Rolls-Royce Coal-Based SECA Program Update

26 July 2011

Ted Ohrn and Zhien Liu

 This material is based upon work supported by the U.S. Department of Energy under Award No. DE-FE0000303.

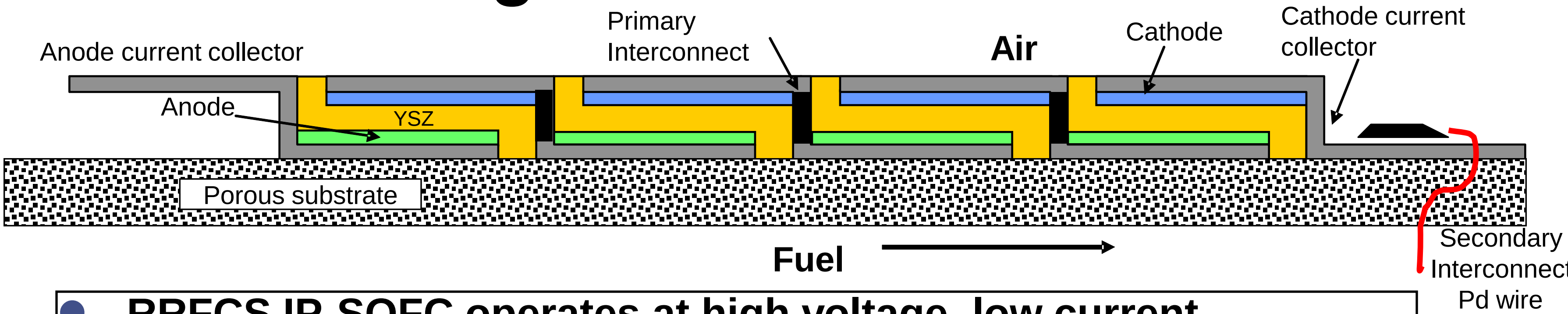
Outline

- RRFCS SECA Program and IP-SOFC Technology
- IGFC Systems Analysis
- Block-scale Test Rigs
- IP-SOFC Durability
- IP-SOFC Optimization

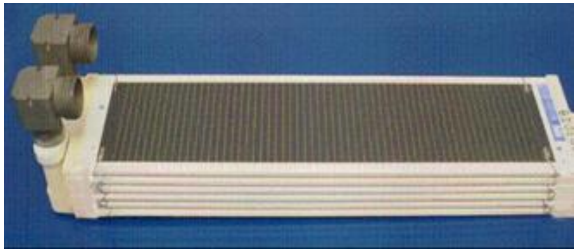
RRFCS SECA Program

- Phase 1
  - Extended to Sept 2011
    - 11 kW Metric Test to commence in Q3
  - Partners:
    - UCONN: BOP alloys/coating, Cr release rates
    - CWRU: detailed analytical analysis (TEM, XPS)
    - ORNL: substrate mechanical properties
    - PNNL: glass-ceramic seal

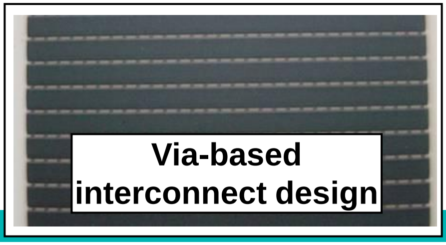
RRFCS Integrated Planar SOFC



- RRFCS IP-SOFC operates at high voltage, low current
- Narrow cell pitch reduces ohmic losses
- Extruded $MgO+MgAl_2O_4$ substrate with screen printed layers

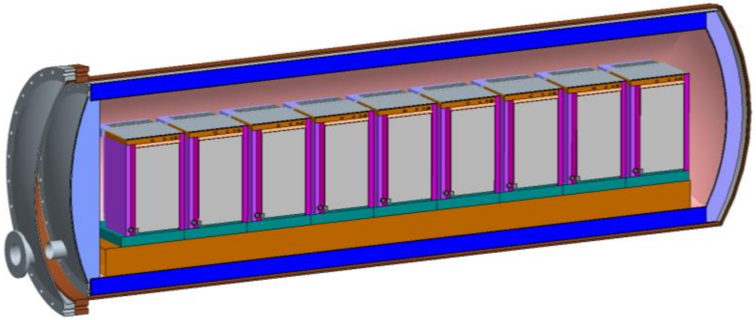


Bundle assembly (~350W):
Serial fuel and current flow



Via-based interconnect design

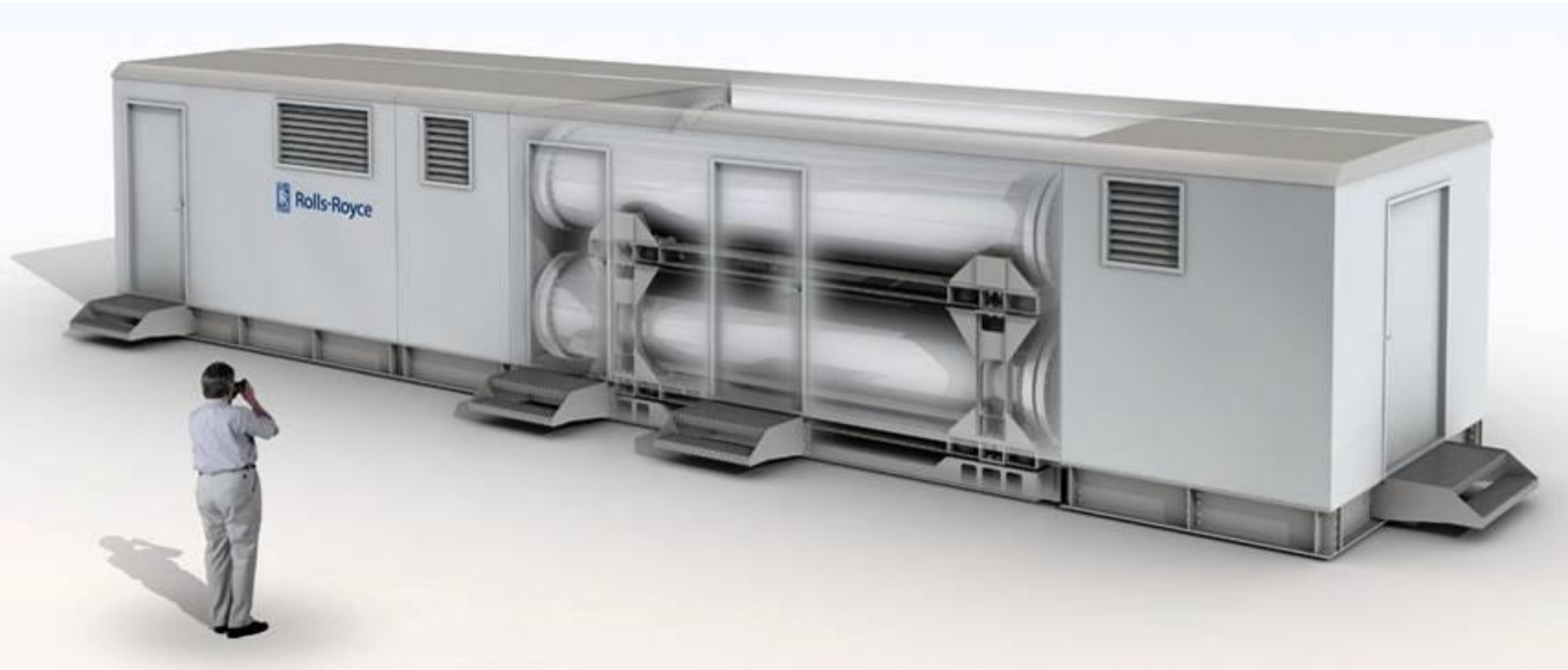
Block assembly (~20kW):
5 strips of 12 fuel-parallel bundles



Initial 1MW distributed power system will consist of ~250kW generator modules with larger blocks

Market Entry is a 1MW Distributed Energy System

- Natural gas fired
- Potential net-AC electrical efficiencies of 60%
- Very low environmental impact, quick wins on air quality

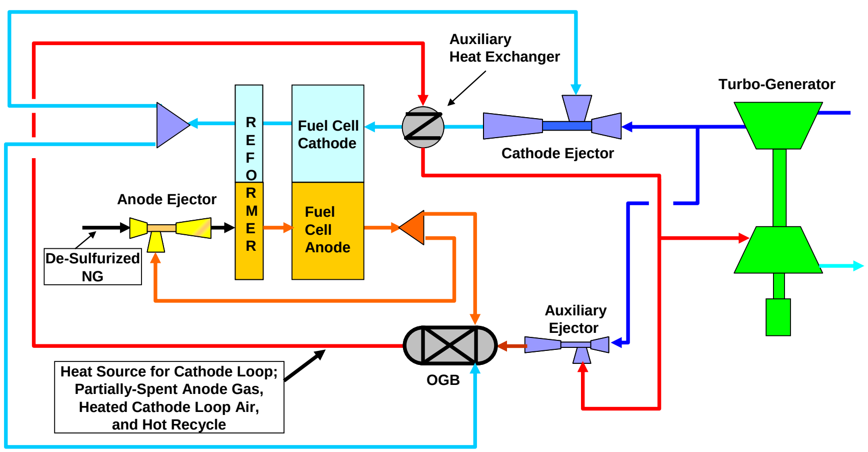


Outline

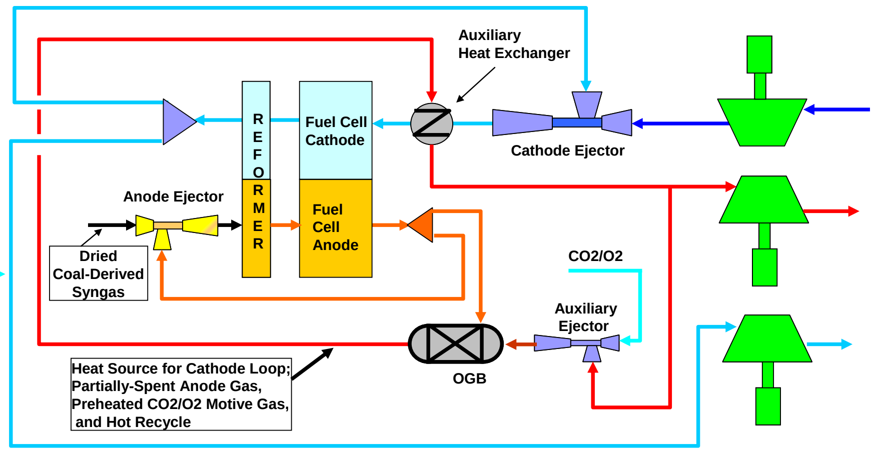
- RRFCS SECA Program and IP-SOFC Technology
- IGFC Systems Analysis
- Block-scale Test Rigs
- IP-SOFC Durability
- IP-SOFC Optimization

Plant Configuration

RRFCS NG “Dry Cycle” Configuration



Current IGFC Plant Configuration



Cycle	NG, dry	IFGC	IGFC
Uf (HHV)	80	80	90
Anode Exit Composition			
H2	16.2	8.0	4.1
CO	8.9	7.7	3.9
Total Flammables	**25.1**	**15.7**	**8.0**
H2O	47.5	44.6	48.7
CO2	23.8	39.2	43.0

- **Uses “Cold Gas Clean-up” providing;**
  - **anode recycle to achieve,**
  - **sufficient steam in feed for reforming**
- **IGFC cycle similar to current RRFCS natural gas cycle**

PRO/II Modeling Results

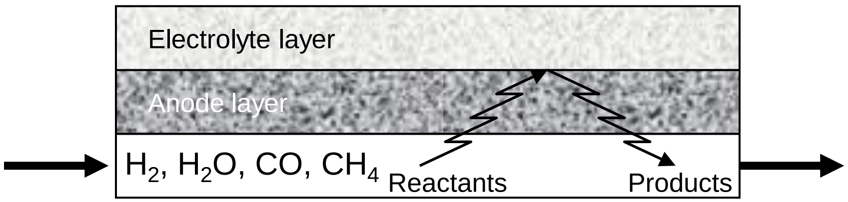
Model run at ~350 mW/cm^2, 5 bar and 810C-910C range

Efficiency Table (based on 1000 MW thermal Input)		Current Fuel Cell Technology	Advanced Fuel Cell Technology
ASR	ohm-cm2	0.320	0.260
Leakage current loss	%	2.5	0.0
FCFU(HHV basis)	%	82.0%	90.2%
Advanced Coal Gas Efficiency	%	90.0	90.0
Fuel Cell DC Power	MWe	473.3	520.5
Fuel Cell DC to AC Inverter Loss (97%)	MWe	459.1	504.9
Turbine Power*			
Syngas	MWe	29.3	29.3
Fuel Cell Air Compression	MWe	-100.5	-92.8
Fuel Cell Air Expansion	MWe	169.0	159.1
Anode Exhaust Expander	MWe	46.1	43.6
Total Gross AC Power	MWe	603.0	644.1
Parasitic Power Loss w/o CO2 (3.82%)	MWe	38.2	38.2
CO2 Compression Loss (3.66%)	MWe	44.1	44.1
Efficiency without CO2 Compression	%	55.7%	60.0%
Efficiency with CO2 Compression	%	51.3%	56.3%

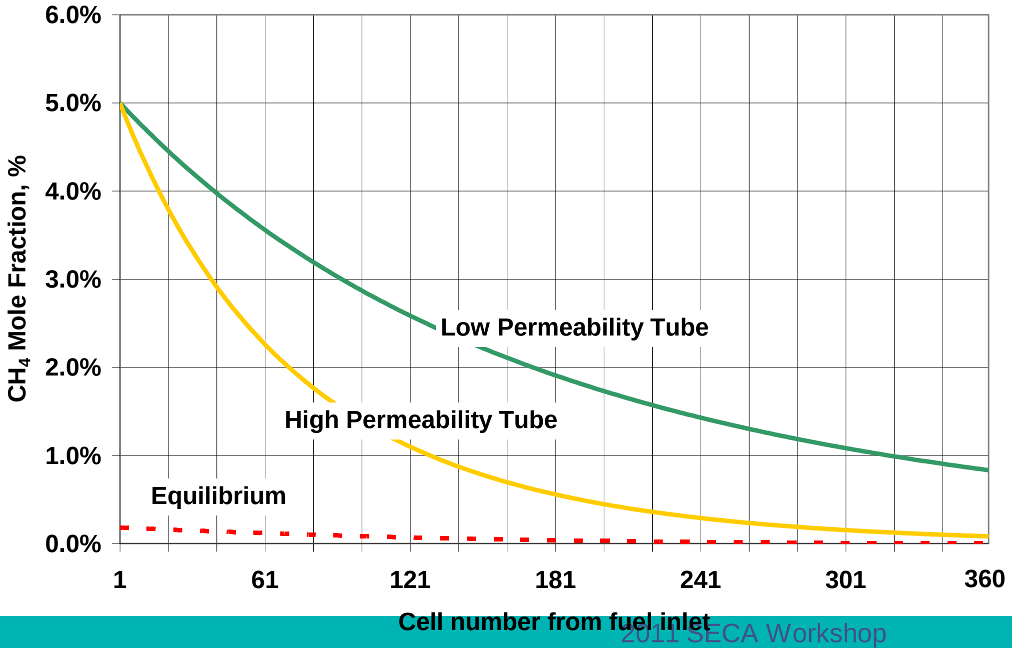
- 60% overall efficiency requires;
  - Inter-cooling of all gas compression
  - 90% coal gasifier efficiency
  - ~90% fuel utilization (challenging)
  - Improved ASR (~30% relative to current technology), demonstrated with advanced cathodes
- Increased pressure did not show performance improvement because;
  - Improved reactivity at elevated pressure was offset by
  - Less air and therefore, increased reaction resistance due to oxygen depletion

Porous Inert Substrate Controls Reforming Endotherm

- **Reforming occurs as CH_4 diffuses to reaction site at anode-electrolyte interface**
  - **Rapid reforming yields equilibrium concentration at anode**
  - **Rate of bulk reforming controlled by diffusion of CH_4 to anode**
- **Small-scale cell experiments support this mechanism.**



CH_4 at Equilibrium at Reaction Site



On-Cell Reforming Provides no Efficiency Improvement in a Pressurized System

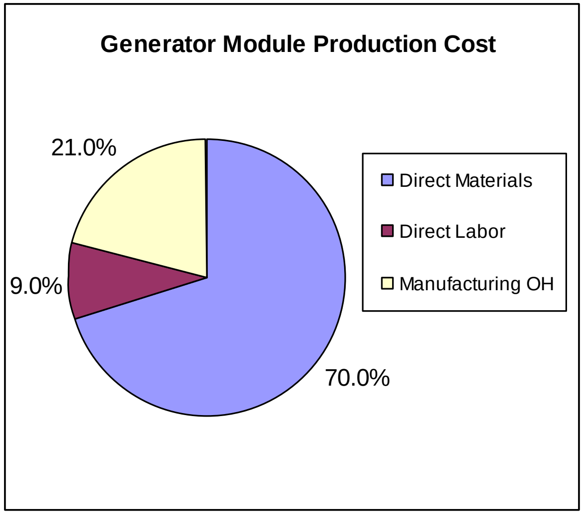
- Heat absorption via reforming at constant cathode recycle ratio,
  - required less air, and enabled
  - a contracted temperature profile (i.e. increasing inlet temperature, higher average temperature)
- Higher average temperature did not yield improved performance because;
  - Decrease in average ASR was offset by
  - Increase in reversible voltage

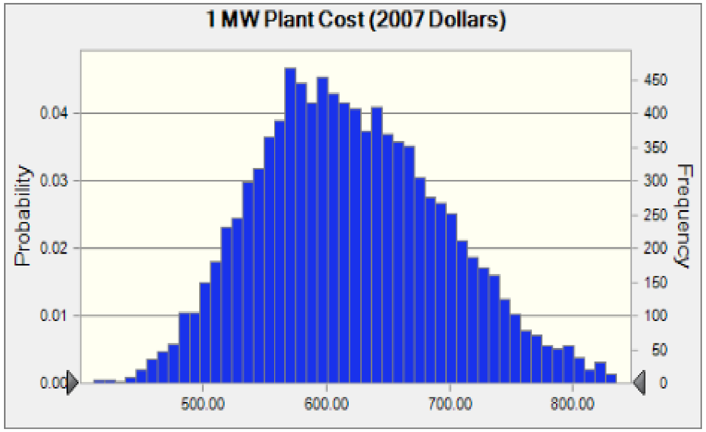
On-Cell Reforming Results for Repeat Unit				
% On-Cell Reforming		0	50	100
Constant Fuel Feed (HHV)	kWe	540	540	540
Constant Uf (HHV)	%	82	82	82
Constant Current Density	mW/cm2	427	427	427
Fuel Cell Anode In				
H2	mole %	26.25	18.31	9.49
CO	mole %	23.49	18.38	11.26
CH4	mole %	0.22	4.55	9.82
Fuel Cell Operation				
Model Calculated ASR	ohm-cm2	0.387	0.350	0.303
Vreversible	volts	1020	1003	977
Air-Side Operation				
Air Inlet Temperature	deg. C	800	817	836
Air Outlet Temperature	deg. C	900	900	900
Air Inlet Flow	g/s	268	251	233
Cathode Recyle Ratio		6	6	6
Predicted Power Output	KW	284	284	283
Predicted Efficiency	%	55.7	55.7	55.7

But, on-cell reforming provides opportunities for stack delta-T management, influencing long-term durability

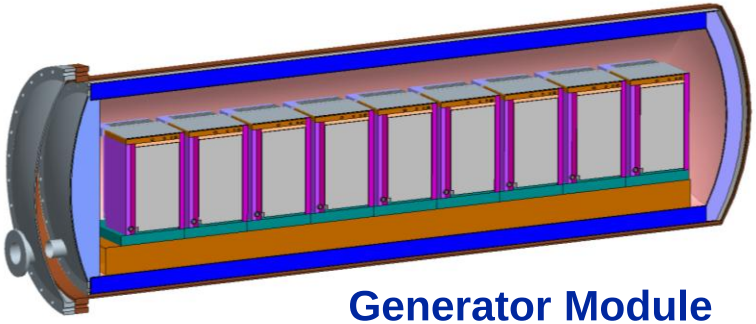
Distribution of RRFCS IGFC System Costs

- Estimates for 2 stages of technology
  - Current technology (Ph. 1 block): 0.29 ohm-cm^2
  - Next generation (Ph. 2 candidate): 0.24 ohm-cm^2, precious metal cost savings
- Monte Carlo simulations with variables having greatest cost uncertainty
- Cost estimates
  - Current technology: $673/kW
  - Next generation: $621/kW





Monte Carlo Simulation



Generator Module

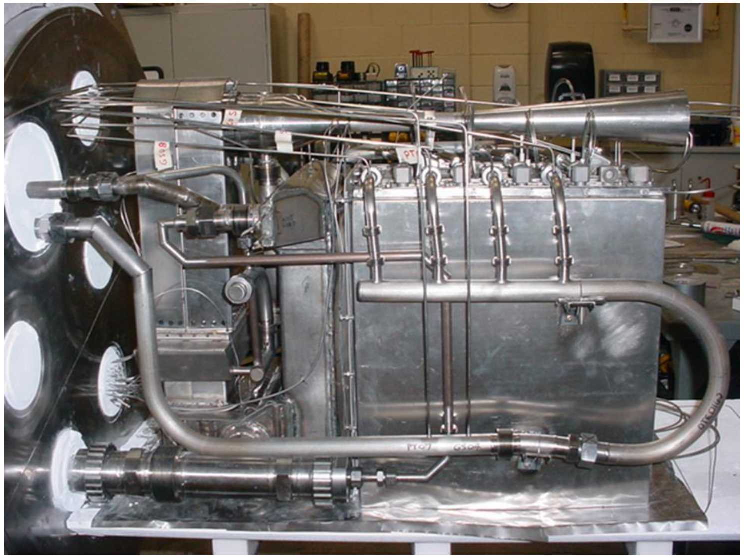
Outline

- RRFCS SECA Program and IP-SOFC Technology
- IGFC Systems Analysis
- Block-scale Test Rigs
- IP-SOFC Durability
- IP-SOFC Optimization

Block-scale Test Rigs

- **Rigs closely represent product**
  - **Anode and cathode recycle**
  - **Heat exchanger**
  - **Reformer**
  - **OGB**
  - **Ejectors**
  - **Insulation system, thermal self-sustaining**
  - **Control system/methodology**
  - **Safety systems**
- **These rigs are providing the foundational precommercial durability database**
  - **3 rigs in Derby, UK**
  - **1 rig in Canton, OH**

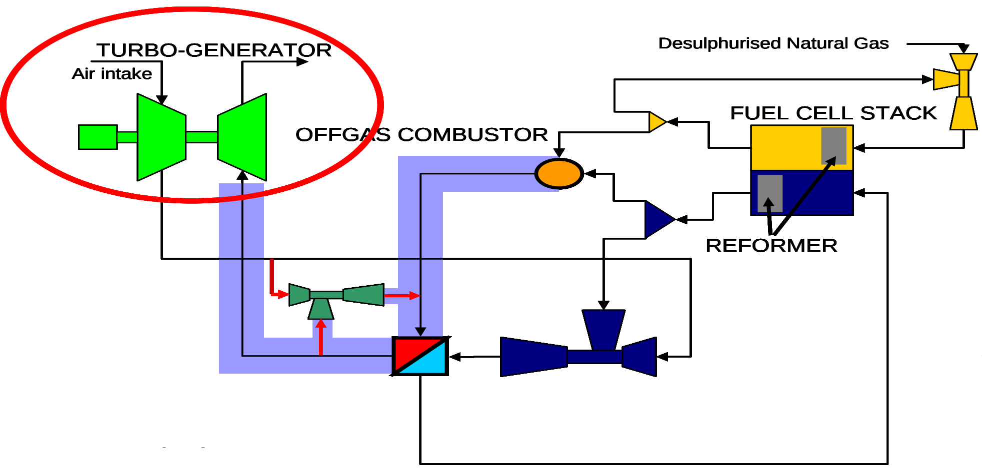
SOFC7x Test Stands (3) hold single-block (UK)

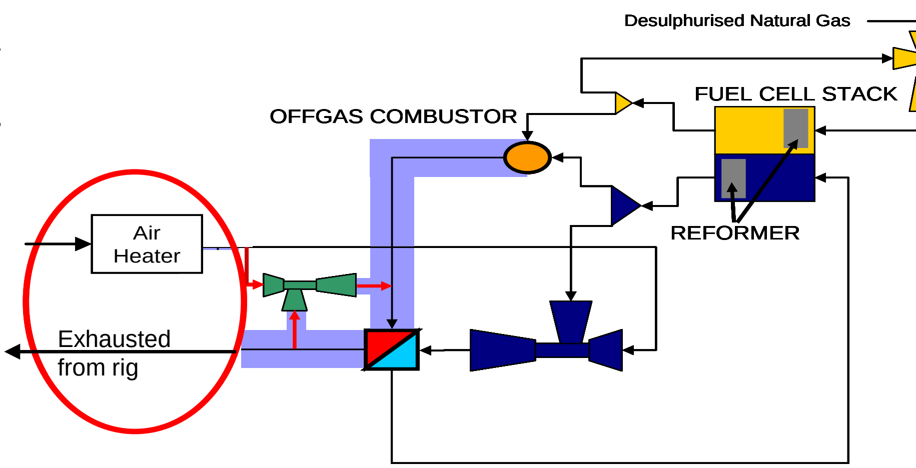


Block Rigs Representative of Heat Balance within Generator Modules and Considered Tthermal Self-Sustaining

Phase 1 metric test meets the TSS requirement in Phase 2

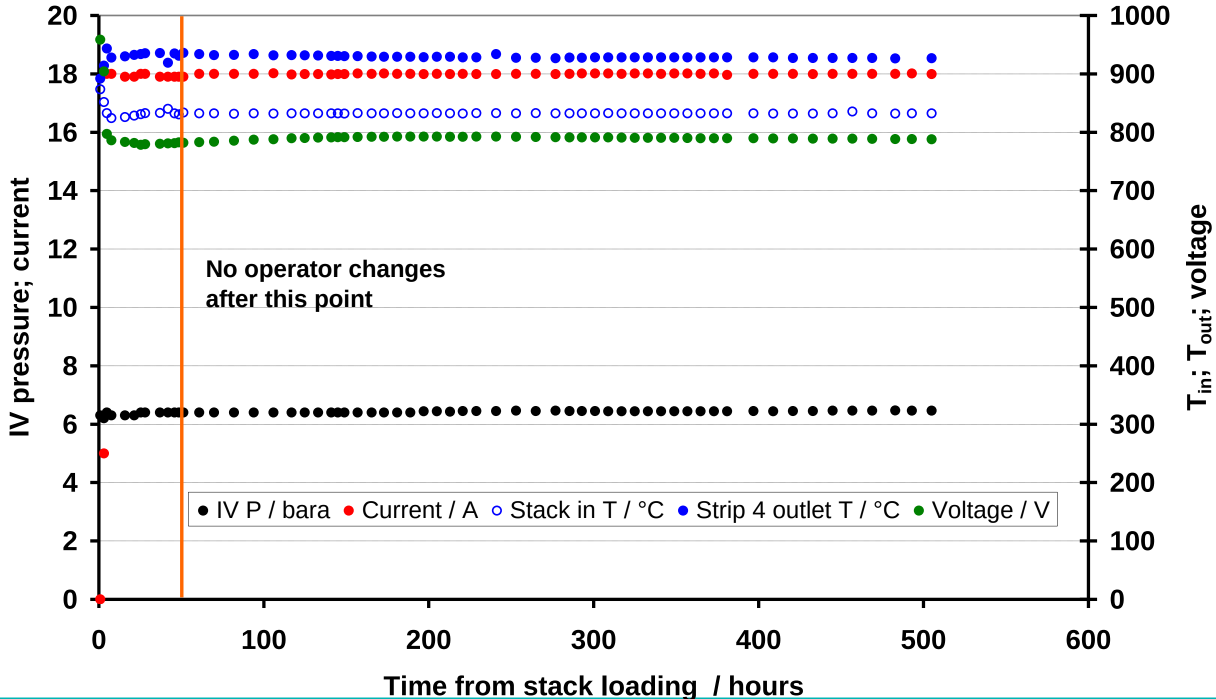
- **Generator Module (GM)**
  - **Exhaust gas expanded through TG**
  - **Provides heat of compression for incoming air**
  - **OGB heat transfer to air by HX**
- **Pressurized Block Rig**
  - **No TG, air compressors used**
  - TG compressor heat simulated with electric heaters upstream of main test vehicle
  - **2kW extra heat to offset greater heat loss for block vs GM (surf. area:volume)**





Schedule for Pressurized Metric Tests

- Completing manufacture of the latest technology 10 kW class metric block
- UK rig has completed recent 1000 and 500 hour block tests of pre-SECA technology that:
  - Confirmed performance expectation with new dry cycle versus original cycle with combustion products in cathode stream
  - Confirmed reliable operation of rig to be used for metric test
- Commence test in 3rd Quarter
- Timing of test influenced by substrate qualification cycle
  - Conservative path taken for substrate selection for strip build
- Additional metric testing through Sept 2012 (~20 kW)



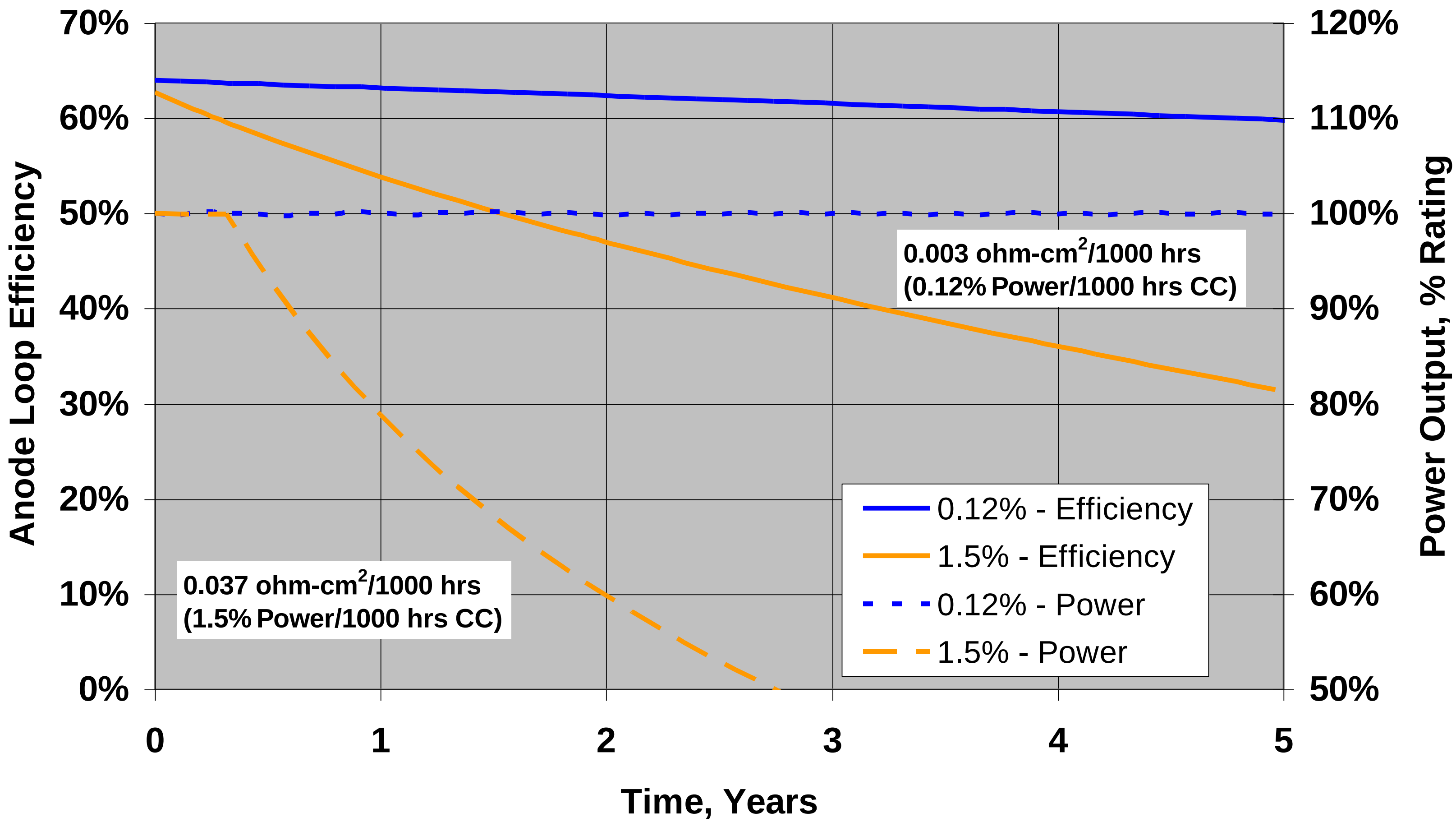
Rolls-Royce data

Outline

- RRFCS SECA Program and IP-SOFC Technology
- IGFC Systems Analysis
- Block-scale Test Rigs
- IP-SOFC Durability
- IP-SOFC Optimization

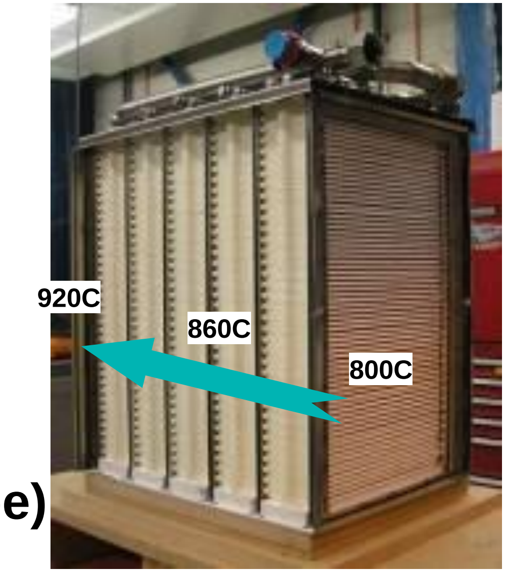
Degradation and Life in Operation

- Degrade efficiency to meet constant power



Durability Testing Program

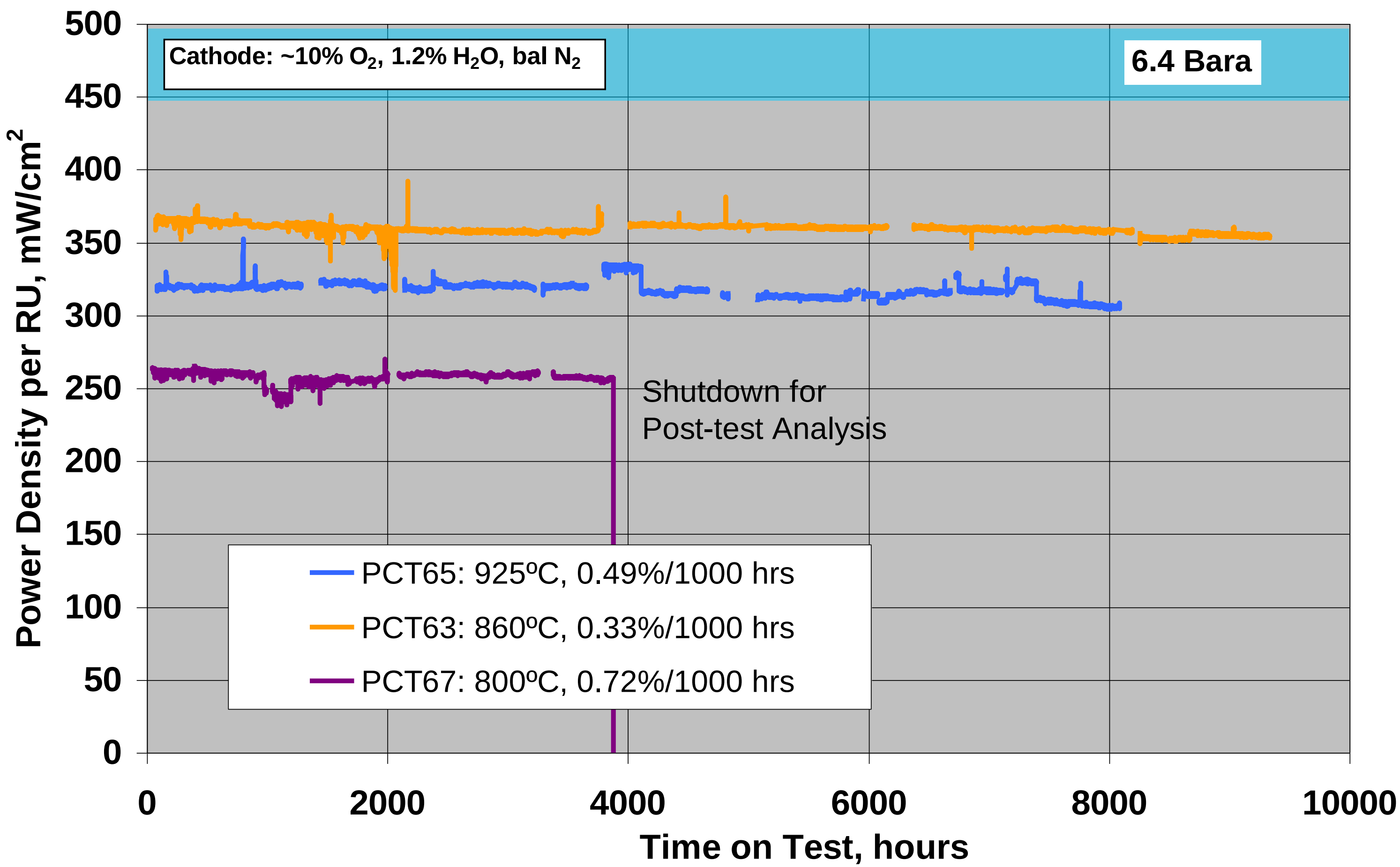
- Map long-term performance over operating envelope
  - Anode Inlet: 67% flammables, 25% H_2O
  - Anode Outlet: 25% flammables, 50% H_2O
  - Cathode Inlet: 800ºC, 12% O_2
  - Cathode Outlet: 920ºC, 10% O_2 (extreme envelope)



- 5-cell Scale Tests
  - Full system conditions
  - Minimum 2000 hours
  - Current longest test ~ 9500 hrs
- Pressurized Bundle Tests
  - Complete anode flow path
  - Single cathode strip condition

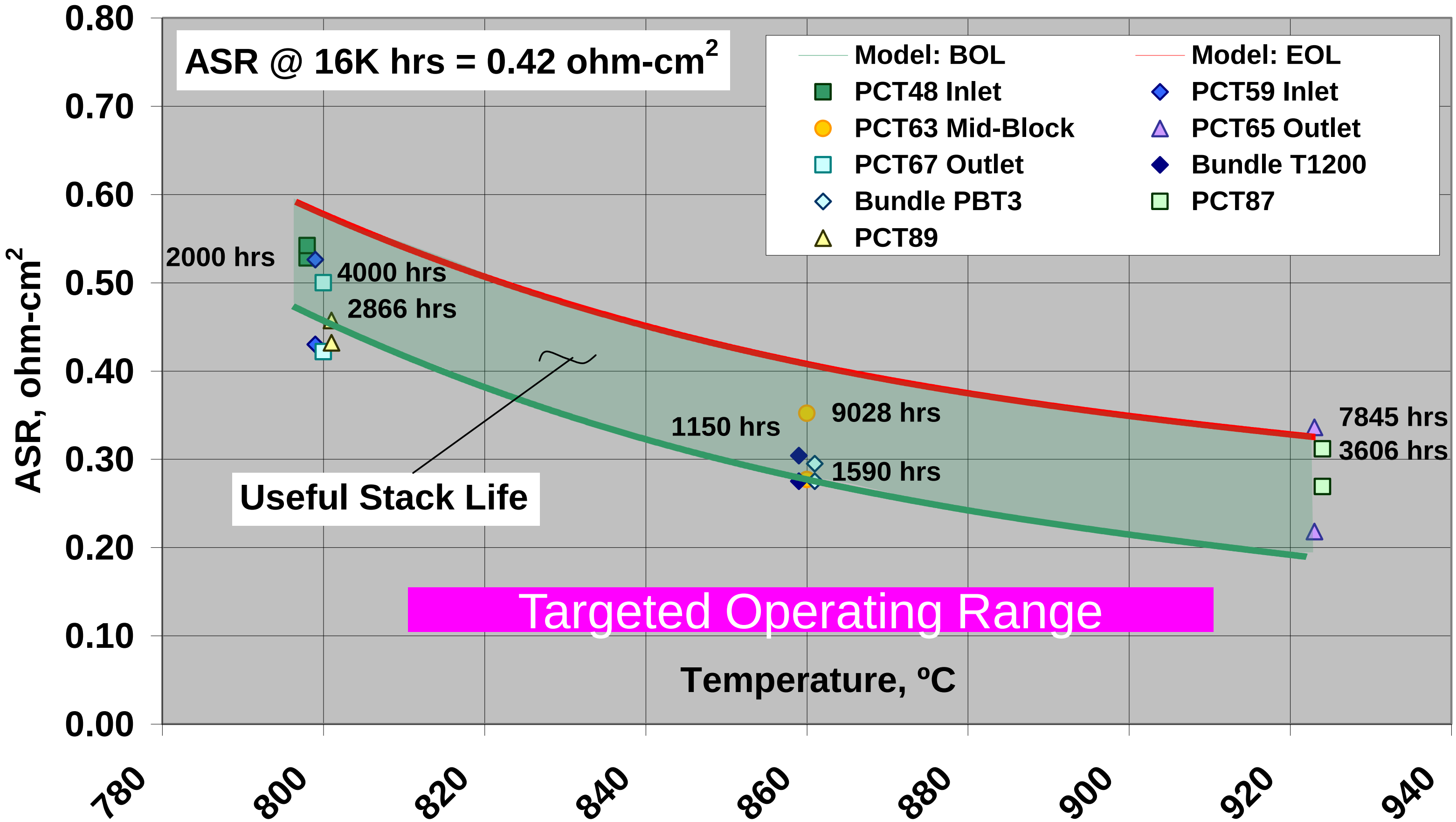
5-cell Power Durability Trends

- **Current IP-SOFC technology meets SECA Phase 1 degradation targets**



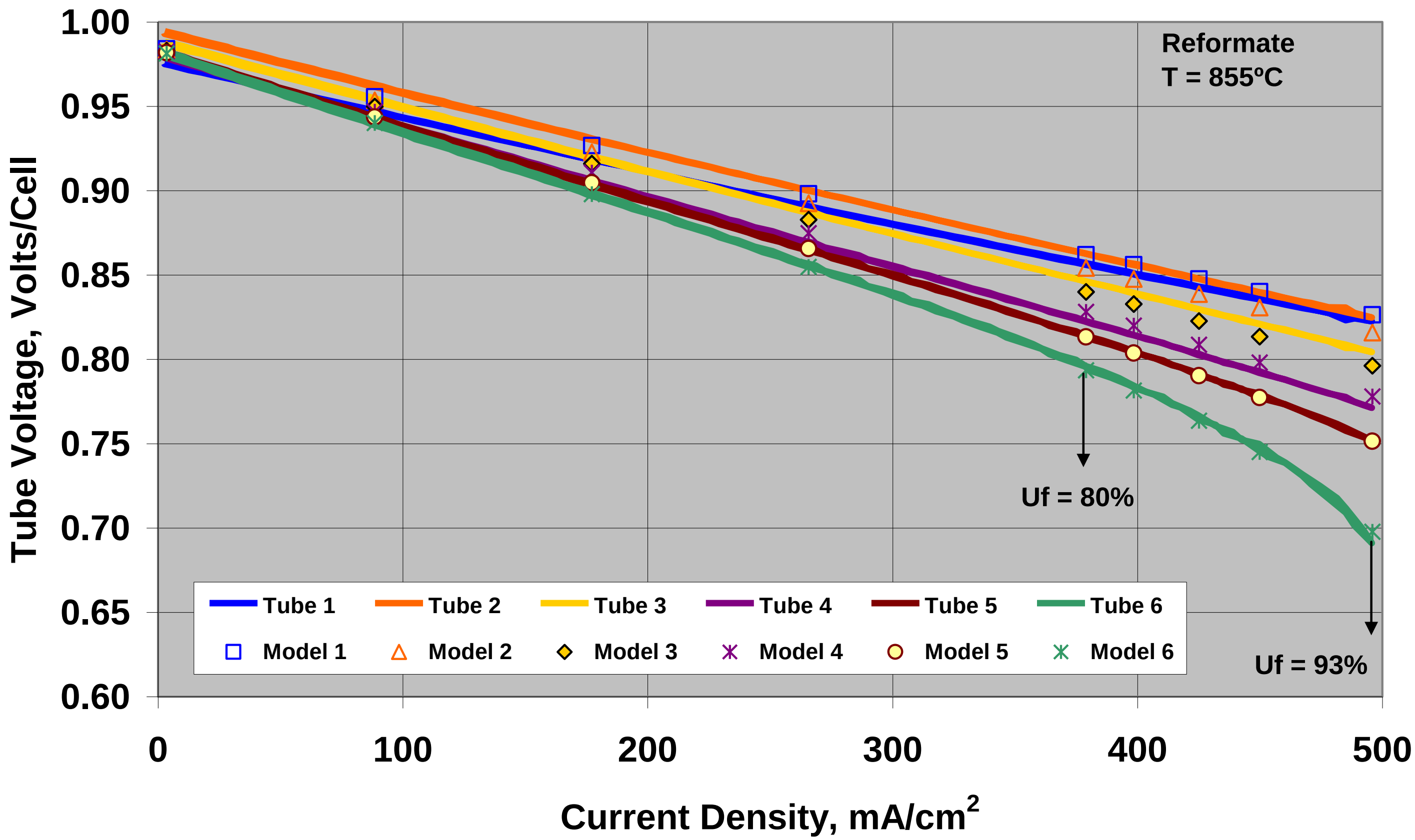
Durability Data Summary

- **Current IP-SOFC technology is projected to meet power and efficiency targets over a 2-year service life**



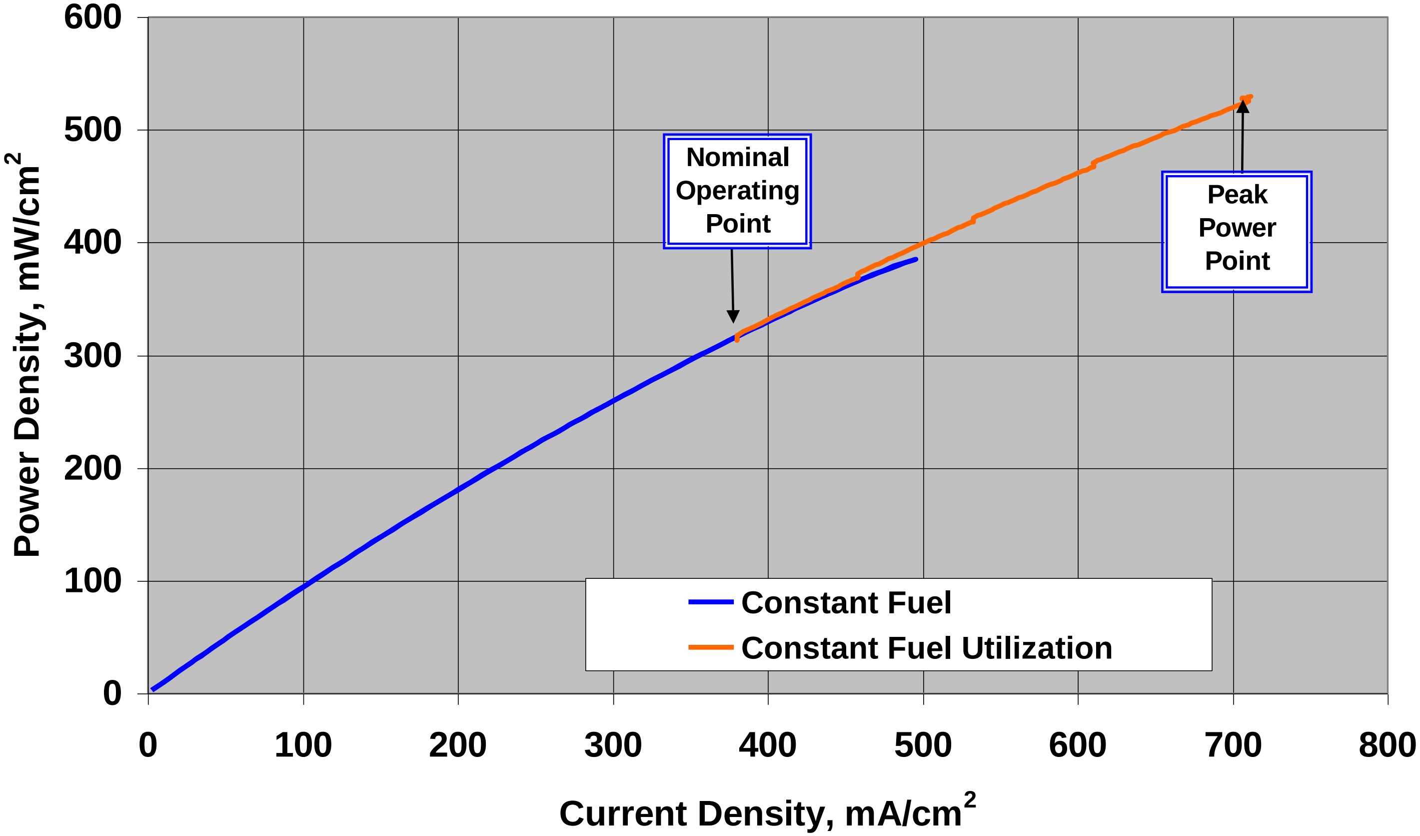
Bundle Scale Performance

- **Bundle performance matches models based on subscale performance**
  - **Bundle and subscale: 0.28 ohm-cm^2 at block average temperature**
- **Performance to > 90% U_F (system) behaves as predicted**



Bundle Peak Power Consistent with Cost Model

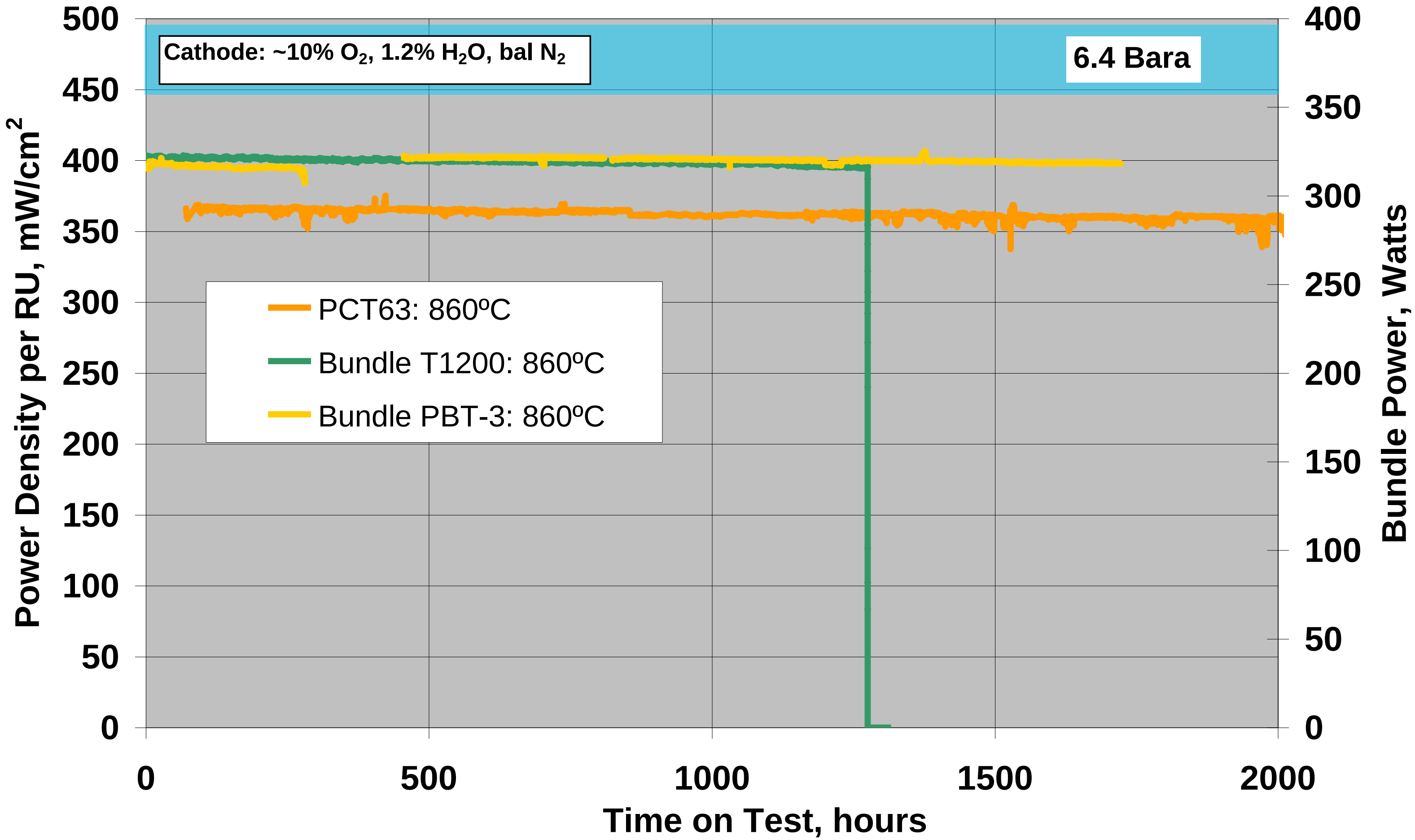
- **Achieved at 75% U_F and 0.75 volts/cell**



Rolls-Royce data

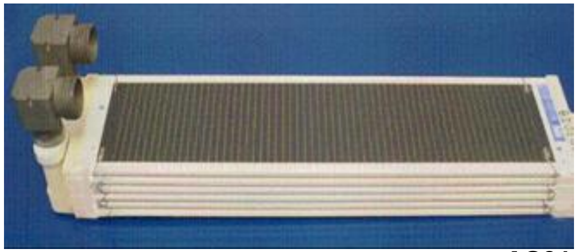
Bundle vs 5-cell Durability Comparison

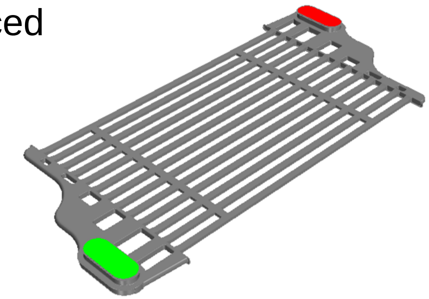
- **Bundle tests (360 cells per bundle) show similar durability trends as 5-cell test (PCT63) at same conditions**

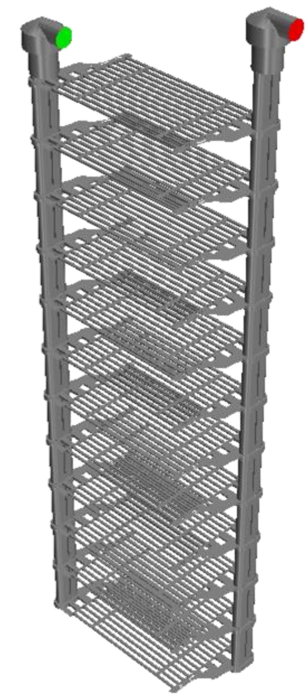


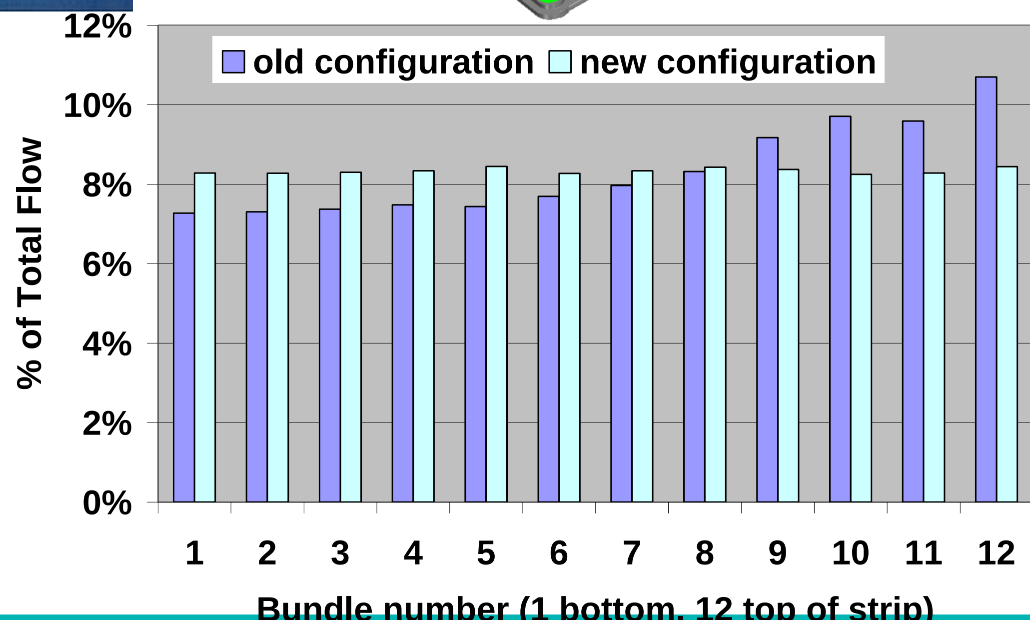
Optimization of bundle-to-bundle fuel distribution

- Bundle geometry simplified to achieve equal pressure drop then stacked into a strip. This results in a simpler and quicker CFD model.
- Redesigned strips achieve improved bundle-to-bundle fuel distribution
- Block-to-block fuel flows are also well balanced





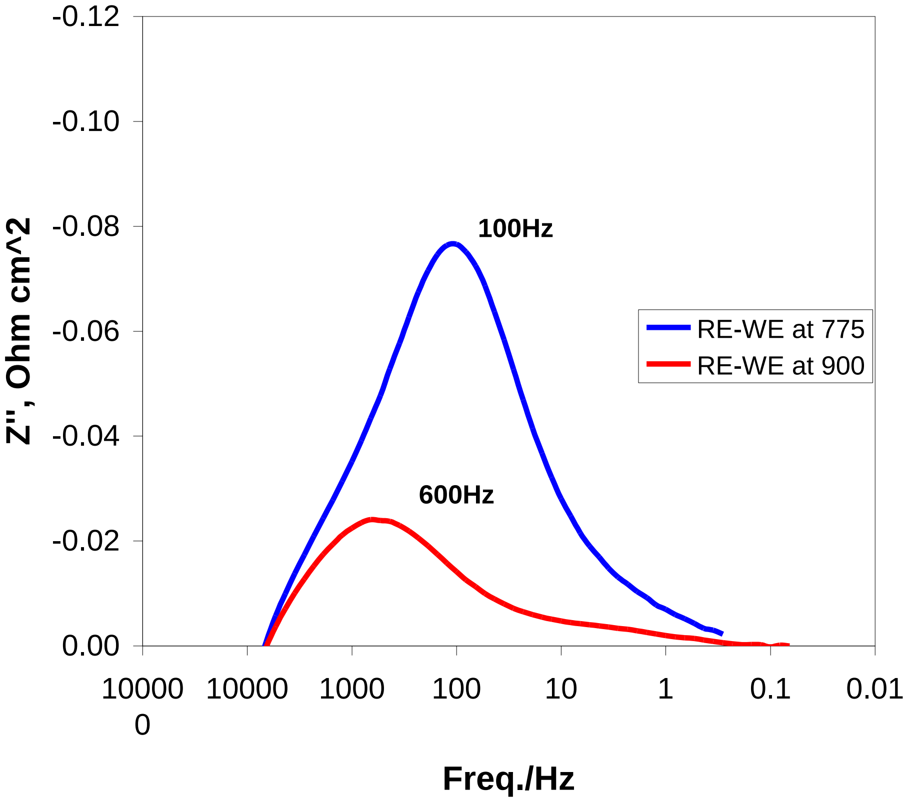


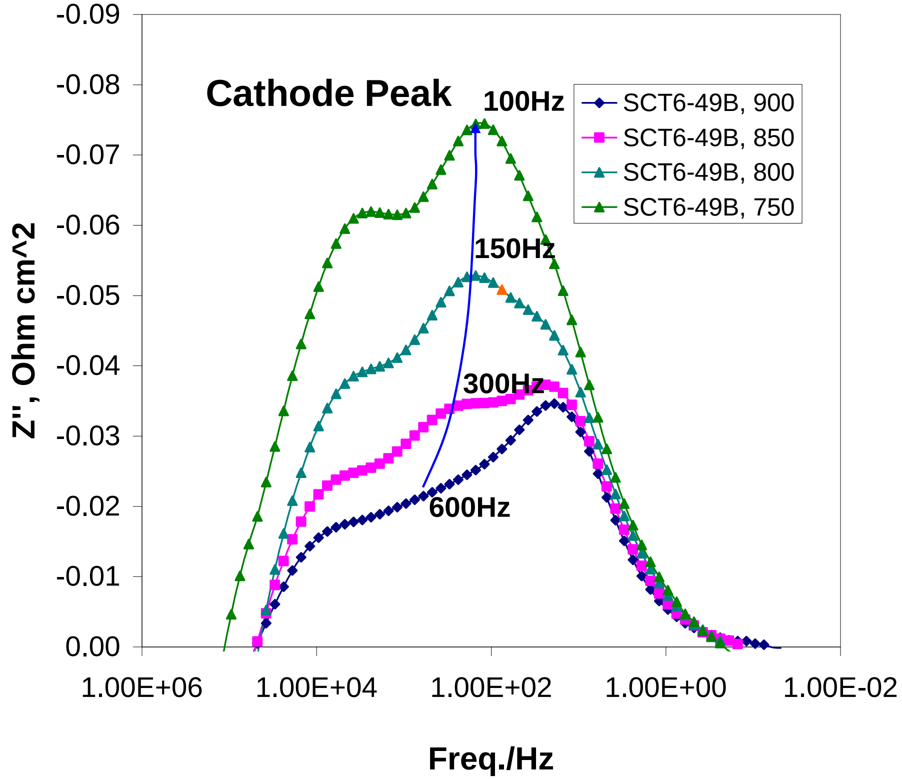


Outline

- RRFCS SECA Program and IP-SOFC Technology
- IGFC Systems Analysis
- Block-scale Test Rigs
- IP-SOFC Durability
- IP-SOFC Optimization
  - Understand Sources of Degradation
  - Active Layers Improvement

Using Impedance Analysis to Track Degradation Sources



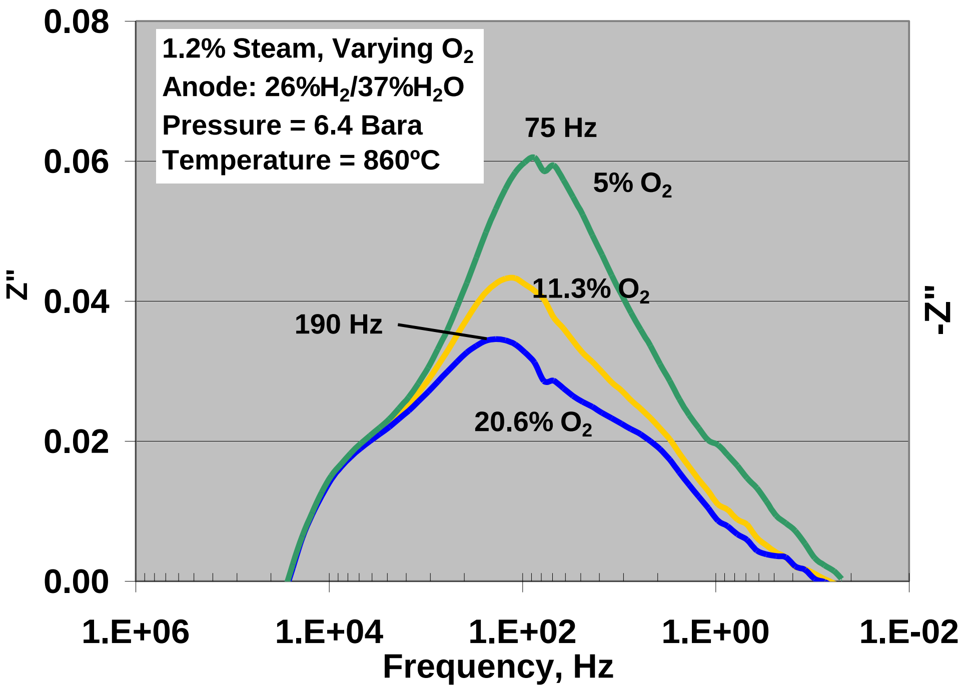


Referenced cathode symmetric cell test

Regular fuel cell with LSM cathode

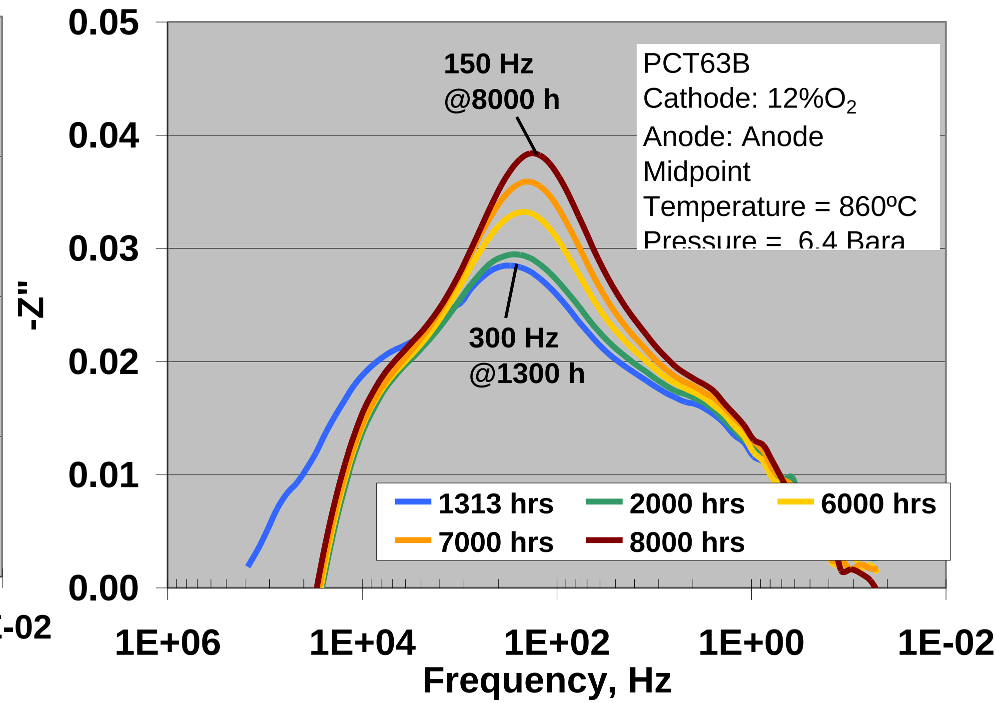
Cathodic Peak Changes with Time

- **Primary degradation mechanism appearing to be associated with the cathode at 860ºC**



Parametric cathode testing

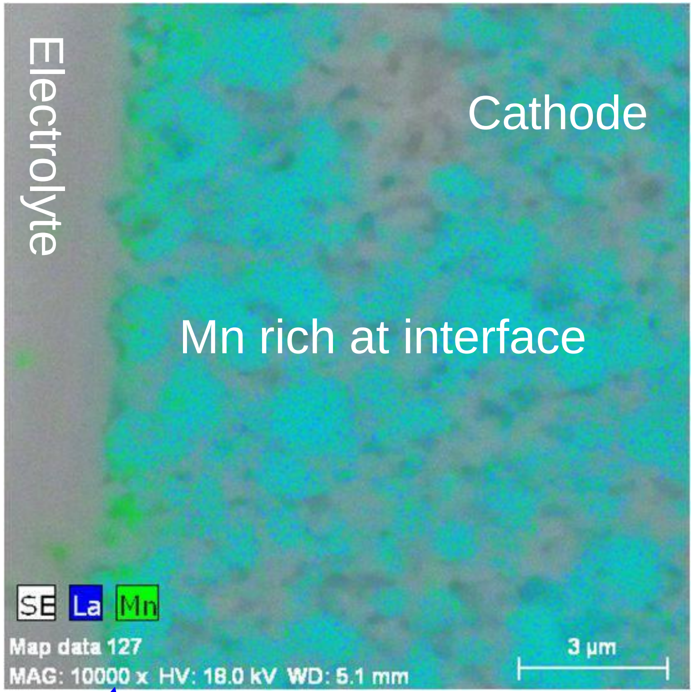
- **EIS to verify cathode processes**



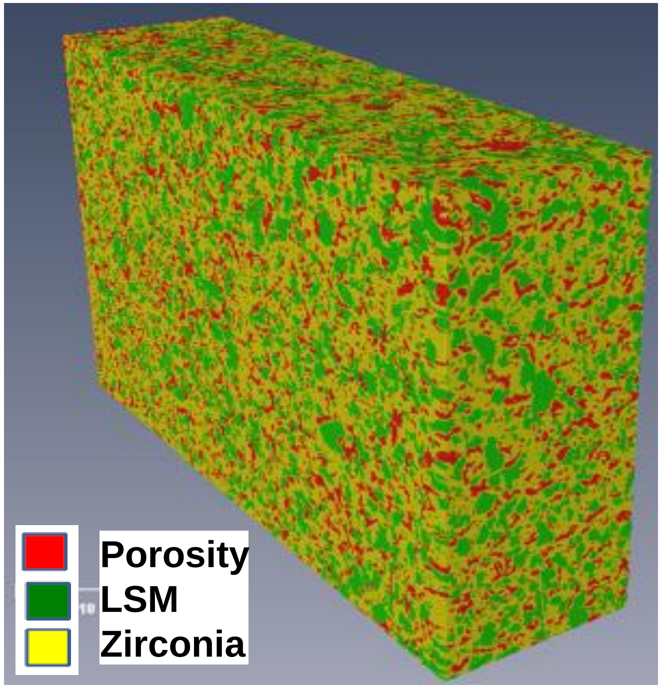
EIS data versus time

Cathode Analysis after Long-Term Testing

- **Mn-rich at cathode/electrolyte interface**
- **3D reconstruction in process. Preliminary results may indicate possible microstructure change (CWRU)**



860°C for 8000 hrs

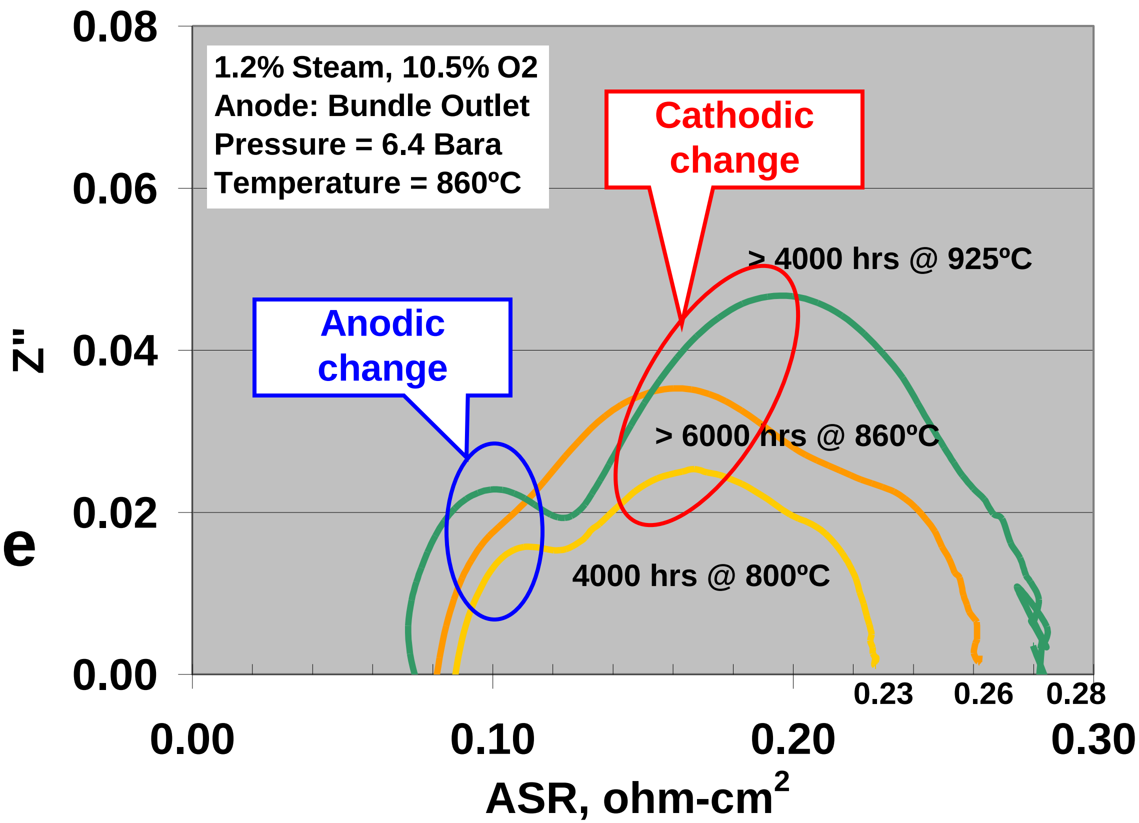


Cathode pillar by CWRU

Degradation Increases with Temperature

Tests run at different conditions (800ºC, 860ºC, 925ºC), but taken to identical conditions for EIS comparison

- **Degradation rate greater at higher temperatures**
- **Increases in both anodic and cathodic peaks**
- **Cathodic peak change is dominant**

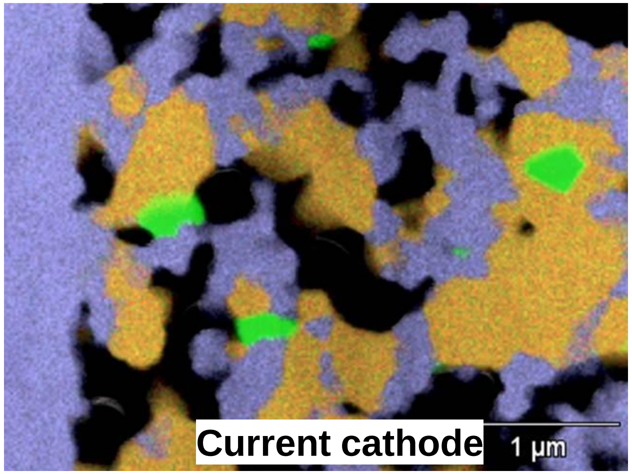


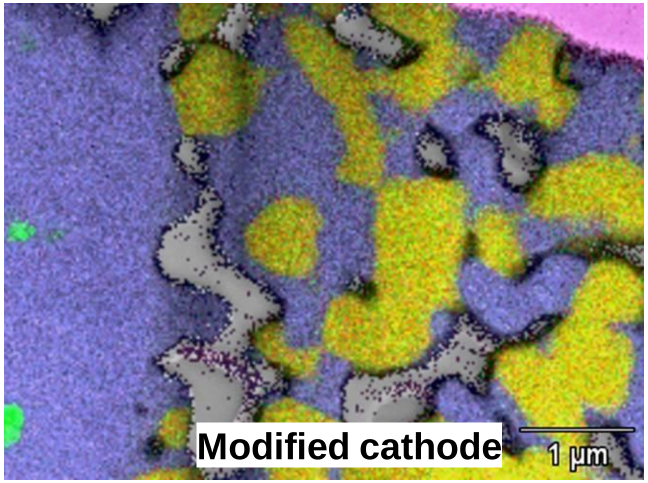
Outline

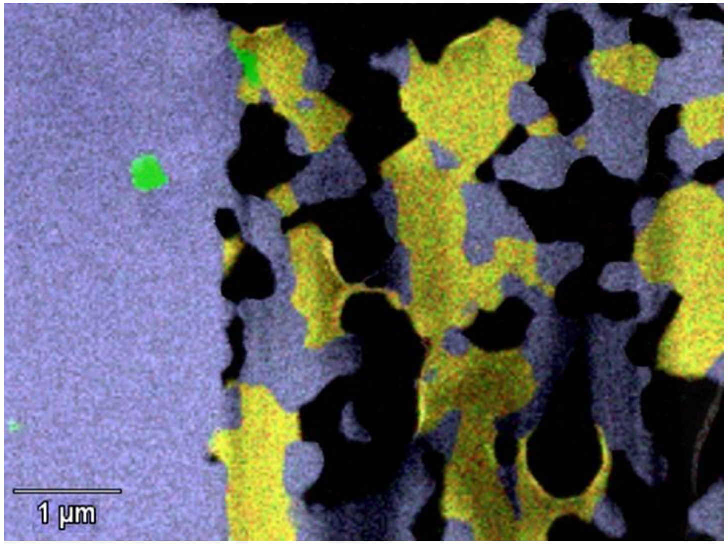
- RRFCS SECA Program and IP-SOFC Technology
- IGFC Systems Analysis
- Block-scale Test Rigs
- IP-SOFC Durability
- IP-SOFC Optimization
  - Understand Sources of Degradation
  - Active Layers Improvement

Modification of LSM-Based Cathode

- Modification to the cathode composition has resulted in less free MnOx
- Minor MnOx observed at interface upon testing



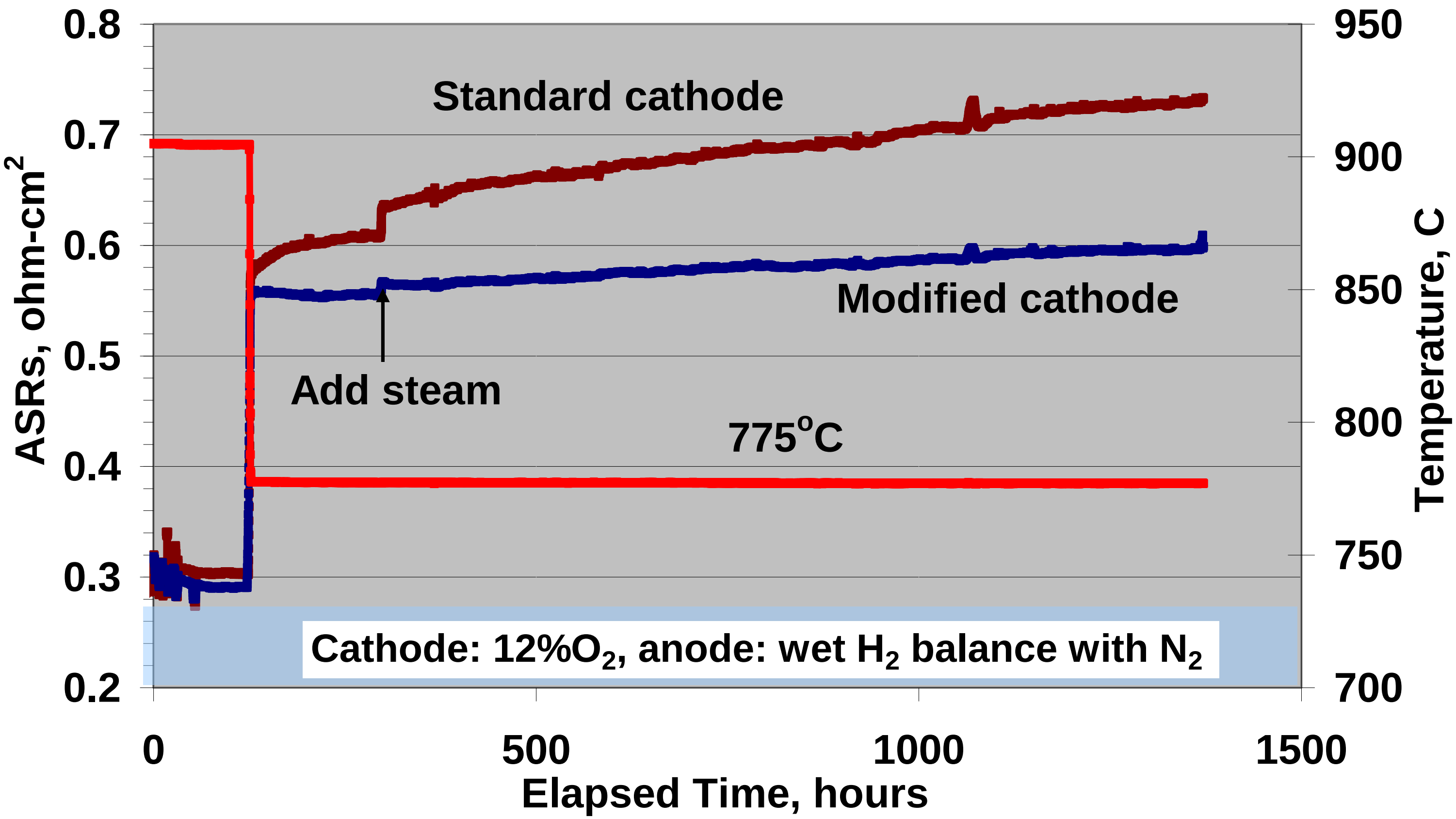




Modified cathode: 925°C for 2000 hrs

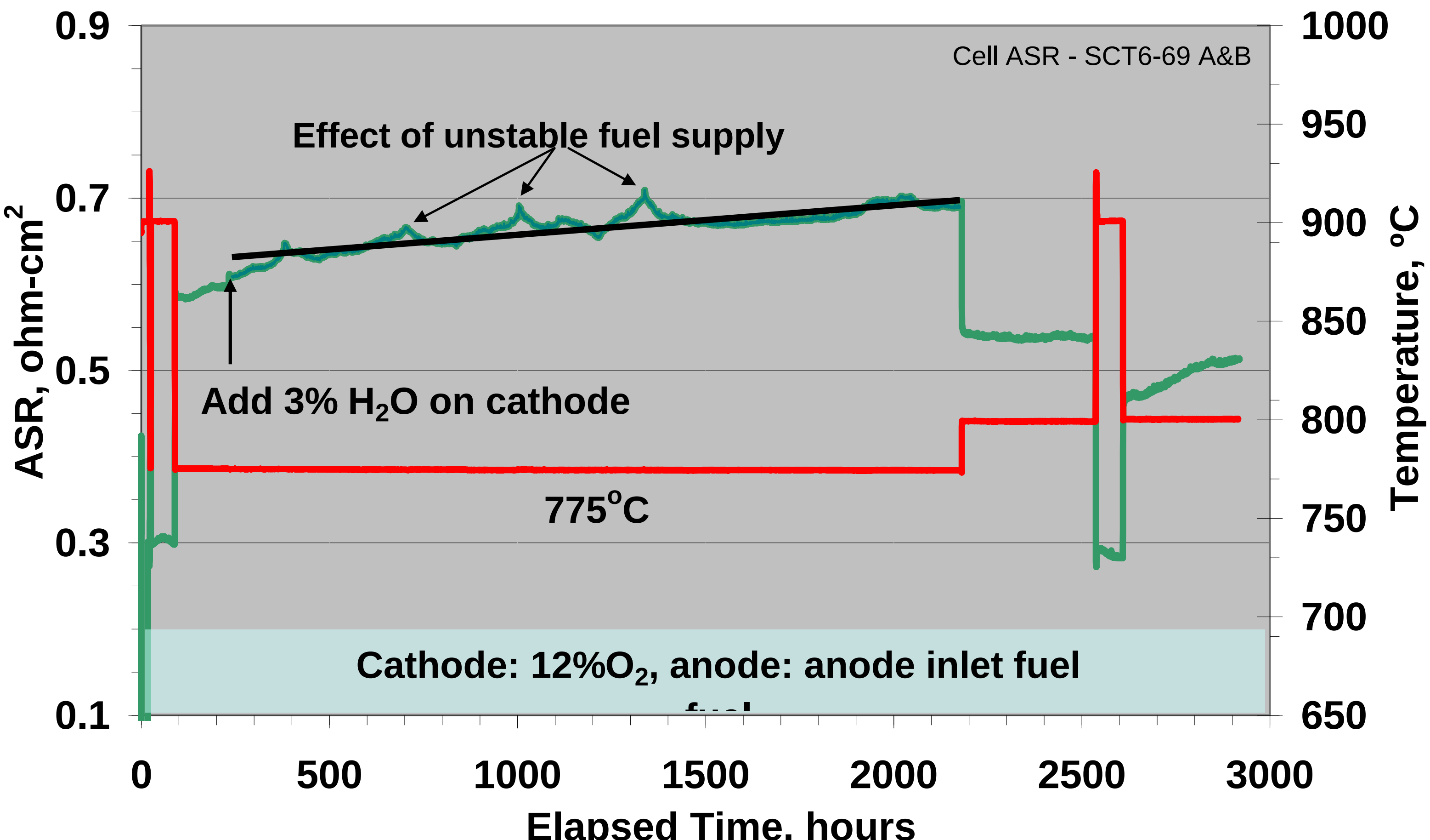
Durability of Modified LSM-based Cathode

- RRFCS has observed an initial degradation when testing in moist (3%) air, accentuated at low temperatures (<800C)
- Improvement shown for a modified LSM-based cathode
- Long term degradation at high temperature is under evaluation



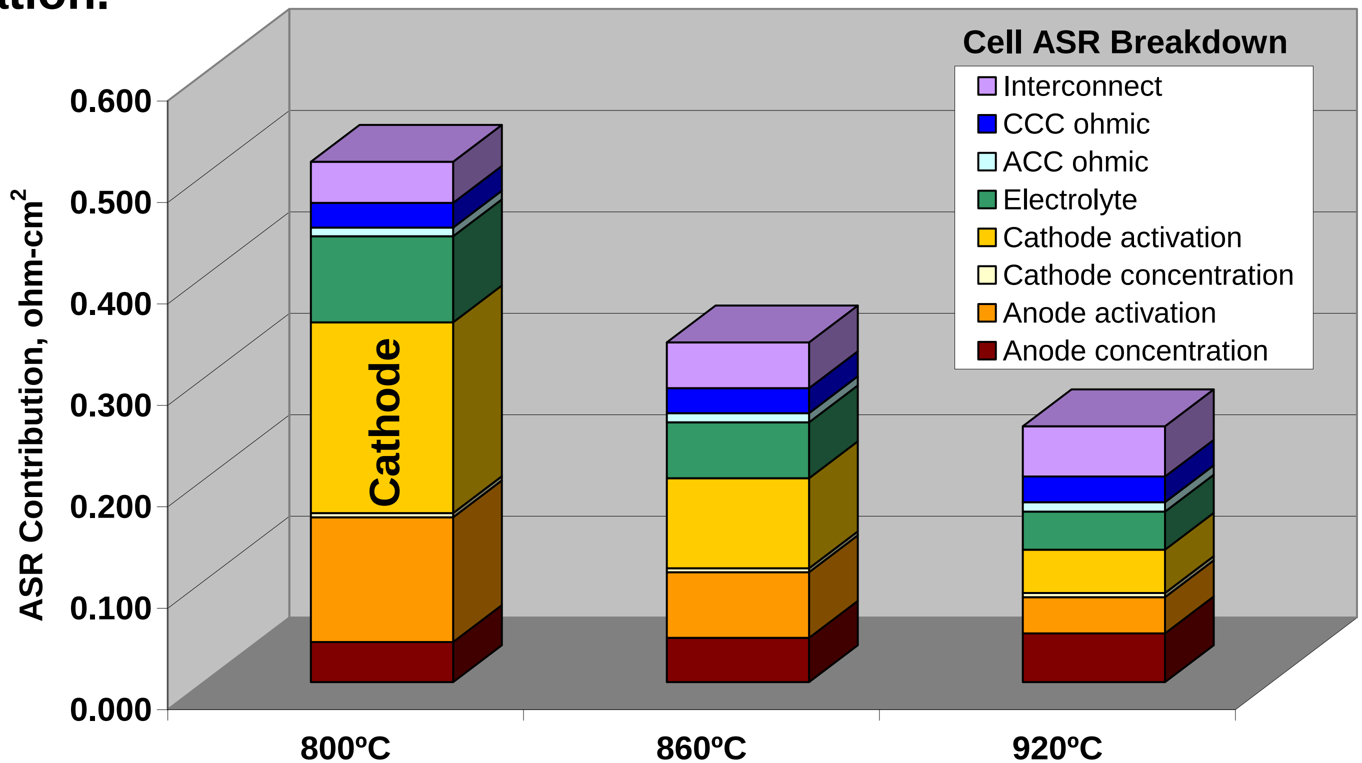
Reversibility of Moisture-Induced Degradation May be a Clue to Origin

- **ASR change at low temperature is reversible at high temperatures**



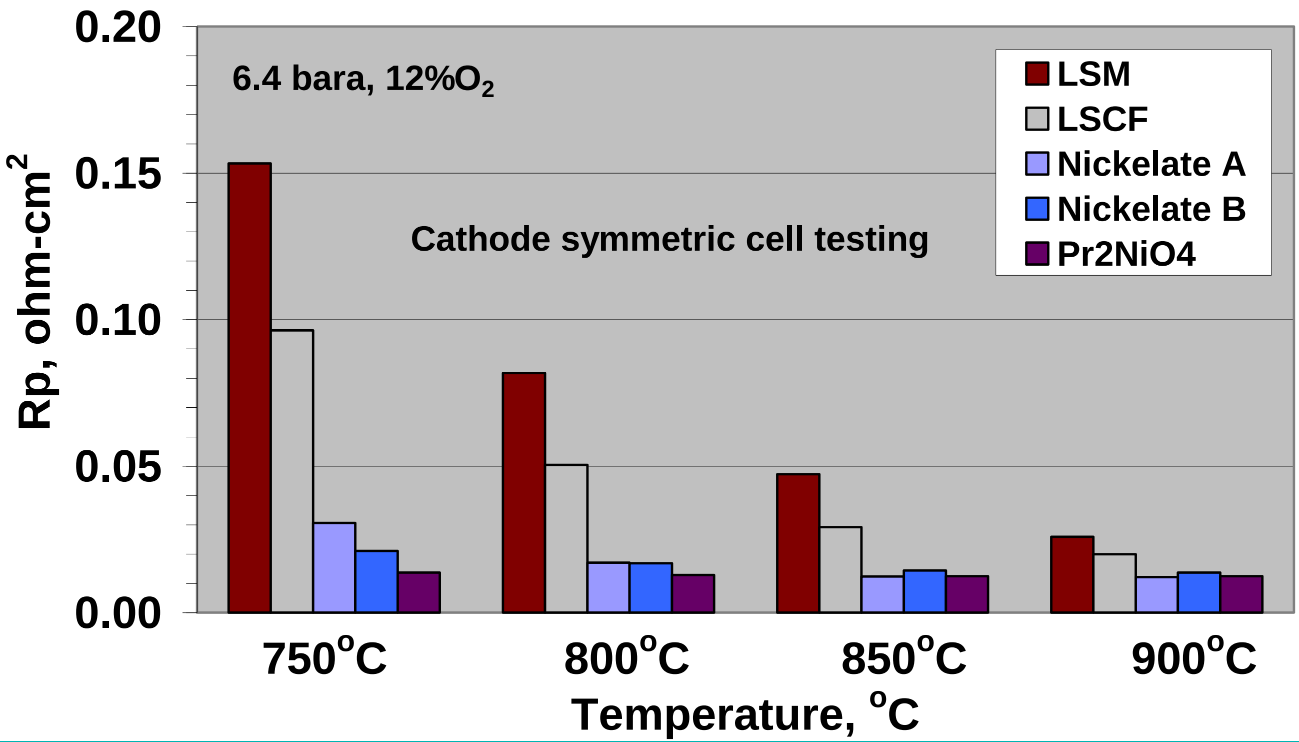
Cell ASR Breakdown

- Full instrumentation to separate ASRs from different components
- EIS plus RC circuit fitting to separate cathode and anode
- Cathode dominates ASR at low temperature
- Cathode development to achieve lower ASR and lower temperature operation.



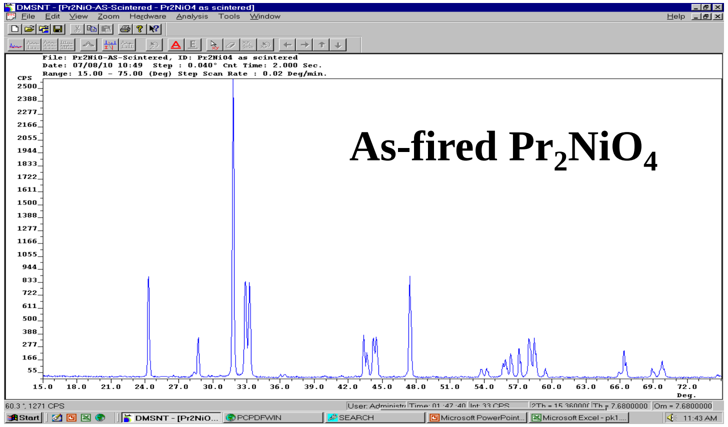
Alternate Cathode for Lower-ASR

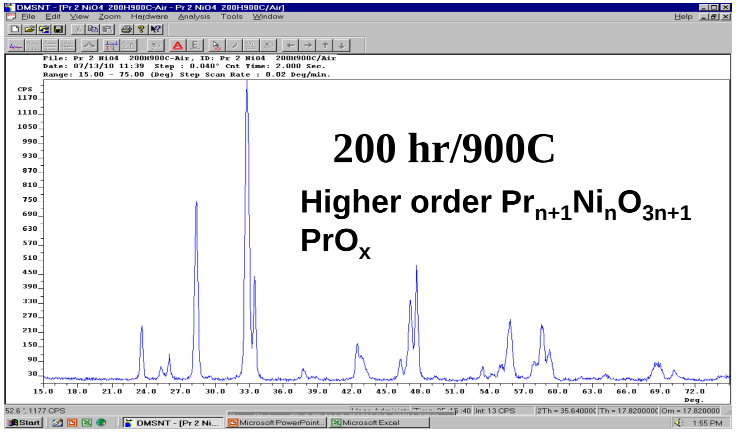
- Lower overall cell ASR can allow reduced stack operation for improved durability and/or improved efficiency or cost
- LSCF, a well-accepted cathode, has CTE mismatch with RRFCS substrate
- Ruddlesden-Popper nickelate cathodes are under evaluation ($Ln_{n+1}Ni_nO_{3n+1}$)
  - Nickelates, with lower E_a , can significantly reduce cathode ASR, especially at lower operation temperatures.
  - This is a long term development activity



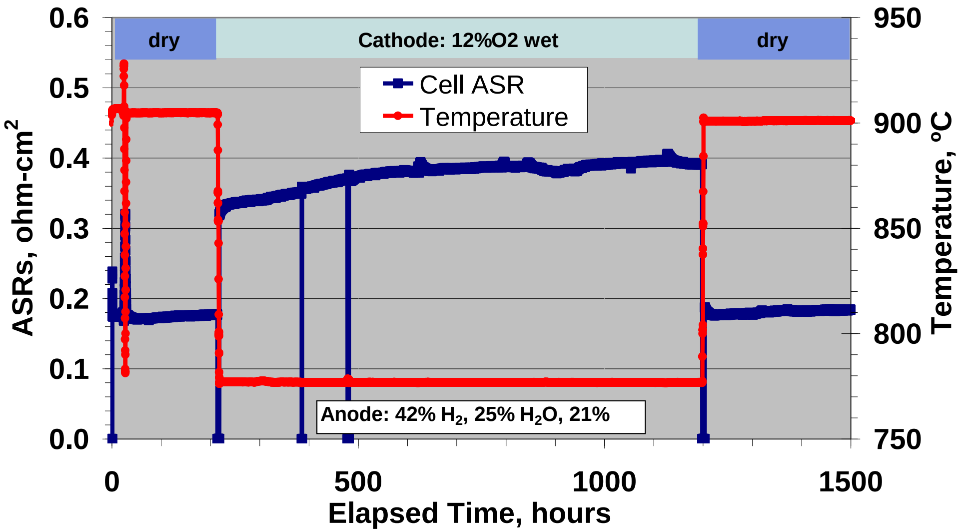
Initial Evaluation of Pr_2NiO_4

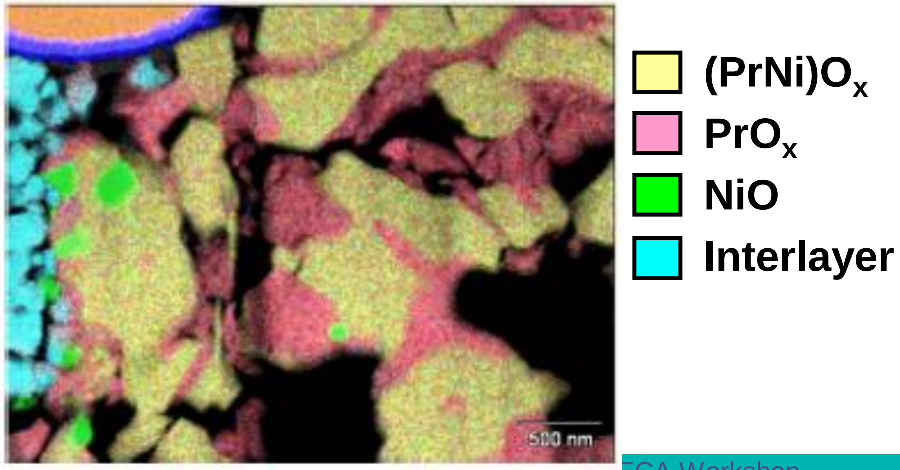
- **Shows phase instability under testing conditions**





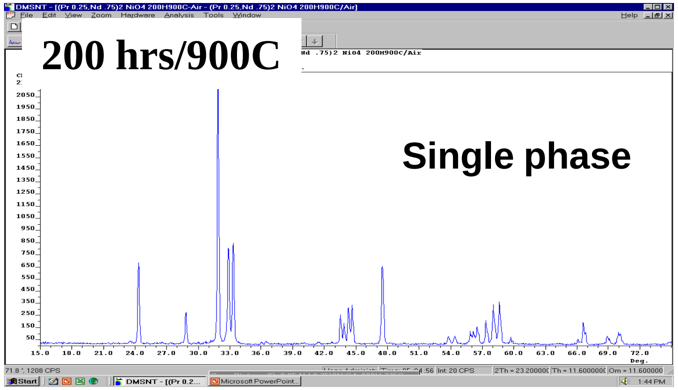
Pr_2NiO_4 is unstable



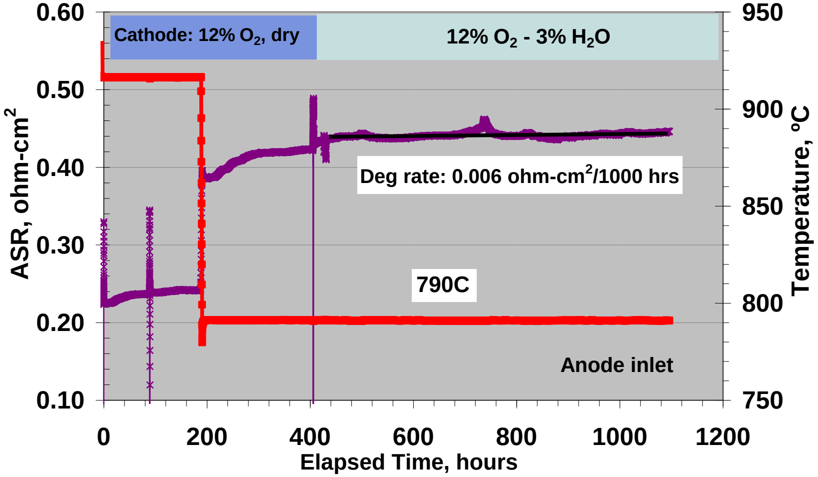


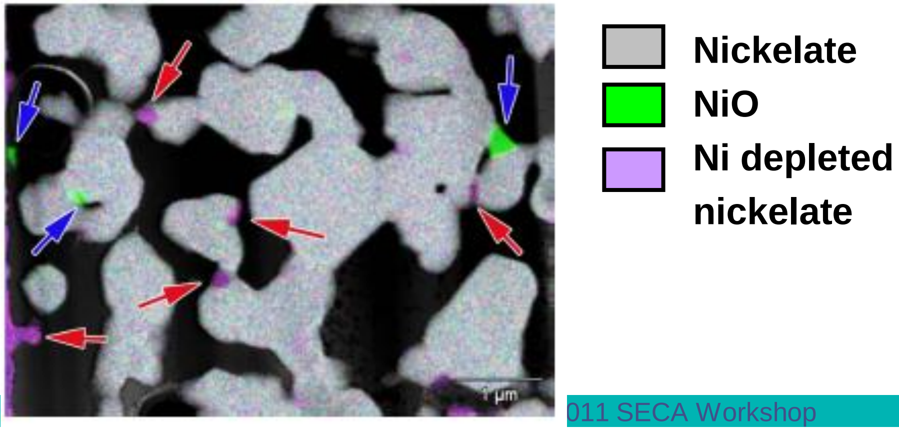
Improved Nickelate Cathodes Show Less Decomposition

- XRD did not identify phase decomposition after short term aging
- TEM shows only minor decomposed phase, further optimization underway



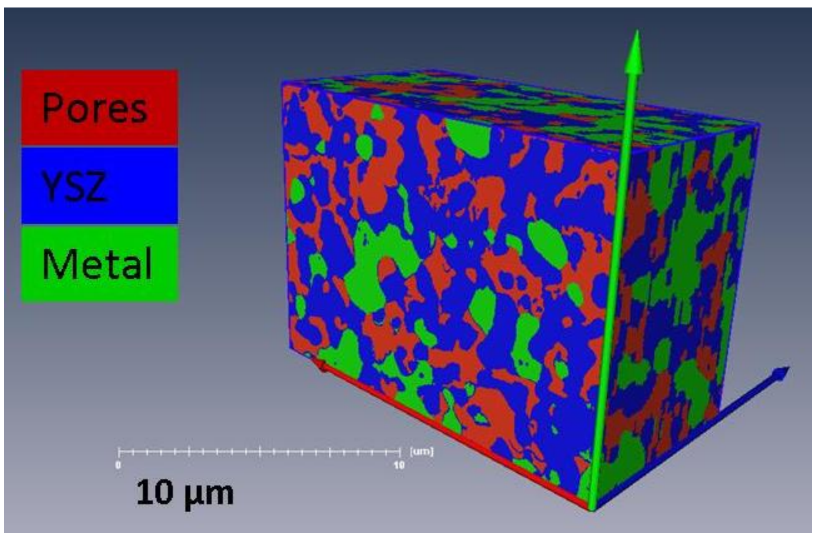
Improved nickelate is more stable



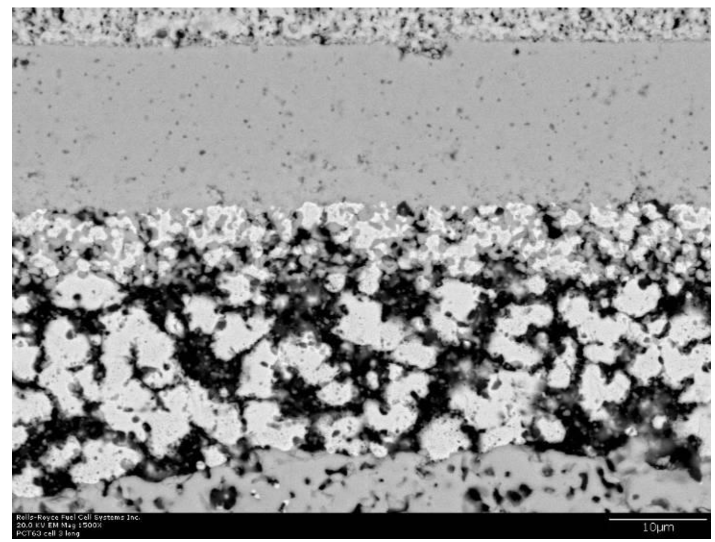


Anode Degradation Mechanisms Identified

- **Noticeable microstructure change after testing, especially at higher temperature, limited impact on performance to 9000 hours**
- **Early evidence of materials migration**
- **Peak block temperature and fuel utilization conditions pose greatest risk to anode long-term durability**
- **Developing even more stable anode side materials for 5-year service life**



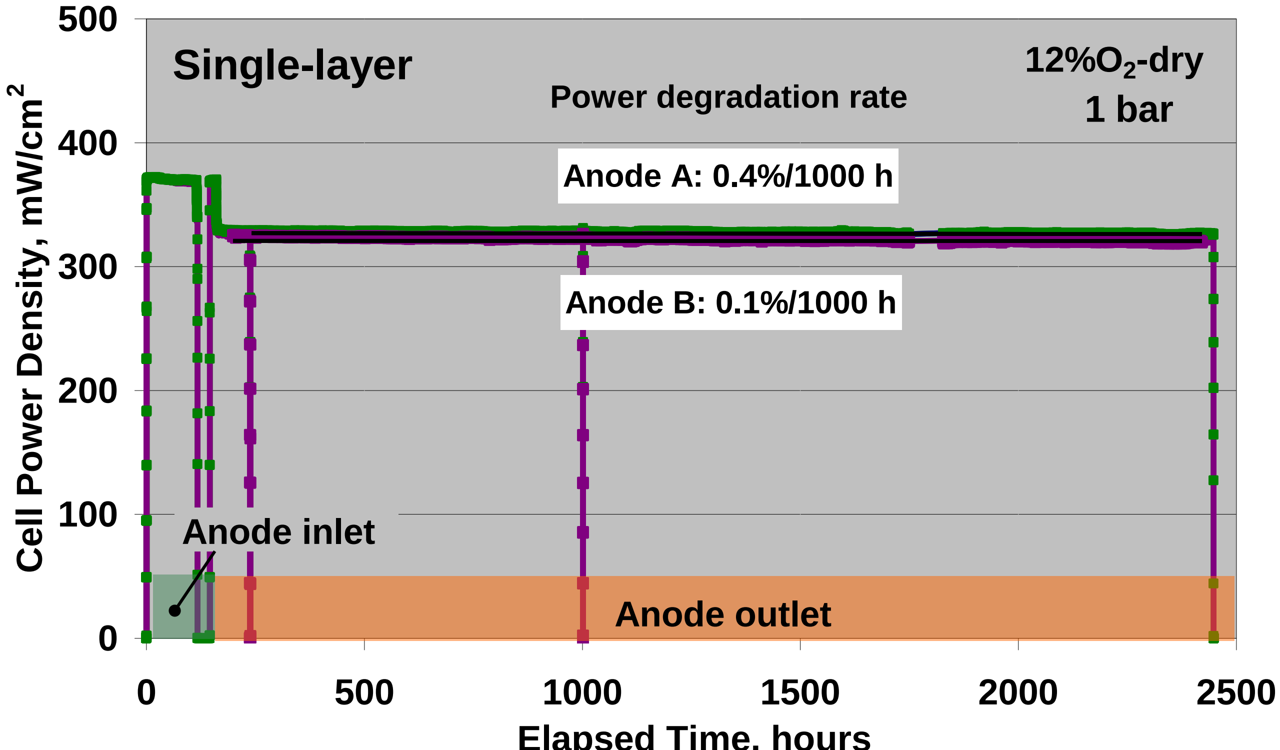
Anode 3D reconstruction by CWRU under separate program



Microstructure state after 8000 hours (860^{o}C, anode midpoint)

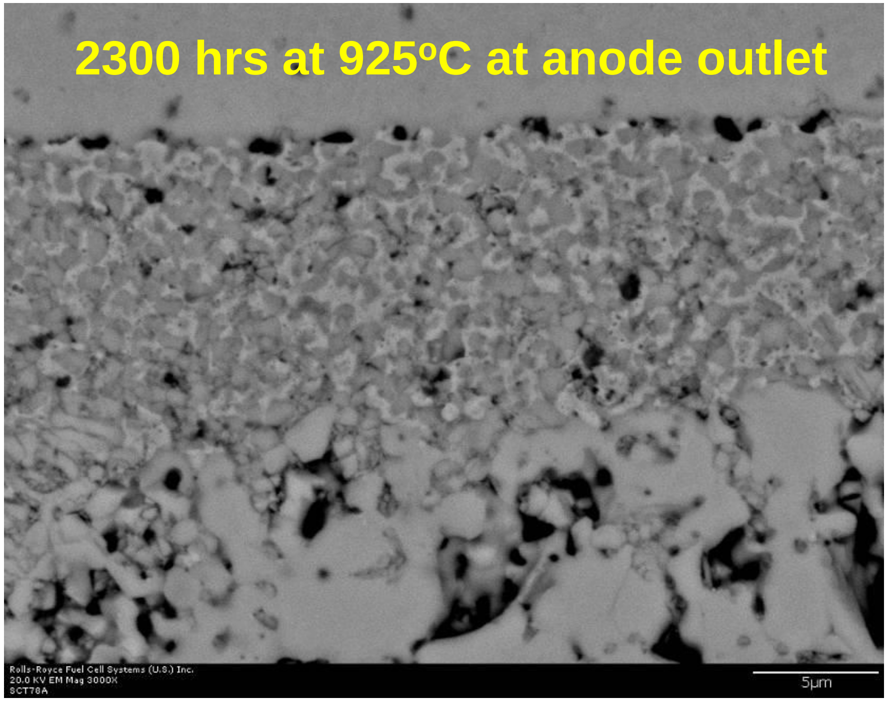
Anode Optimization for 5-year Service

- More stable microstructure
- Maintain reliability: interfacial strength/cell adhesion to substrate
- Promising initial results for screening under aggressive system conditions (925°C, low flammables)



Microstructure of Single Layer Anode Tested at Aggressive System Conditions

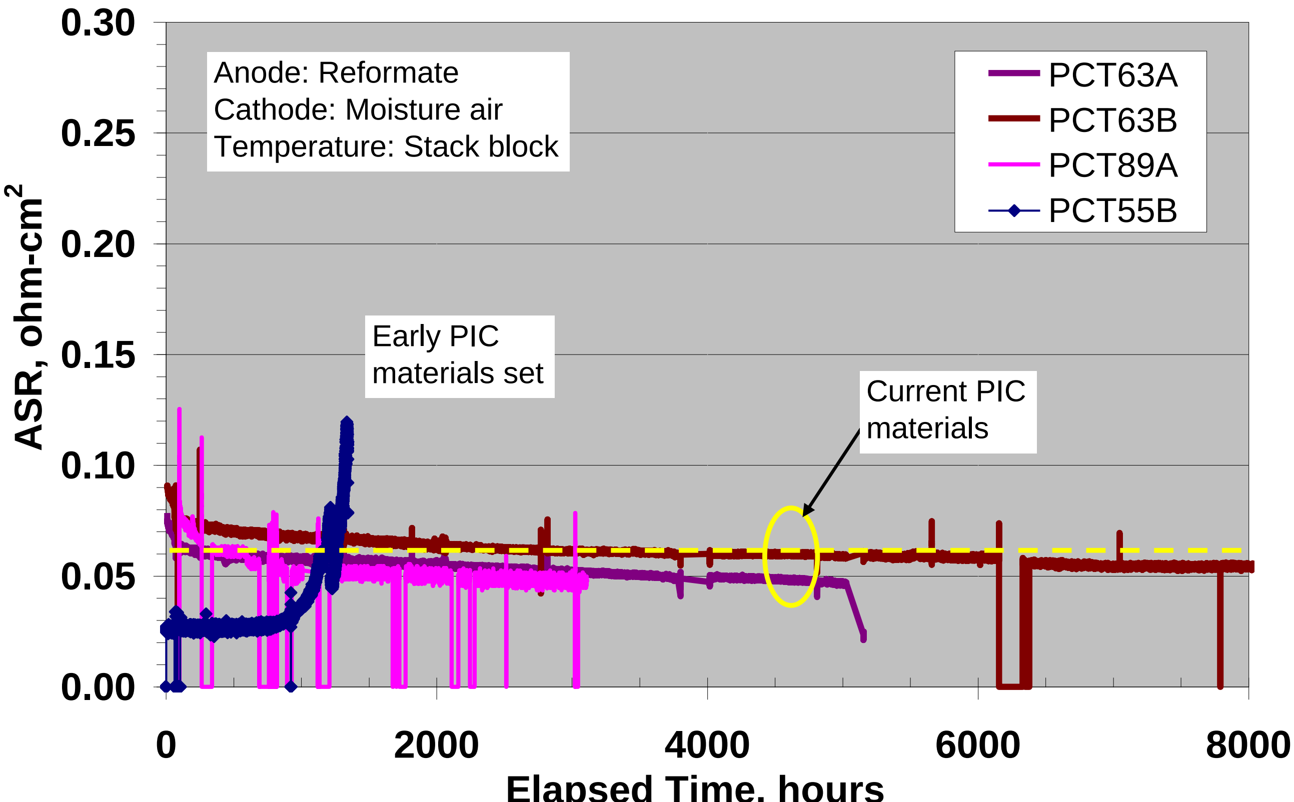
- **Single layer performs as anode and in-plane current collector, engineered conductance**
- **Candidates show stable uniform microstructures**
- **Improved interfacial, cell attachment characteristics**



Uniform microstructure after testing under aggressive system conditions

Durability of the Primary, cell-to-cell, Interconnect (PIC)

- Mitigated a major degradation mechanism in 2010, further validation in 2011
- Interconnect shows no degradation trend in 8000 hrs required for SECA metric test

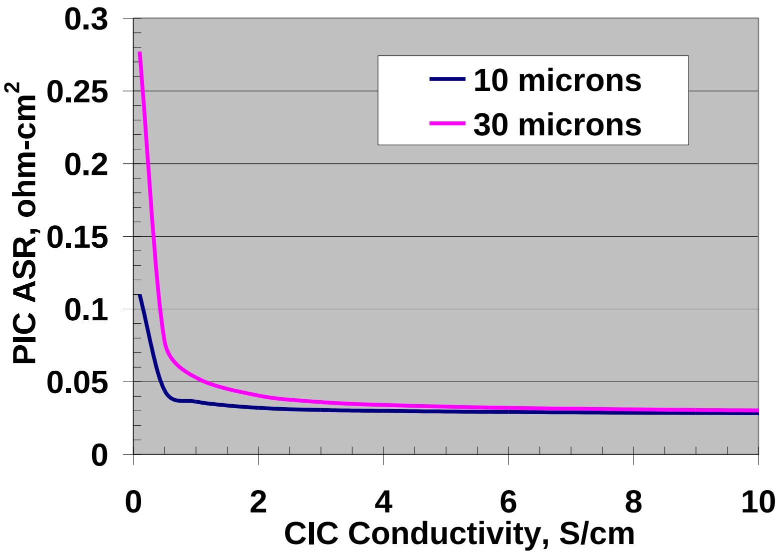


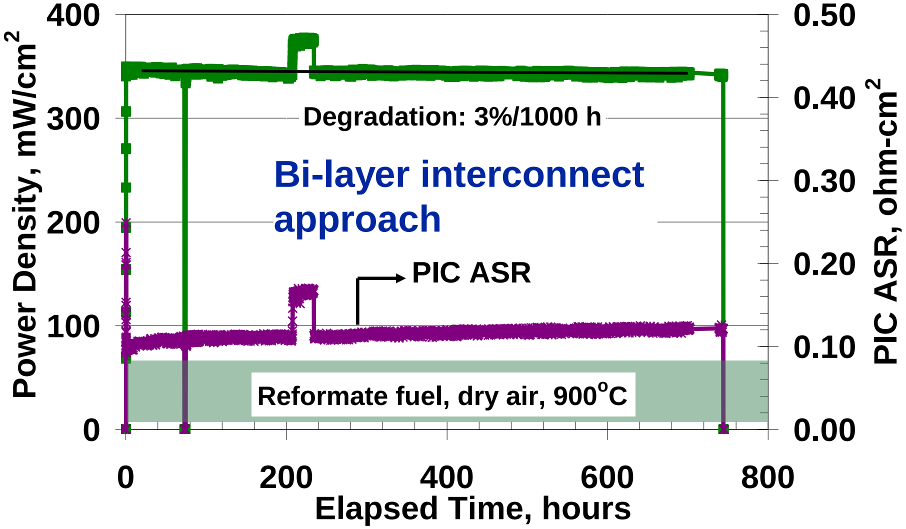
Ceramic Interconnect: Long Term Objective

- **Modeling Results:**
  - **Low conductivity requirement**
  - **Many material options**
- **Materials and design:**
  - **Single chromite layer**
  - **Bilayer structure*: p-type conductor on air side, n-type conductor on fuel side**

*Srikanth Gopalan:
- Solid State Ionics 177 (2006) 347-350

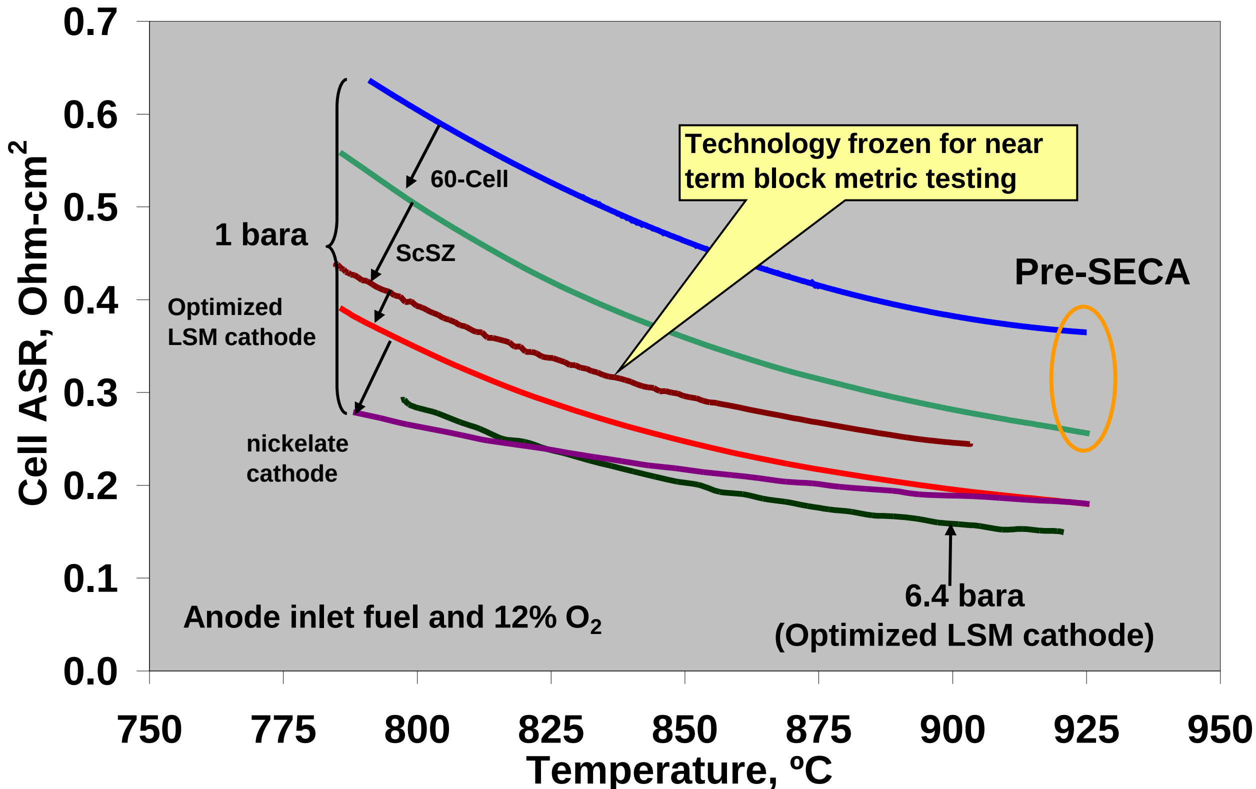
- **Challenge: achieve gas-tight under constrained sintering conditions**
- **Collaborating with Core Technology team PNNL**





Historical Cell Development Trend

- Single cell performance data for anode inlet fuel composition
- Factor of 2 improvement in ASR from pre-SECA
- Pressurized operation ASR benefit is ~0.05 ohm-cm^2



Conclusions

- Durability testing of IP-SOFC technology to >9000 hours exhibits average degradation rates <0.5%/1000 hours
- RRFCS hierarchic design shows scaling from subscale to full-scale bundle test articles
  - Similar performance expected at block-scale
- Current cell technology is on-track for initial commercialization
  - Also meets SECA defined cost targets
- Optimized anode and cathode approaches are being screened to achieve lower degradation rates
  - RRFCS views anode durability as top challenge for efficient IGFC systems operating at high U_F
  - Modified cathodes exhibit improved low-temperature moisture tolerance
- Thermal self-sustaining block test rigs prepared for metric test to commence later this quarter

Acknowledgements

- This material is based on work supported by the Dept. of Energy National Energy Technology Laboratory under Award Number DE-FE0000303
- RRFCS project manager Patcharin Burke and the entire SECA program management team
- UK and US based RRFCS team
- RRFCS SECA partners