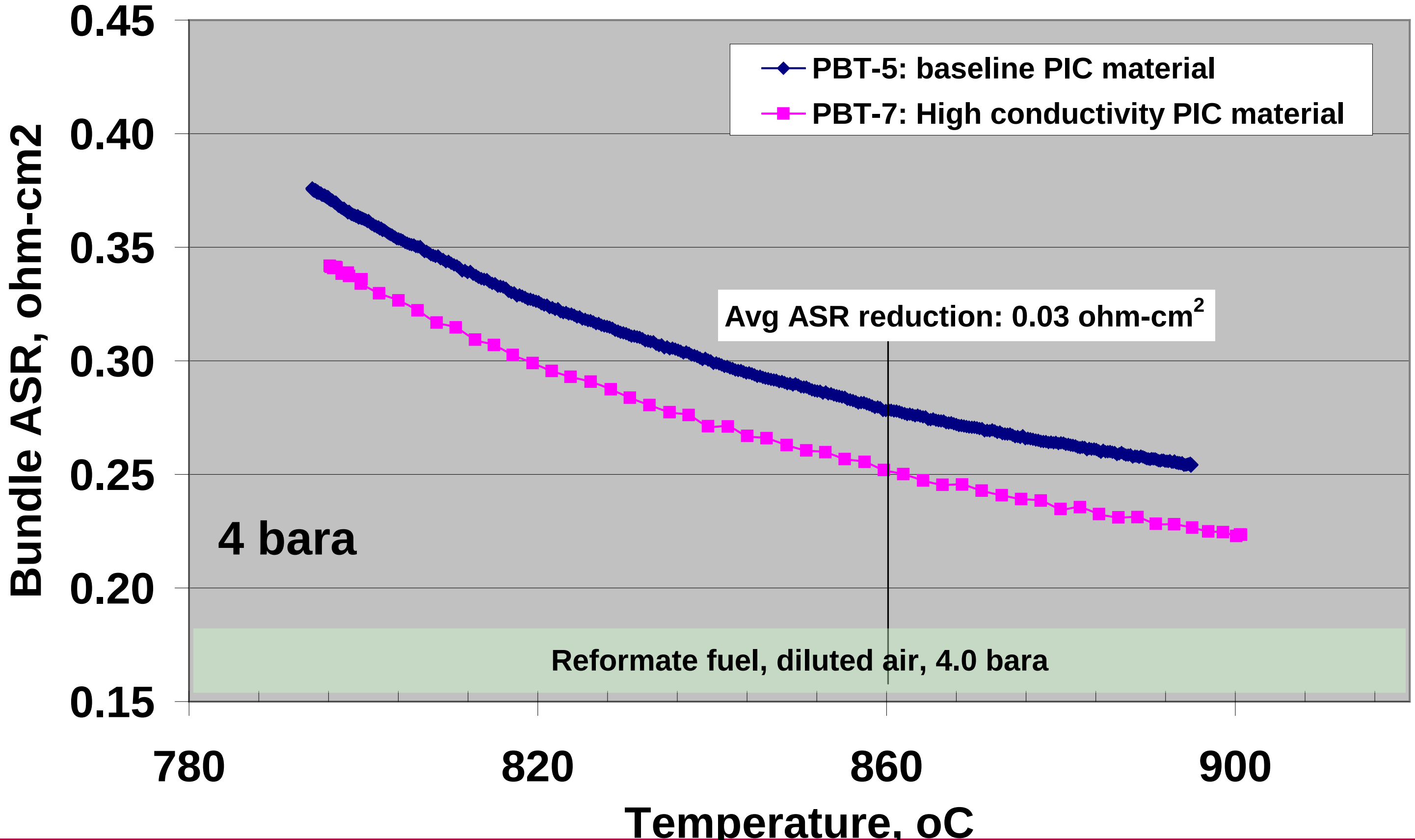
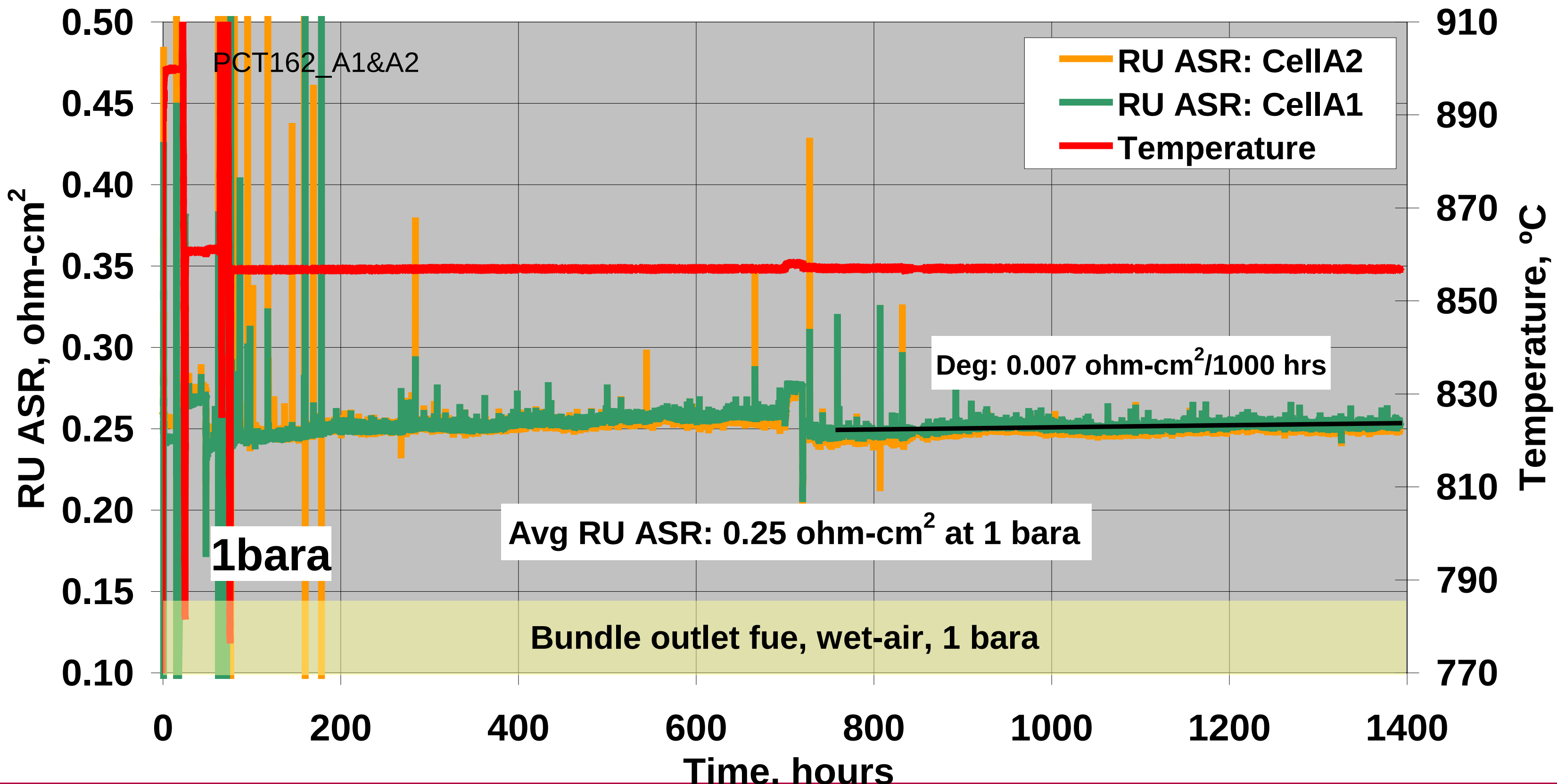
Bundle ASR Improvement by using High Conductivity Via Material

- **Average bundle ASR is 0.25 ohm-cm^2 vs. 0.28 ohm-cm^2 for baseline bundle without increasing the cost**



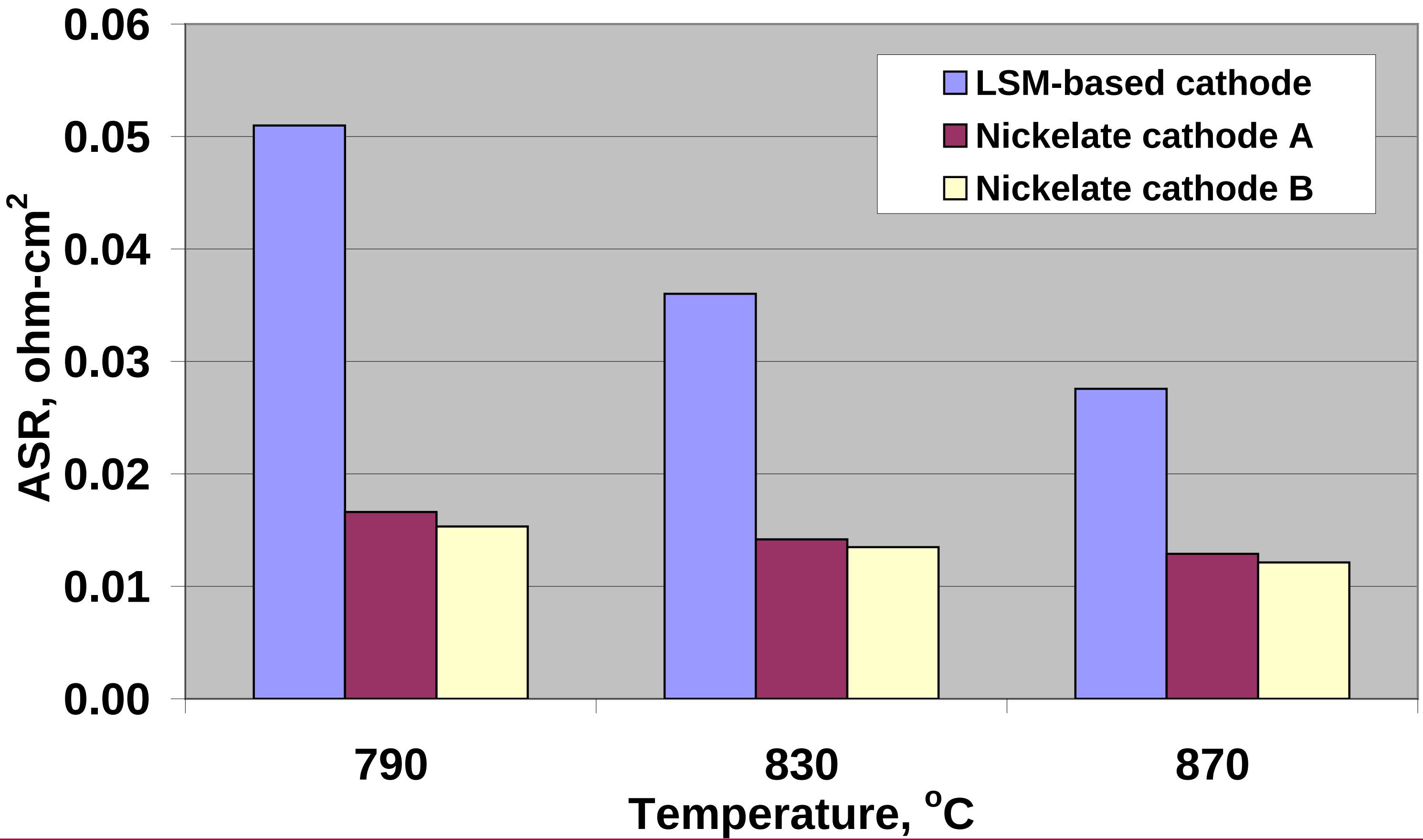
Expected Performance for Next Generation Anode, Cathode, and PIC Technology

- Average repeat unit (RU) ASR of 0.25 ohm-cm^2 at 1 bara
- Projected to 0.22 ohm-cm^2 at 4 bara and ≤0.20 ohm-cm^2 using higher conductive ACC & thinner substrate



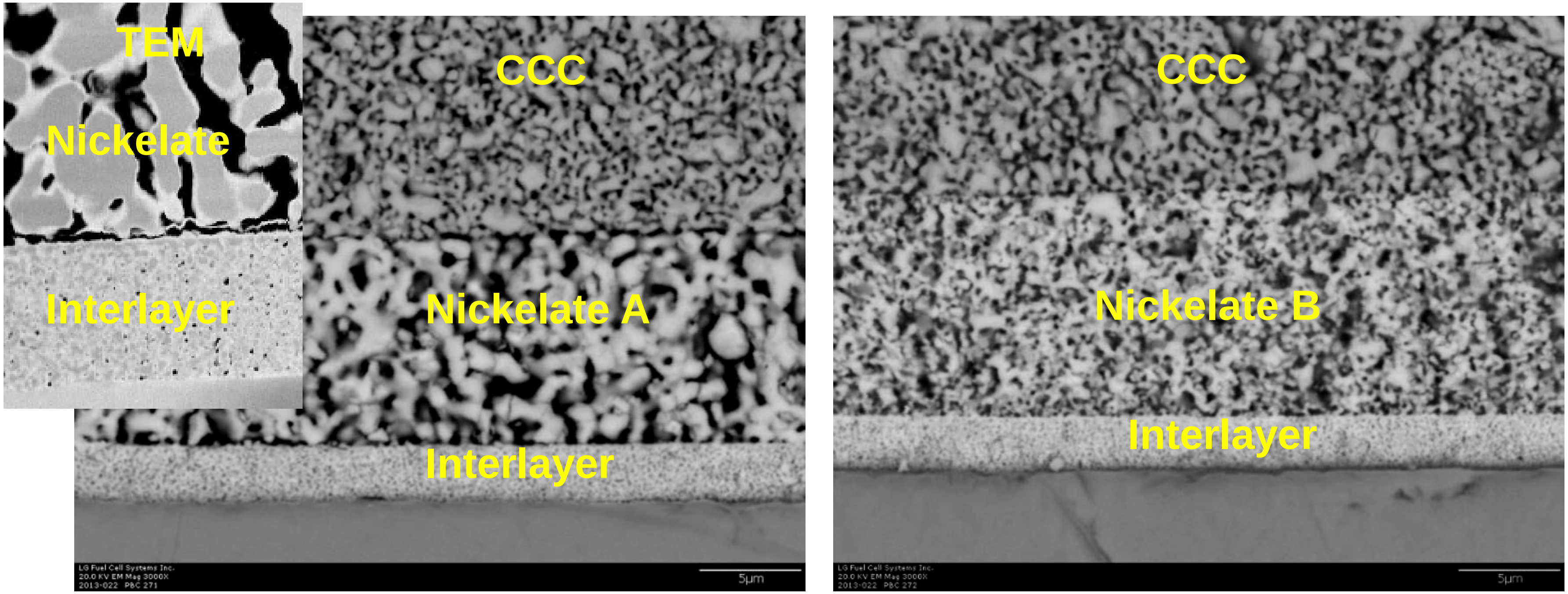
Need for Alternate Cathode Driven by Desire for Lower Operating Temperatures

- **Focusing on nickelate cathodes due to its CTE, lower ASR and activation energy**



Modified Nickelate Cathode Shows Significant Interface Improvement

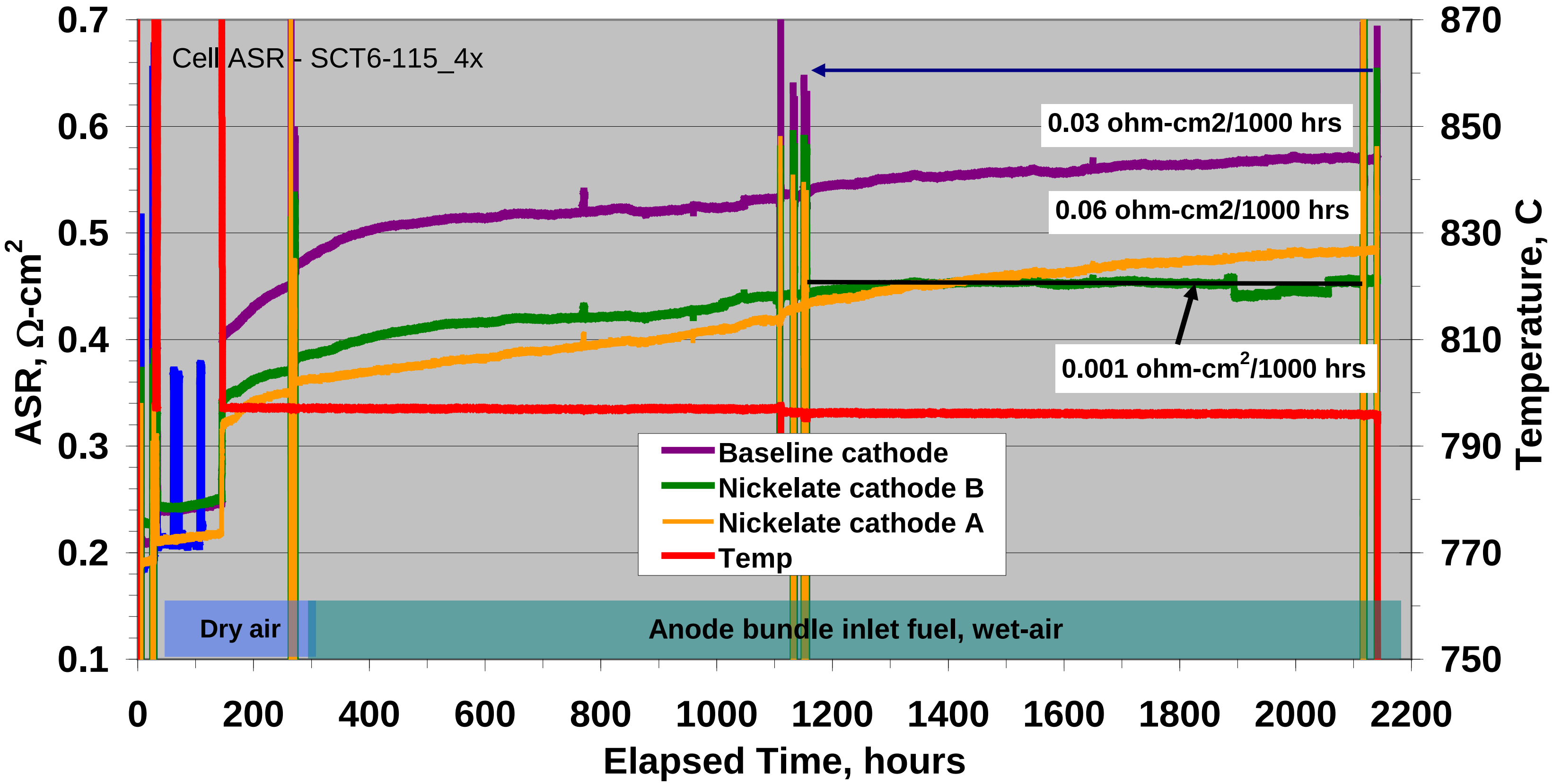
- **Fine microstructure/more triple phase boundaries**
- **Stronger interface may improve both durability and reliability**
- **The key challenge of phase stability needs further effort**



Button cells tested for 150 hrs at 790^{o}C

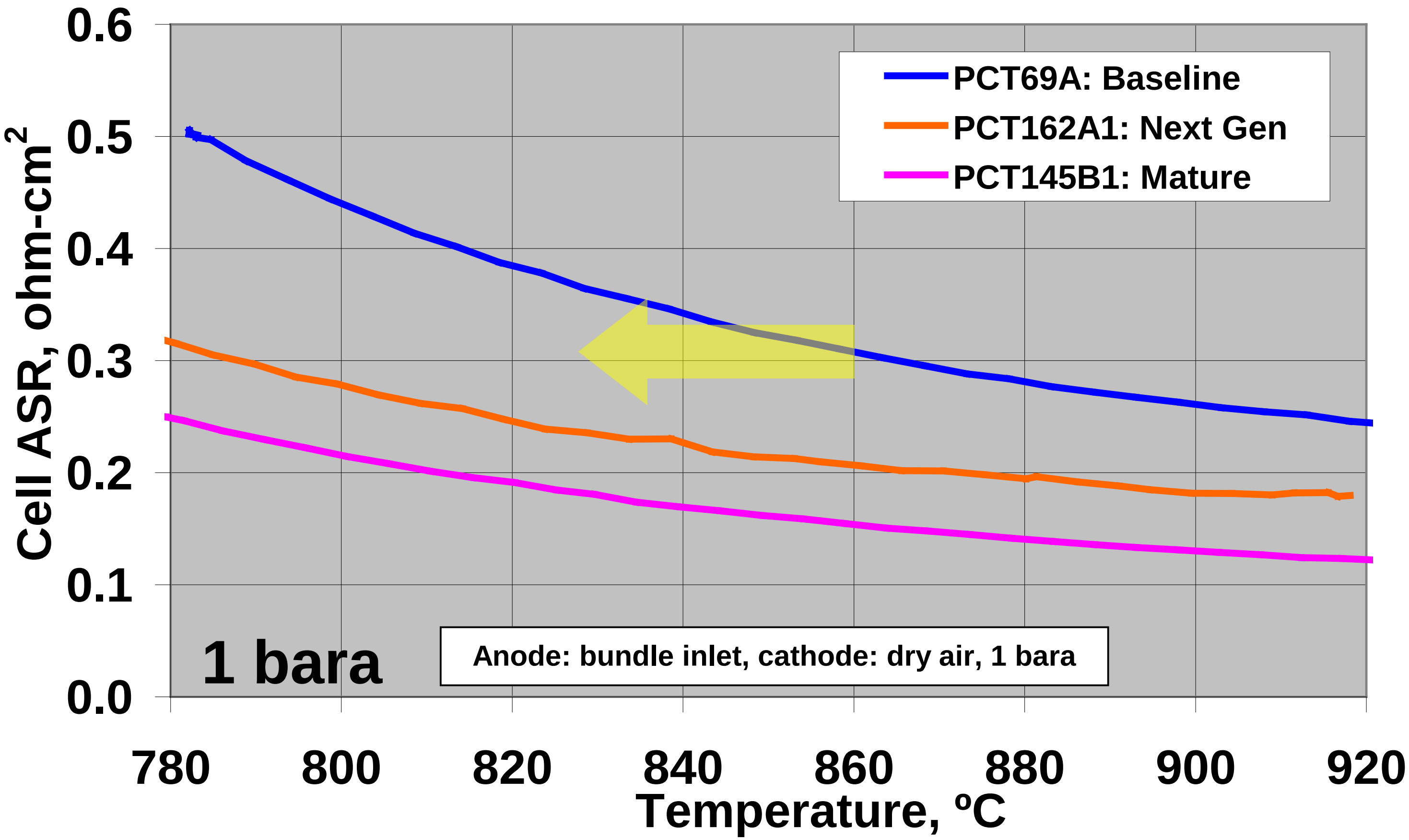
Nickelate Cathode Shows Promising Short Term Durability

- **Nickelates also show low-temperature steam effect**
- **Lower degradation after stabilization for optimized nickelate cathode**



Improved ASR for Future Cell Technologies Gives Operating Flexibility

- **Block operating temperature: 810-910ºC for baseline**
- **Allow fuel cell system operation at lower temperature and/or improved efficiency**



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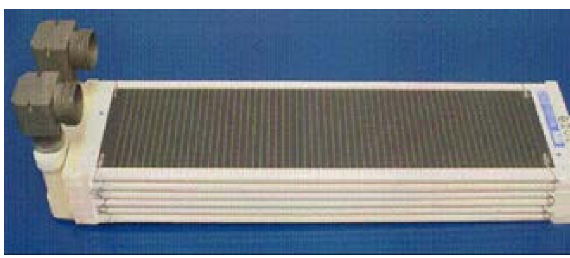
Structural Reliability Considerations

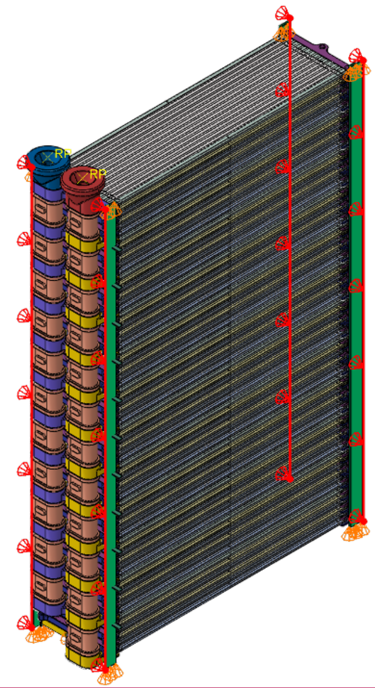
- LGFCS utilizes all ceramic strip
- Weibull probabilistic analysis required for all components
- Evaluating reliability against fast-fracture/infant mortality and time-dependent mechanisms:
  - Initial emphasis on understanding slow-crack growth of porous substrate
  - Now adding focus on properties of dense ceramics and glass-ceramic based joints



Bundle assembly (~350W):
Serial fuel and current flow

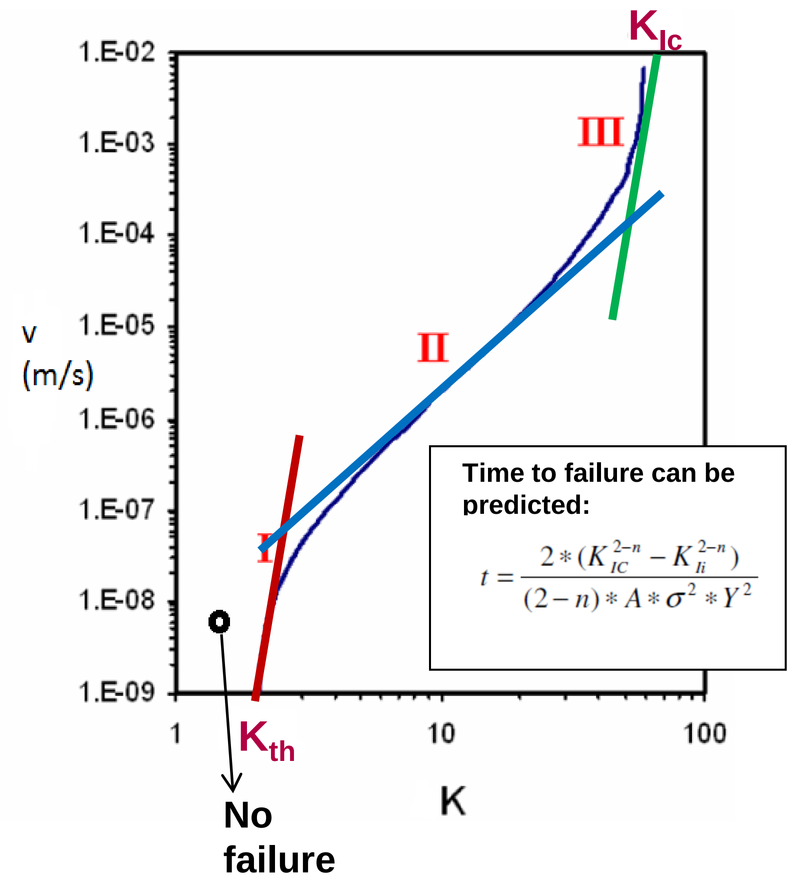
Block assembly (~20kW):
5 strips of 12 fuel-parallel bundles

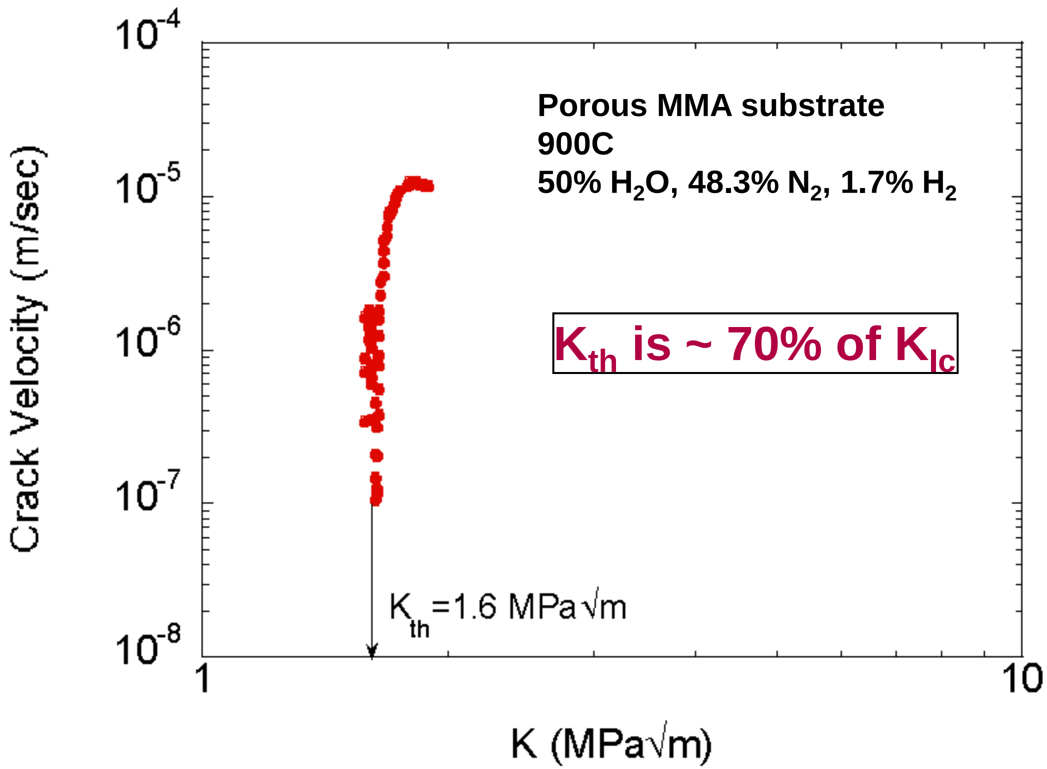
Strip Global Model
1,431,903 Elements
4,961,557 Nodes



LGFCS Substrate Exhibiting High K_{th} for Slow Crack Growth

Typical Slow Crack Growth Curve for Ceramics Showing Three Regions (I = threshold, II = linear, III = instability)





Summary

- Stack power degradation rate met SECA Phase 2 target
- Accelerated testing technique developed under this program proving to be a good tool for cathode material screening for long term stability
- Next generation/optimized electrodes being identified under long-term durability testing to advance to 5-year service life
- Improved ASR for future cell technologies gives operating flexibility and allow fuel cell system operation at lower temperature and/or improved efficiency
- Porous MMA substrate material showing promising properties to benefit long-term structural reliability

Acknowledgements

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- LGFCS SECA partners: Case Western Reserve University and Oak Ridge National Laboratory for permission to use certain of their images in the presentation.

Acknowledgements_Continued

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