Update on the LGFCS SOFC Technology and SECA Program

2012 SECA Workshop, July 24, 2012

Gerry Agnew and Rich Goettler

LG Fuel Cell Systems Inc.

- A group of LG companies (Corp, Electronics, & Chemical) acquired 51% ownership of Rolls-Royce Fuel Cell Systems Inc. (June 2012)
- The business focus remains on the commercialization of a “megawatt-scale” natural gas fueled fuel cell power system for stationary power generation
- The business will have its primary activities in Canton, Ohio with continued support from the team in Derby, England and a new team of resources based in Seoul, Korea.
- The business will leverage and benefit from expertise and capabilities from both LG Group and RR Group

LG Fuel Cell Systems Inc.

- LG and R-R are investing in the next phase of the business aimed at the development and testing of an integrated-system demonstrator, then transitioning to a commercial business with products and services
- A program of work has been planned which is aimed at designing, developing, and testing a prototype system in a “string-test”
- The “string-test” fuel cell power system will…
  - be at a smaller scale than 1MW, but include a product architecture capable of ‘scaling’ to ~1MW
  - Gas in to Grid Power out
- New Co-CEO alongside Mark Fleiner:
  - Dr In Jae Chung

Outline

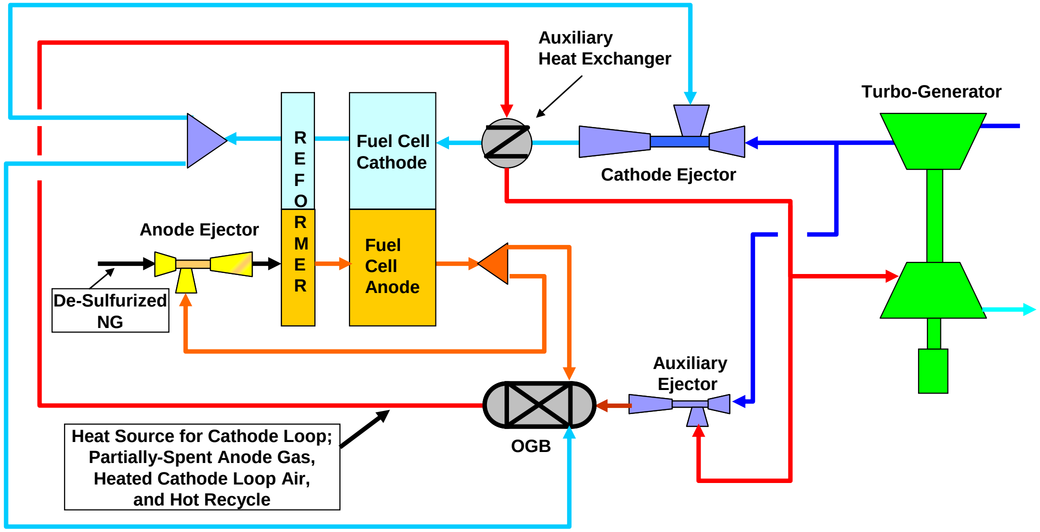
- System Relevant Block-Scale Testing
- Cell Technology Status:
    - Long-term durability
    - Degradation mechanisms and electrode optimization
- Reliability Methodology

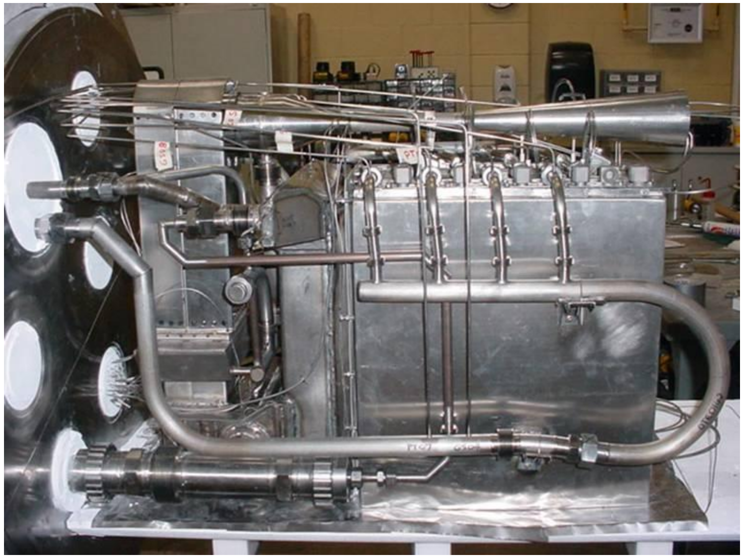
Plant Configurations Similar for NG and IGFC

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

LGFCS NG "Dry Cycle" Configuration

Same configuration for an IGFC cycle



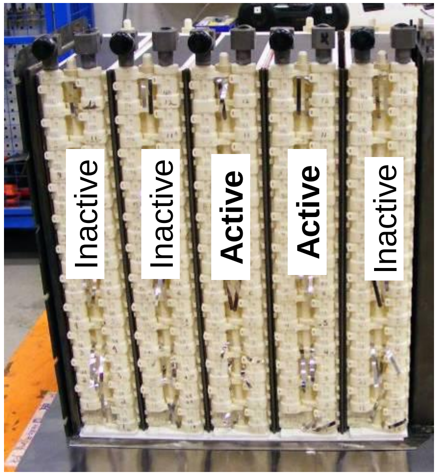


- Anode and cathode ejectors
- Reformers and heat exchangers
- Off-gas burners
- Insulation
- System control methodology

Phase 1 Metric Test (5,000 hours)
Operating Conditions:

- **2 active/3 inactive strips**
- **Cathode Conditions**

Time	Pressure	Block Inlet Temp.	O_2	H_2O
0-300 hrs	6.4 Bar	830C	14.1%	4.2%
>300 hrs			16.0%	3.0%

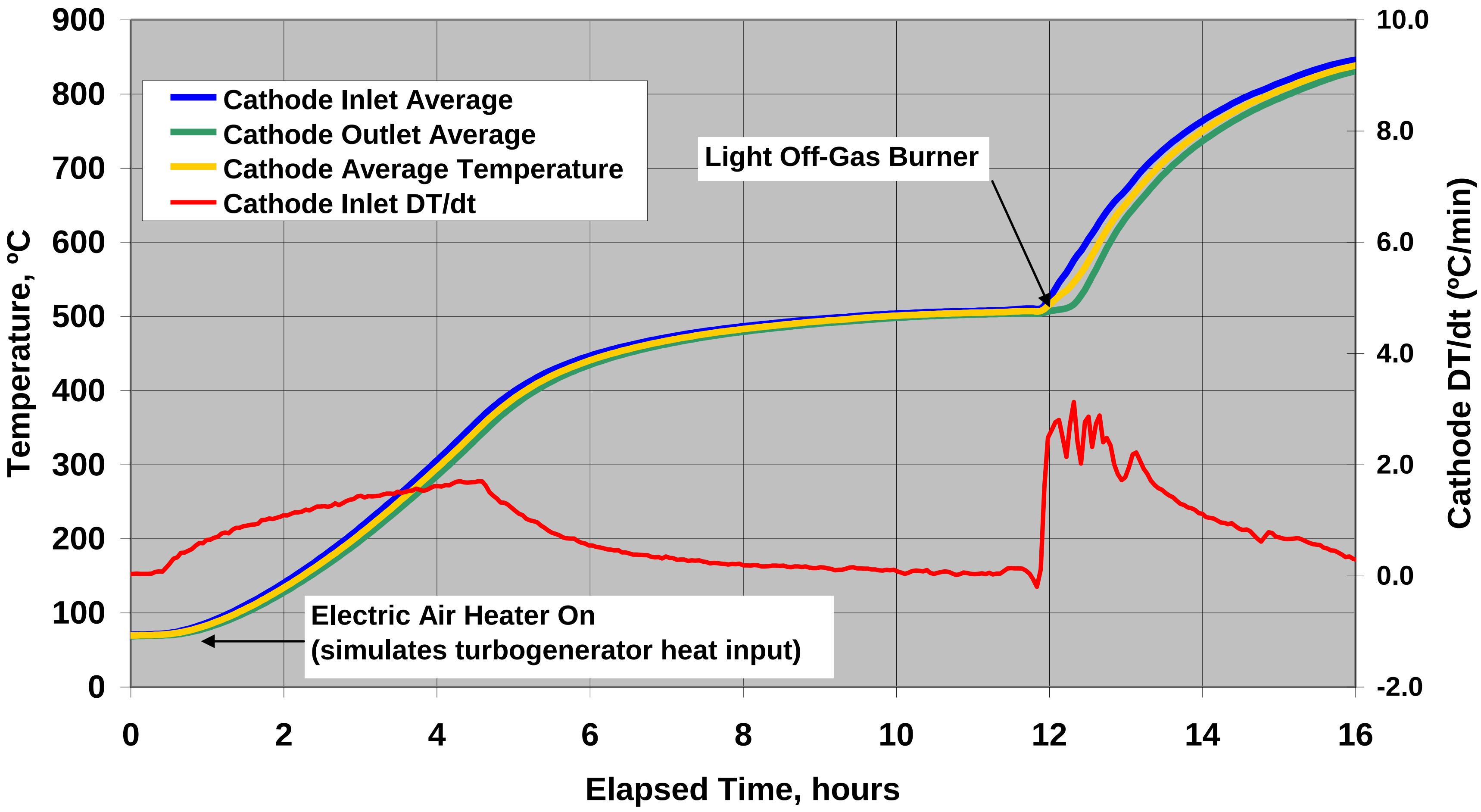


CATHODE AIR FLOW ←

- **Anode Conditions**
  - **Canton rig single pass, no anode recycle**
  - **Inlet composition matches that with recycle**

Time	Fuel Feed	H_2	CO	CO_2	CH_4	N_2	H_2O	S
0-300 hrs	H_2+CO_2 (RWGS)	43%	18%	10%	2%	3%	24%	na
>300 hrs	pipeline NG, H_2O, O_2, CO_2 (Oxy-CPOX)	41%	17%	11%	1%	9%	21%	~35 ppbv

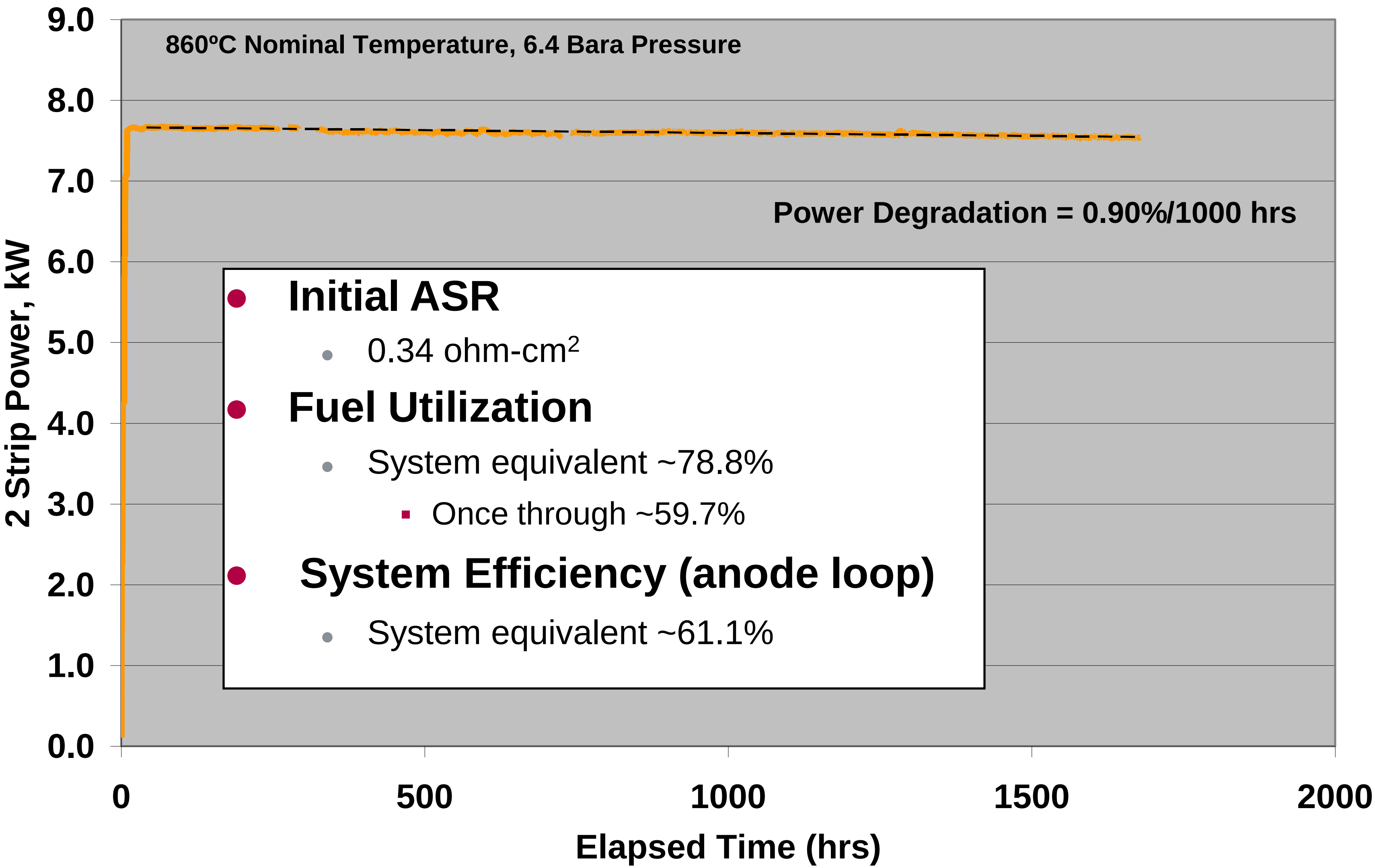
Block start-up similar to full system operation



Light Off-Gas Burner

Electric Air Heater On
(simulates turbogenerator heat input)

Phase 1 Test – Performance and Durability



860ºC Nominal Temperature, 6.4 Bara Pressure

Power Degradation = 0.90%/1000 hrs

- **Initial ASR**
  - 0.34 ohm-cm^2
- **Fuel Utilization**
  - System equivalent ~78.8%
    - Once through ~59.7%
- **System Efficiency (anode loop)**
  - System equivalent ~61.1%

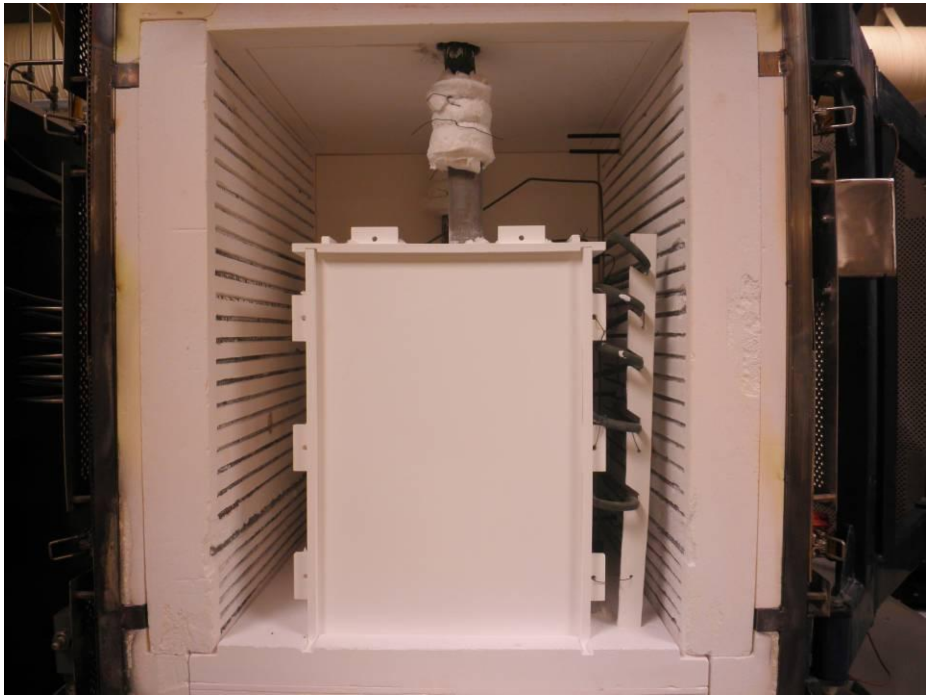
LG data

Phase 2 Metric Test (3,000 hours)

- Test rig in Derby, UK more closely matches the system configuration:
    - anode recycle loop
    - implements primary and auxiliary cathode recycle loops
- Phase 2 test used bottled CH_4
- Status:
    - 5 strips built and pre-reduced
    - Early-Sept start date

Pre-reduction of Strips

- **Planned for high volume manufacturing QA**
- **Now being implemented for block-scale testing**



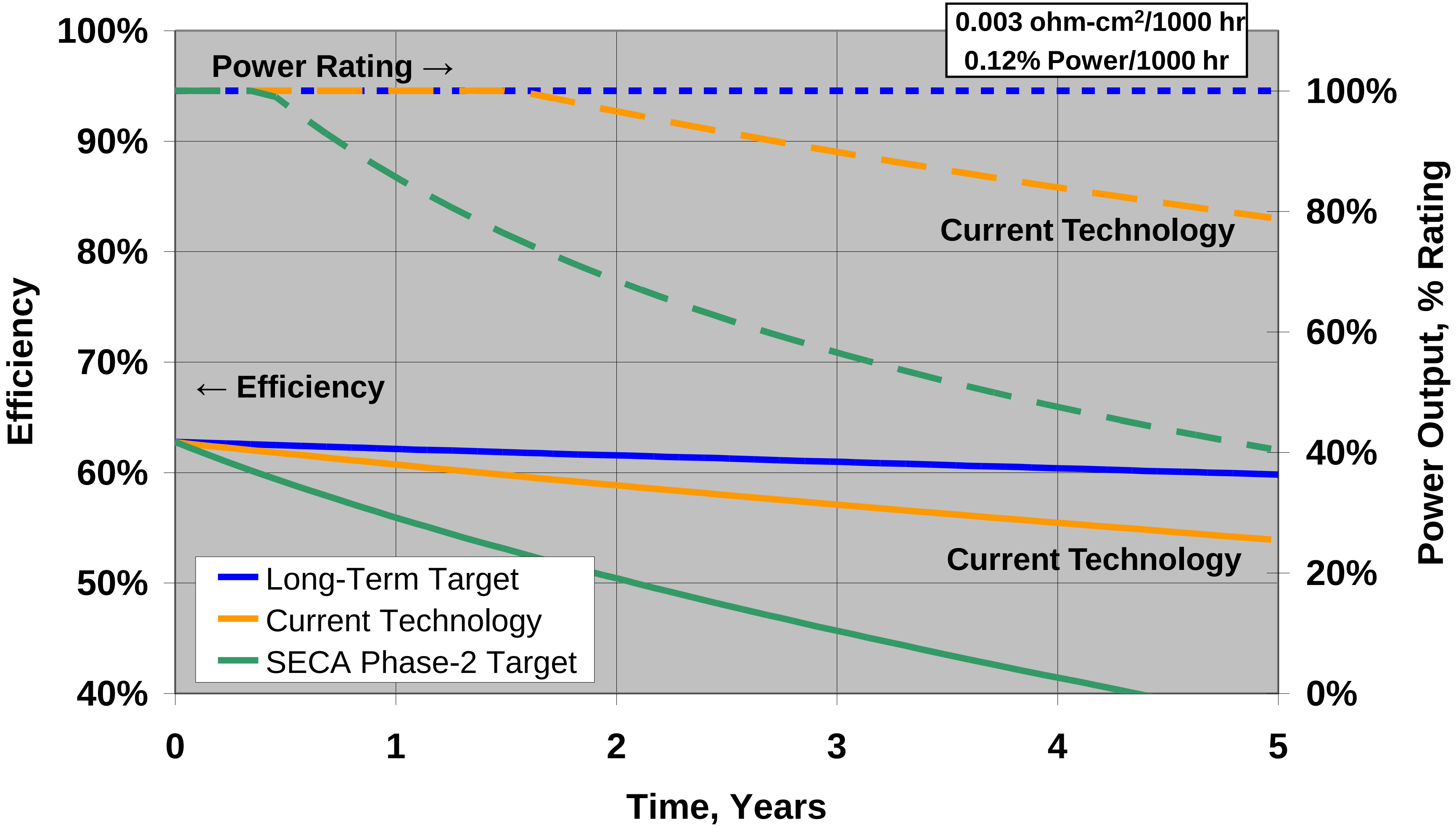
Bundle OCV					
Bundle	**Strip 1**	**Strip 2**	**Strip 3**	**Strip 4**	**Strip 5**
1	358	352	352	353	354
2	355	349	349	350	350
3	356	349	349	350	352
4	352	347	347	346	350
5	351	348	348	348	350
6	351	347	347	348	349
7	353	348	348	348	350
8	354	349	349	349	351
9	355	350	350	349	352
10	355	351	351	349	351
11	354	352	352	350	353
12	353	354	354	353	355

Outline

- System Relevant Block-Scale Testing
- Cell Technology Status:
  - Long-term durability
  - Degradation mechanisms and electrode optimization
- Reliability Methodology

Degradation and Life in Operation

- **Degrade efficiency to meet constant power**

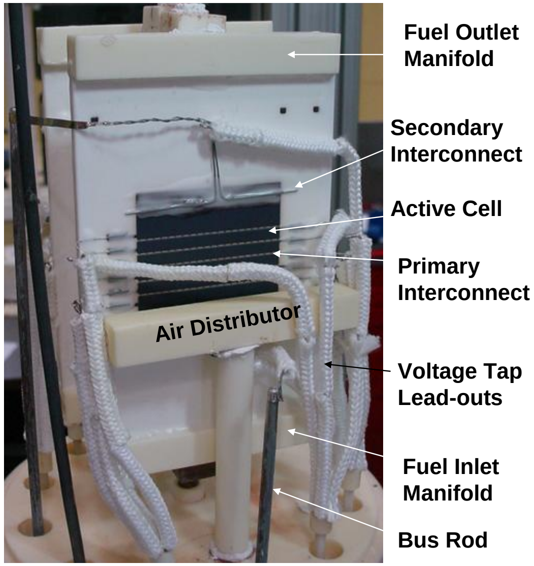


LG data

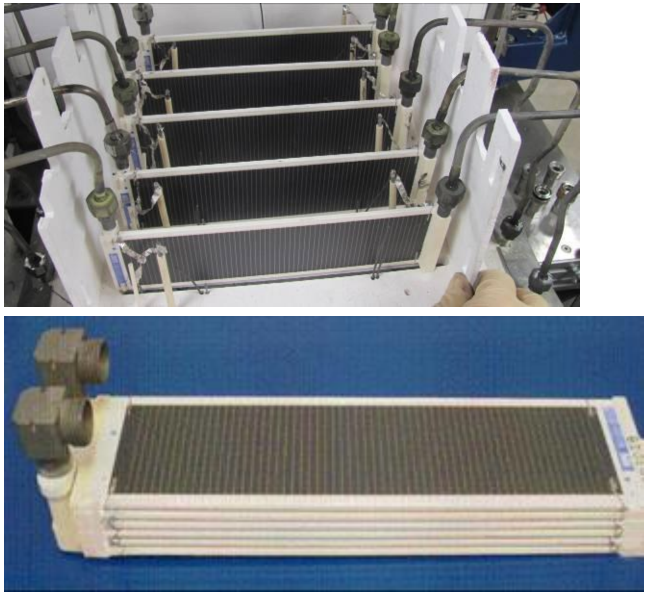
Durability Testing Approach Builds up from Subscale Testing

- Map performance and durability over operating envelope
- Confirm at larger scales while improving manufacturing consistency

Atmospheric Stands – Technology Screening
Pressurized Stands – Full System Testing

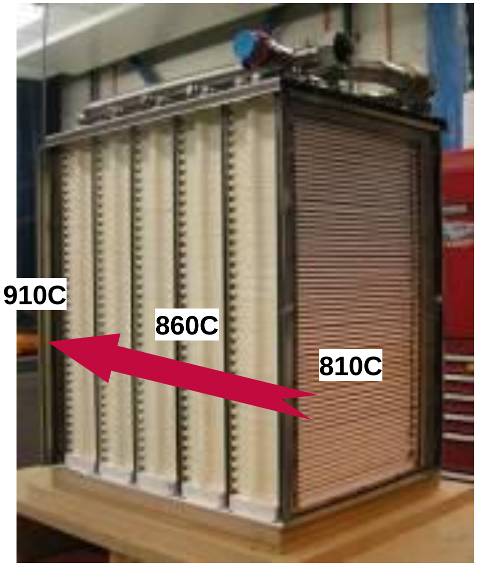


Provides Detailed Cell Component Analysis



Prototypic Tube Manufacture
Tube-Level Performance

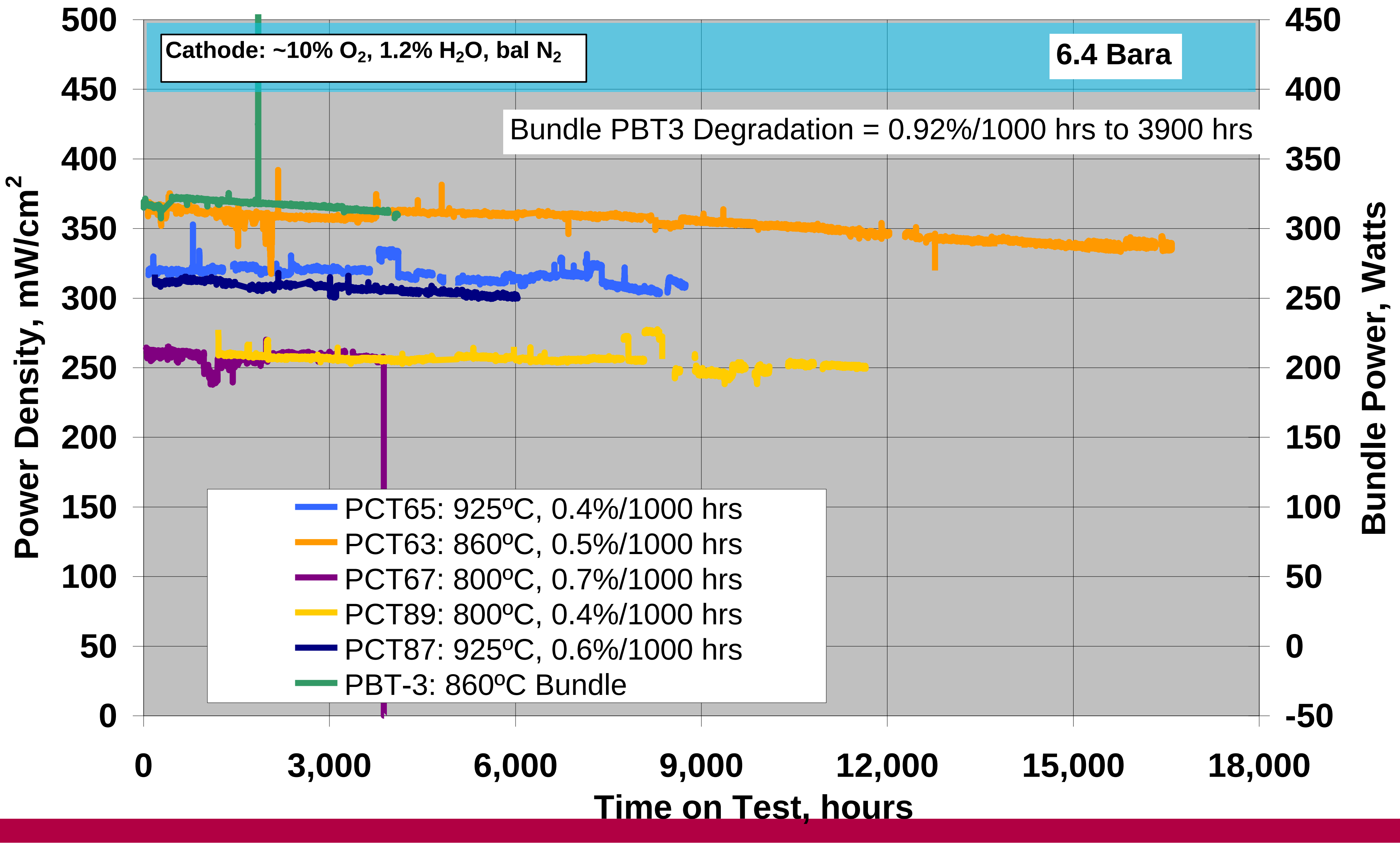
Fully Prototypic Environment Including BOP Components



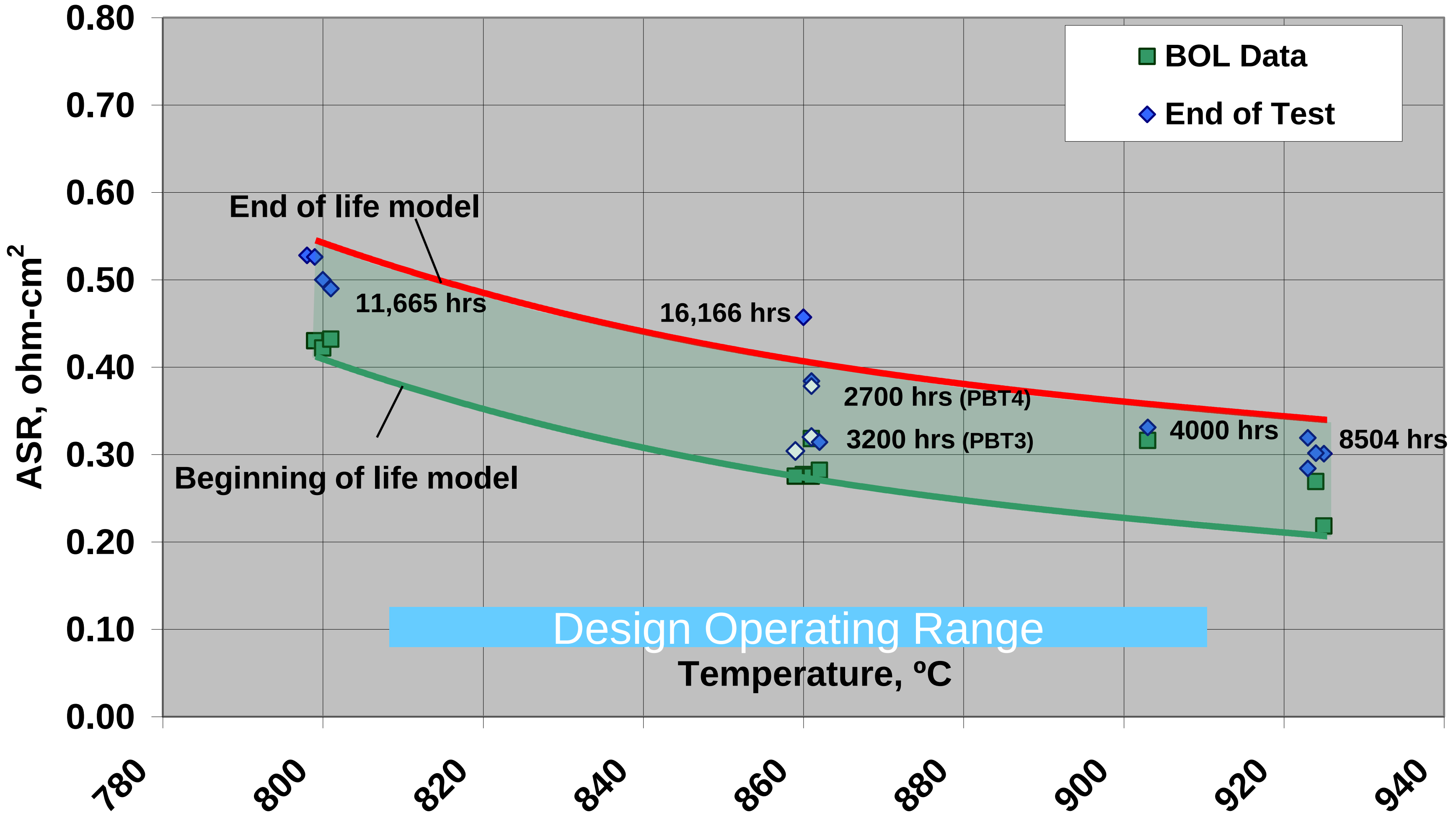
Full Prototypic Scale

LG data

Long-Term Degradation < 1%/1000 hours

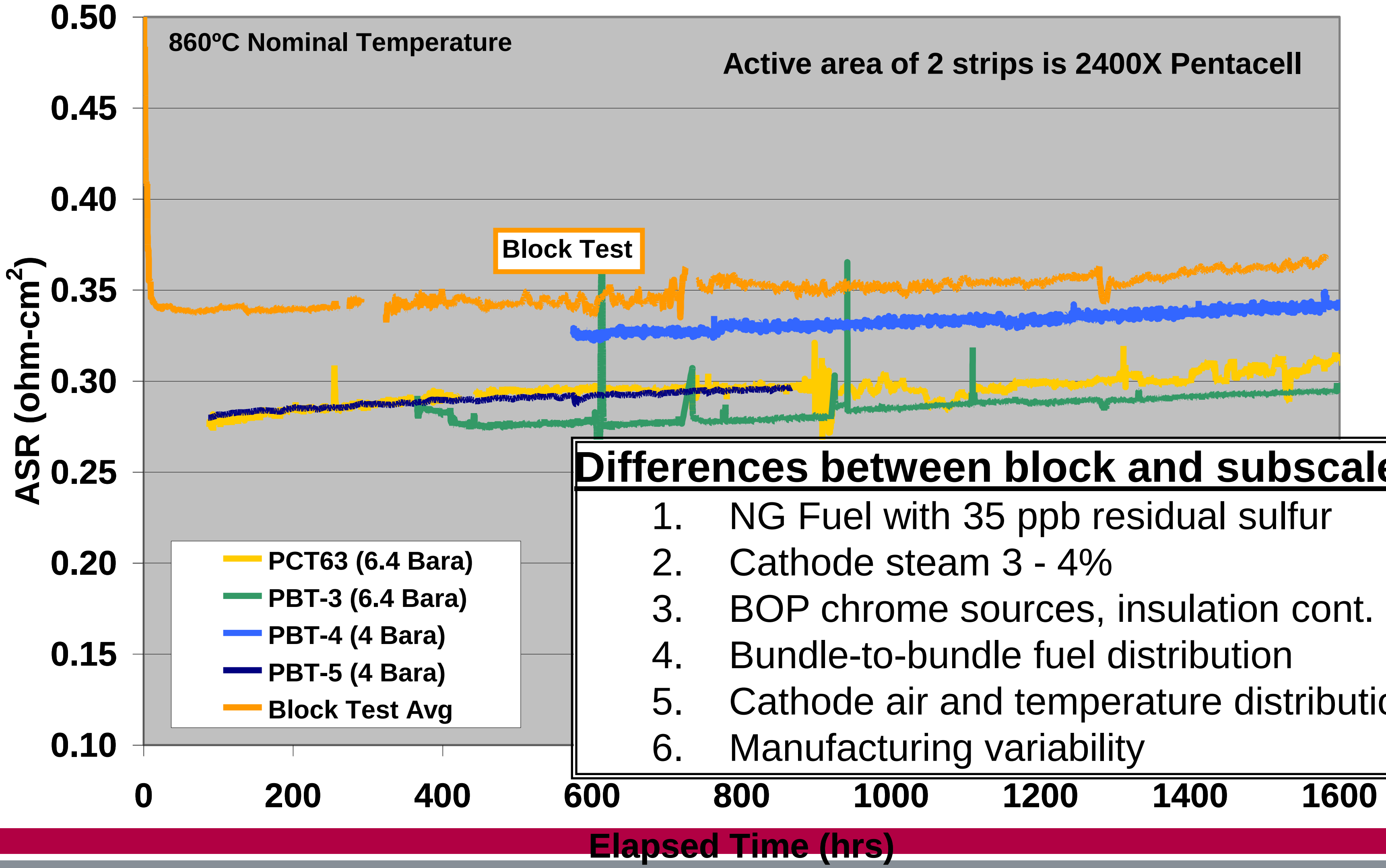


Subscale Durability Map Demonstrates Durability Trends



LG data

Scale-up of durability demonstrated, some variation in performance



Differences between block and subscale

1. NG Fuel with 35 ppb residual sulfur
2. Cathode steam 3 - 4%
3. BOP chrome sources, insulation cont.
4. Bundle-to-bundle fuel distribution
5. Cathode air and temperature distribution
6. Manufacturing variability

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- System Relevant Block-Scale Testing
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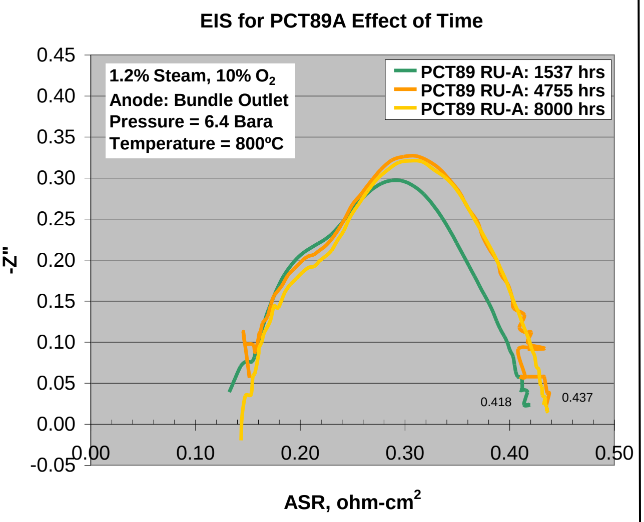
- Reliability Methodology

Key Degradation Contributions Identified: Anode and Cathode Polarization Resistance

Low-Temperature (800ºC)

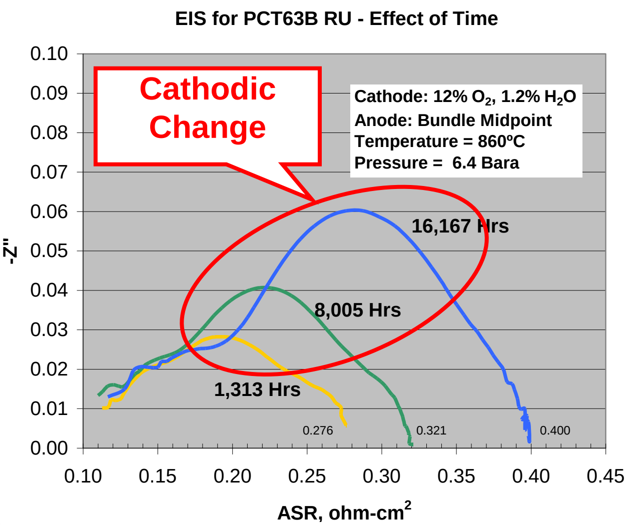
Initial Cathode degradation then stability



Overall Degradation Rate: 0.0038 ohm-cm²/1000 hrs

Mid-Temperature (860ºC)

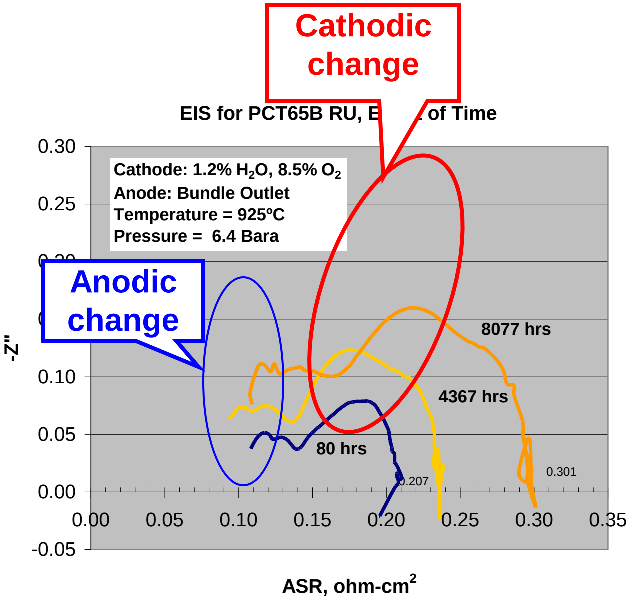
Cathode degradation is dominant



Overall Degradation Rate: 0.0083 ohm-cm²/1000 hrs

High-Temperature (925ºC)

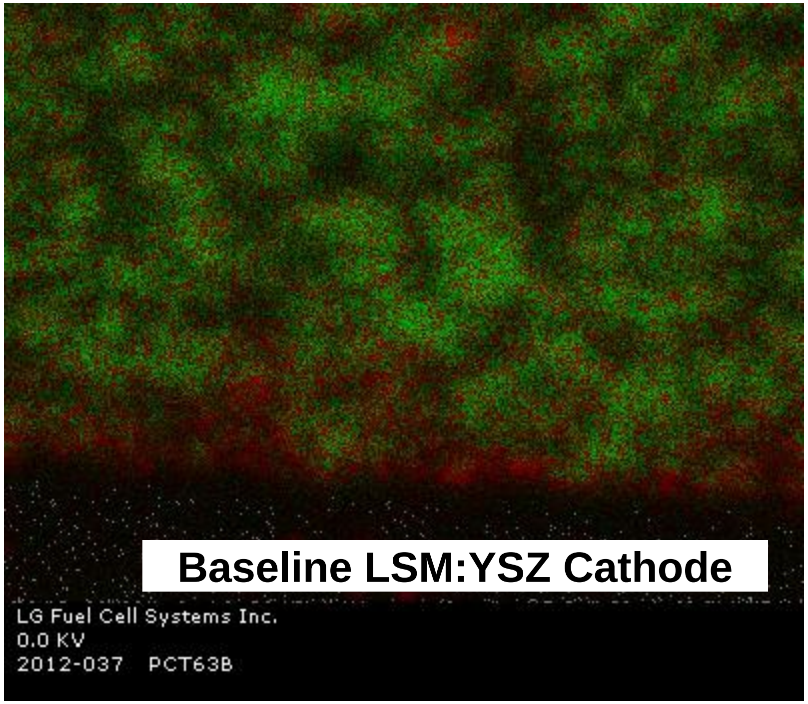
Anode + Cathode degradation observed



Overall Degradation Rate: 0.0120 ohm-cm²/1000 hrs

Cathode Changes Observed Long-Term

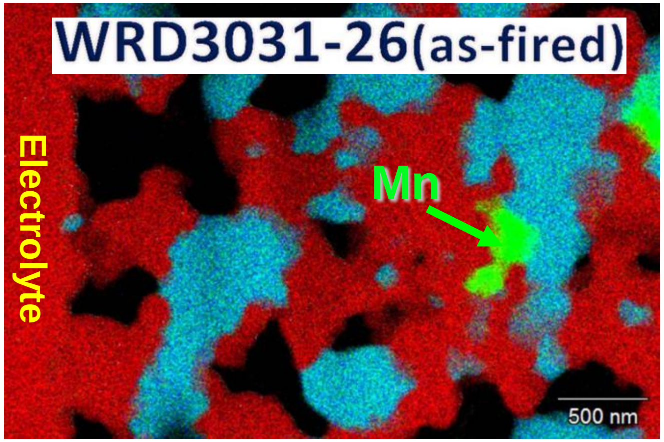
- Mn-rich at cathode/electrolyte interface
- Some cathode densification showing up at 16,000 hours, relatively absent at 8,000 hours (for testing at 860C)

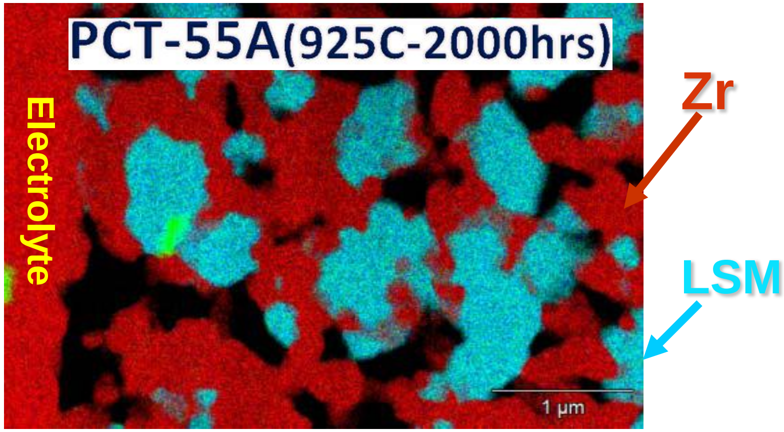


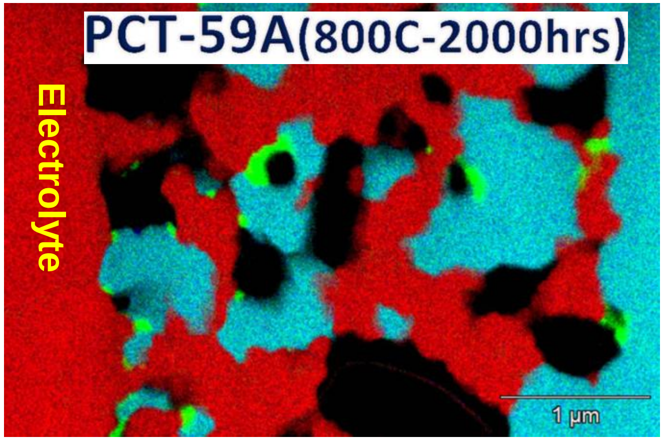
860^{o}C for 16,000 hrs (PCT63)

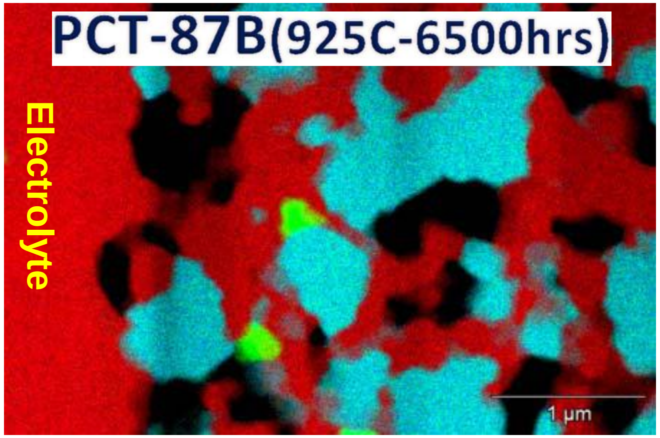
Exploring MnO_x presence vs. operating temp.

- Free MnO_X observed in both as-fabricated and tested cells
- Initial analysis: more smaller MnO_x grains observed at TPB for cell tested at lower temperatures



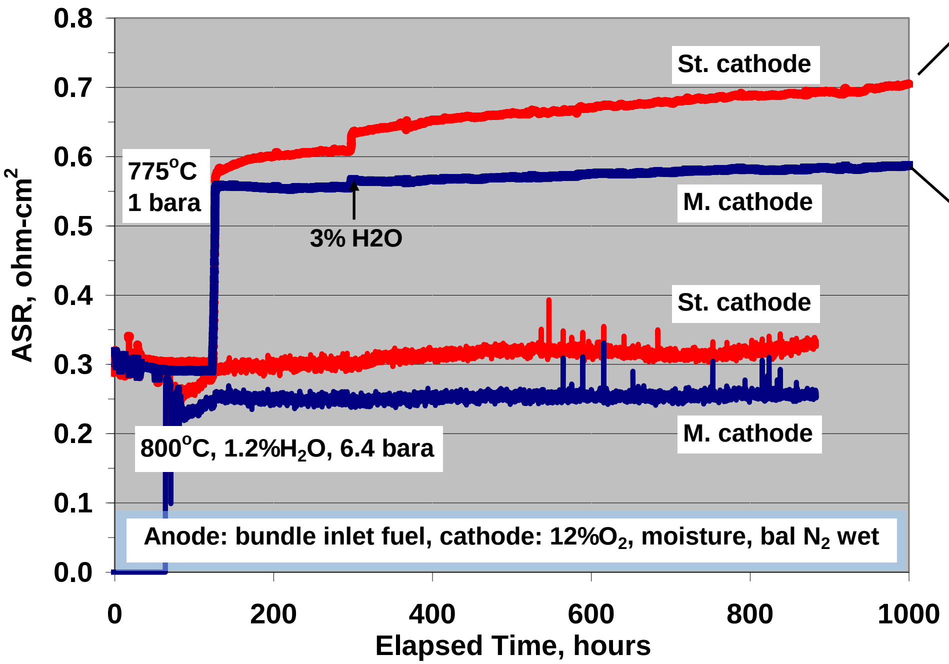




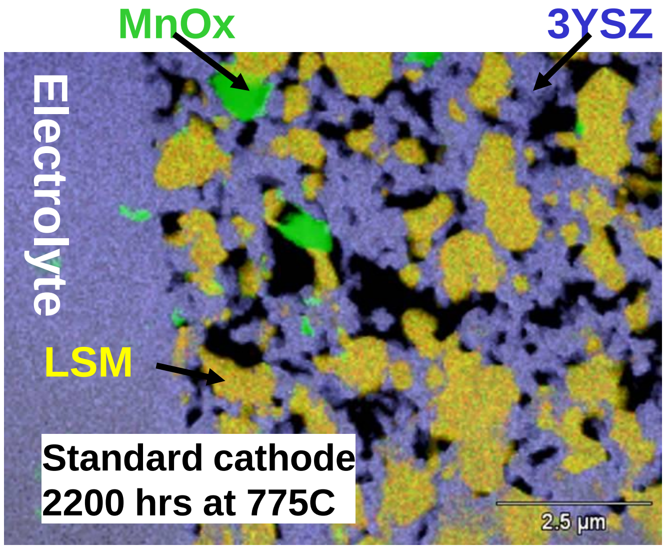


Improved Cathode – Promising Results at Low Temperatures

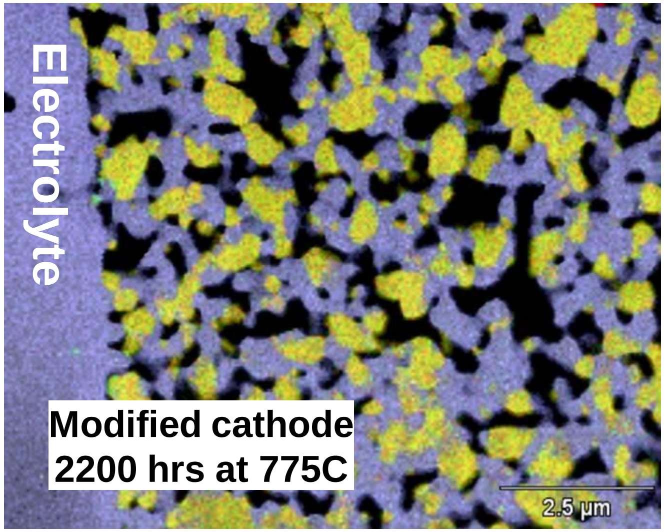
- **Lower degradation rate than standard cathode at low-temperature operation**
- **Free MnO_x segregation from LSM may cause performance loss**



Anode: bundle inlet fuel, cathode: 12%O_2, moisture, bal N_2 wet



Standard cathode 2200 hrs at 775C

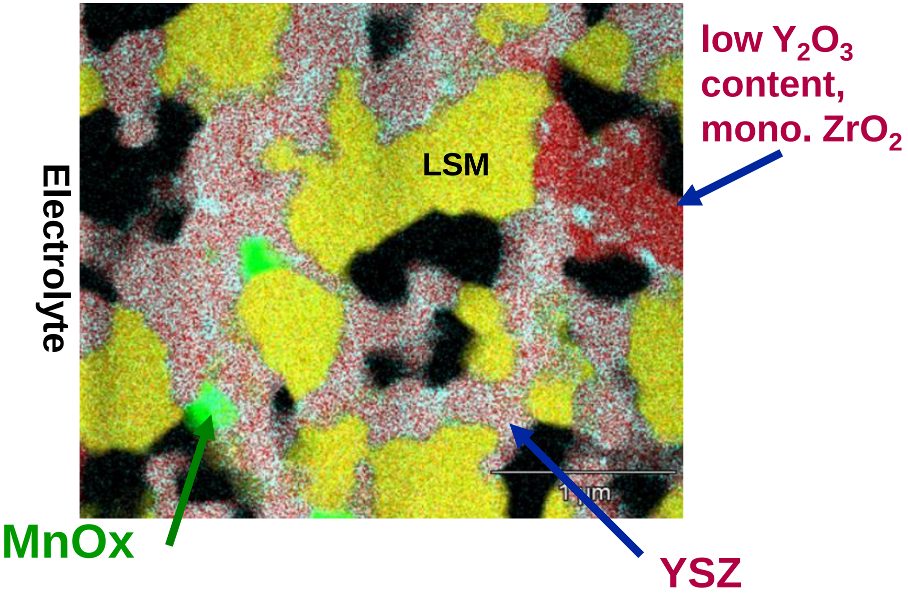


Modified cathode 2200 hrs at 775C

Standard Cathode Shows Segregation of Stabilizing Ion from Ionic Phase

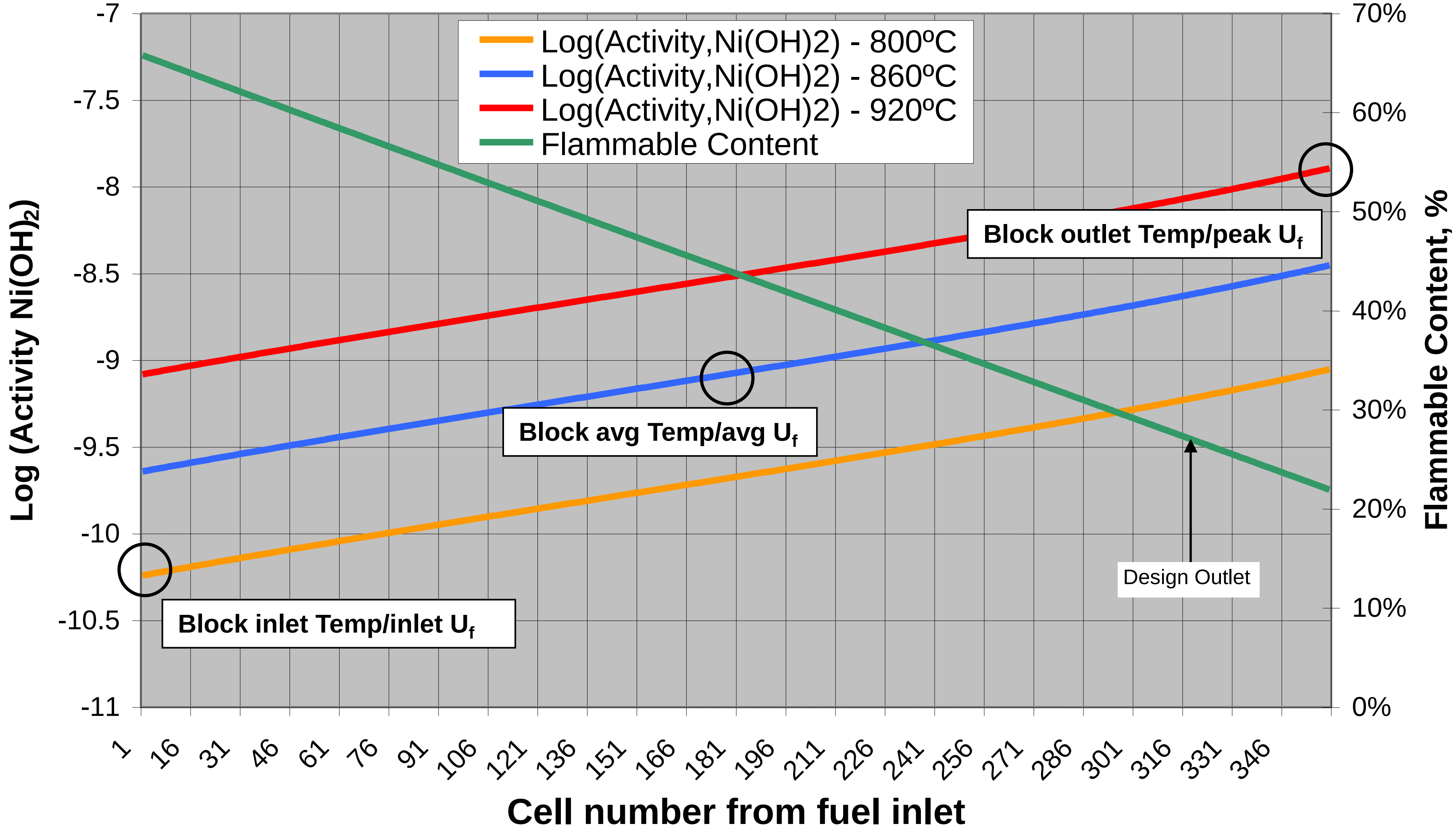
- YSZ is stable after short period of operation at both low and high temperature operation
- Local Y depletion was detected after 6500 hrs of operation at 925ºC leading to monoclinic ZrO_2
- Modified LSM cathode shows no evidence of monoclinic ZrO_2

Standard cathode at 925ºC for 6500 hrs

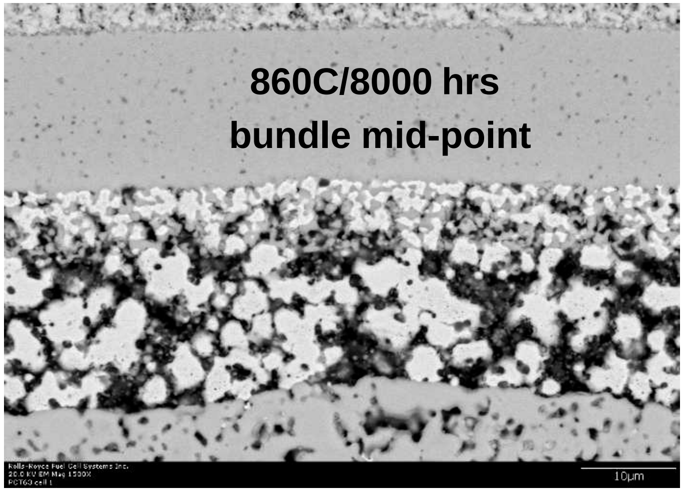


CASE WESTERN RESERVE UNIVERSITY EST. 1826

Ni(OH)$_2$ Equilbrium within Blocks

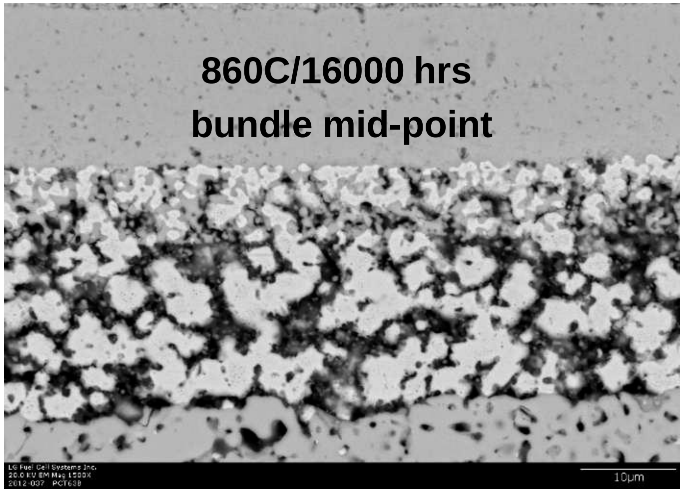


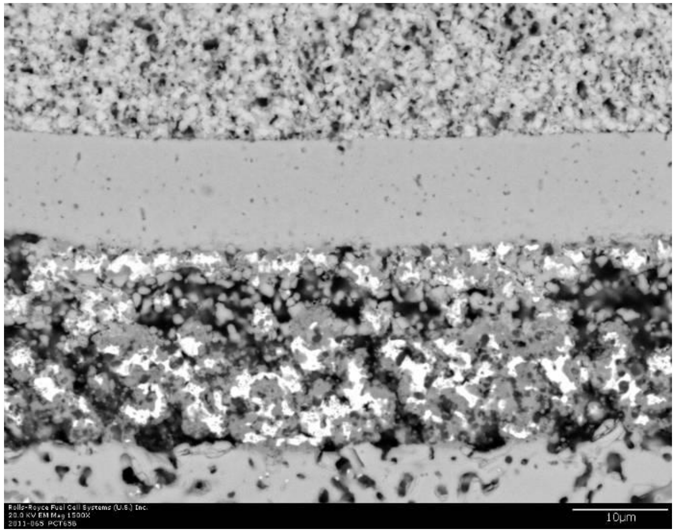
Anode microstructure changes greatest at extremes of temperature and U_f



Active anode

Anode current collector

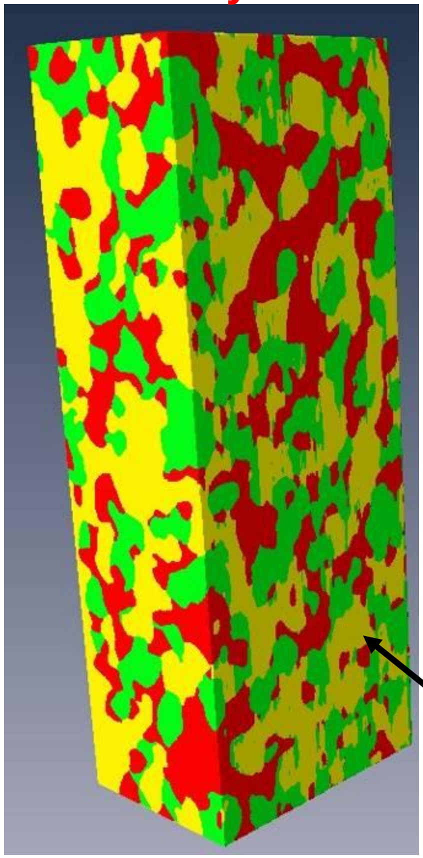




Aggressive testing outside block envelope

Anode 3D Reconstruction Highlights Changes at Anode/ACC Interface

Porosity=29%

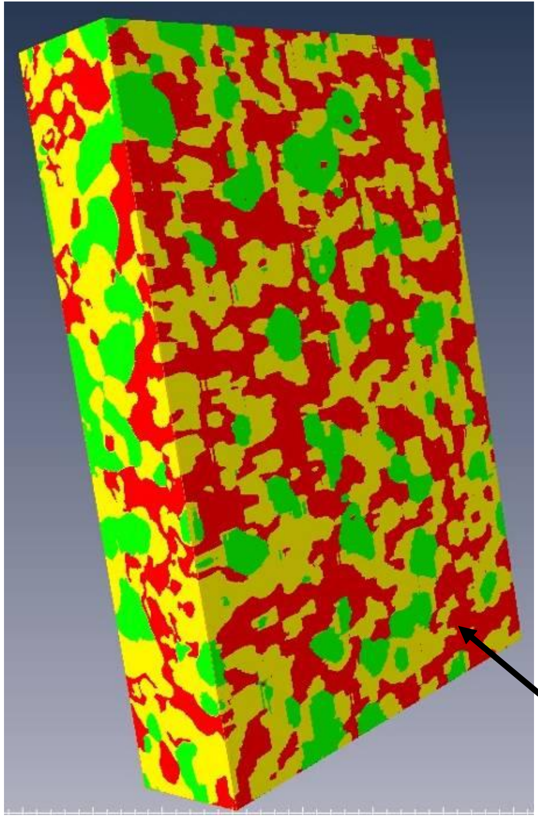


Surface close to Anode/ ACC Interface

As-reduced anode

3D pillar was constructed By FIB milling of series of thin slices

Porosity=41%



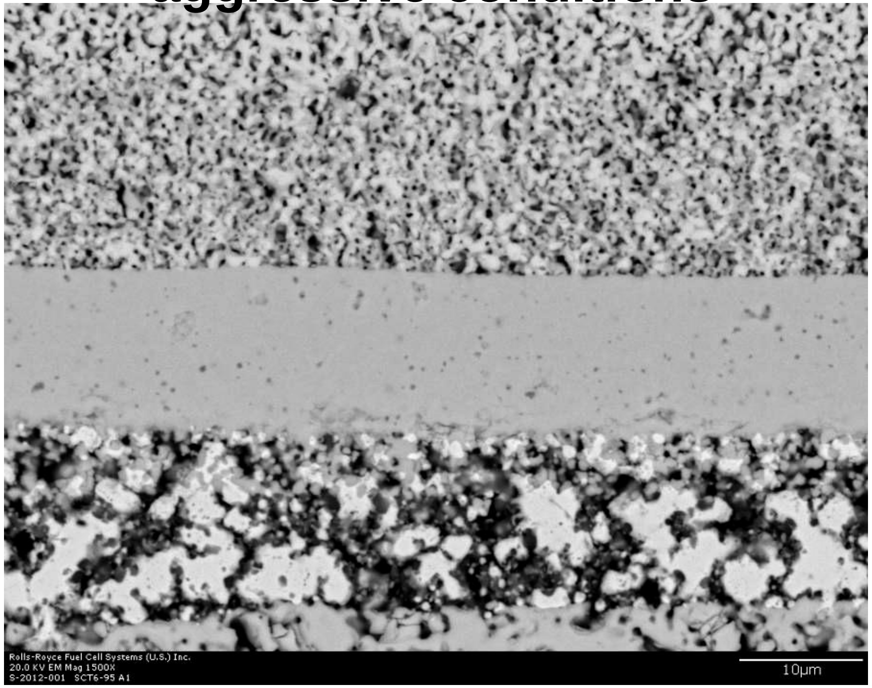
Surface close to Anode/ACC Interface

Aggressively tested anode

- 🟥 Pores
- 🟨 ionic
- 🟩 metal

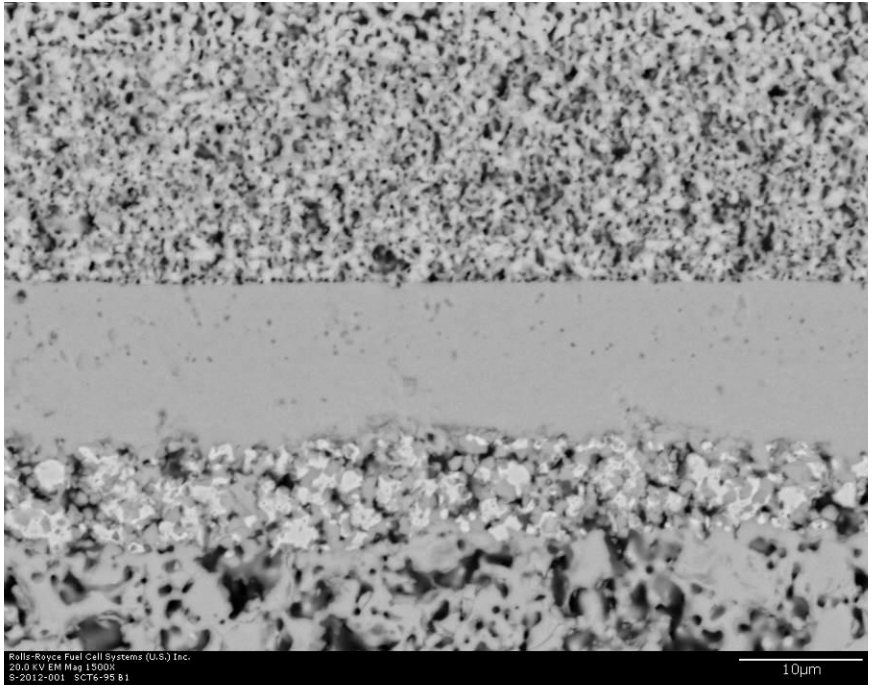
Single Layer Anode Technology Showing Improved Microstructure Stability

- Two single cells were tested in same rig under aggressive temperature and fuel utilization conditions
- Post test analysis performed after 630 hrs of testing at aggressive conditions



SCT6-95A: Standard anode

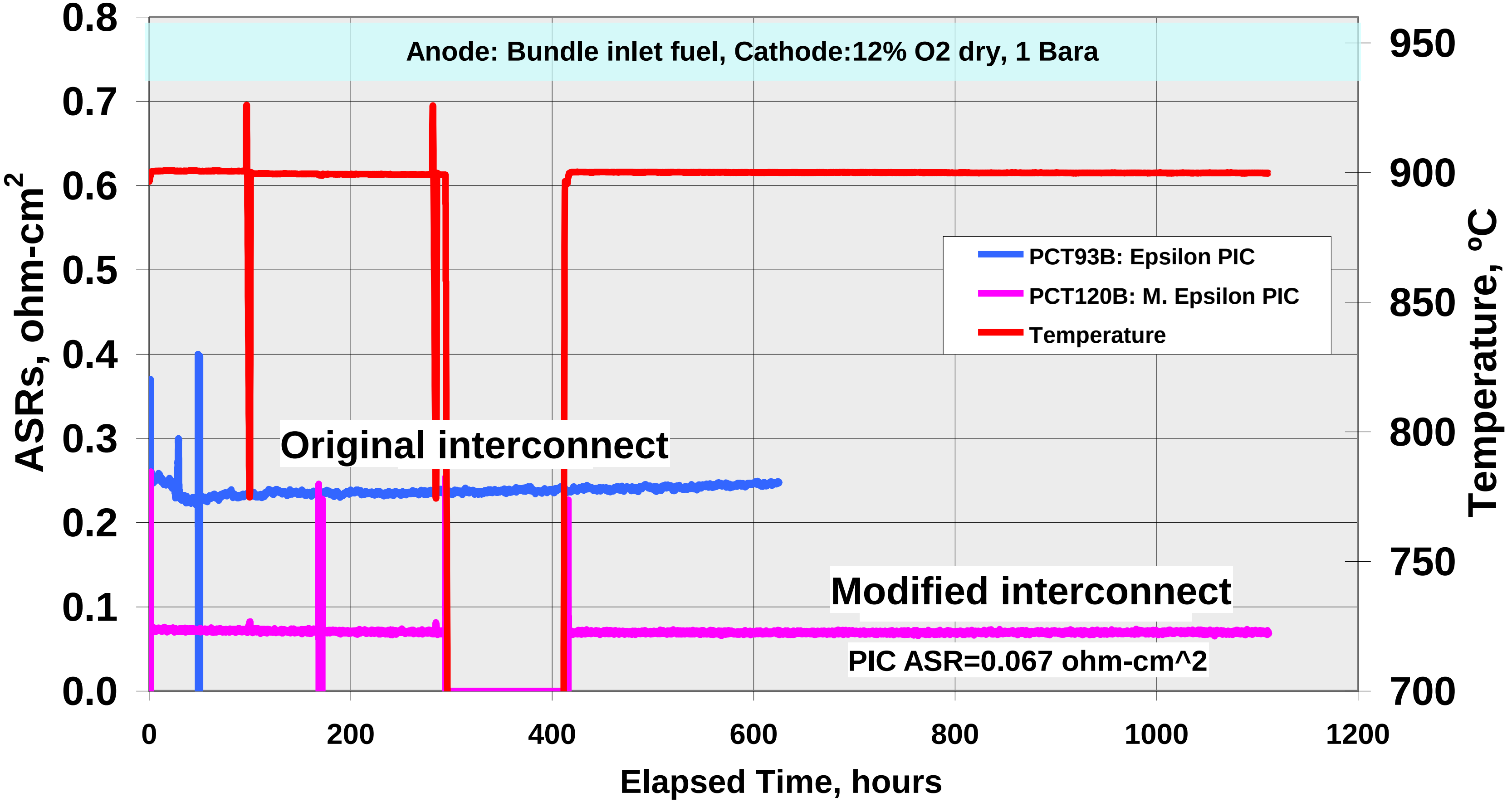
6.4 bar



SCT6-95B: Single layer anode

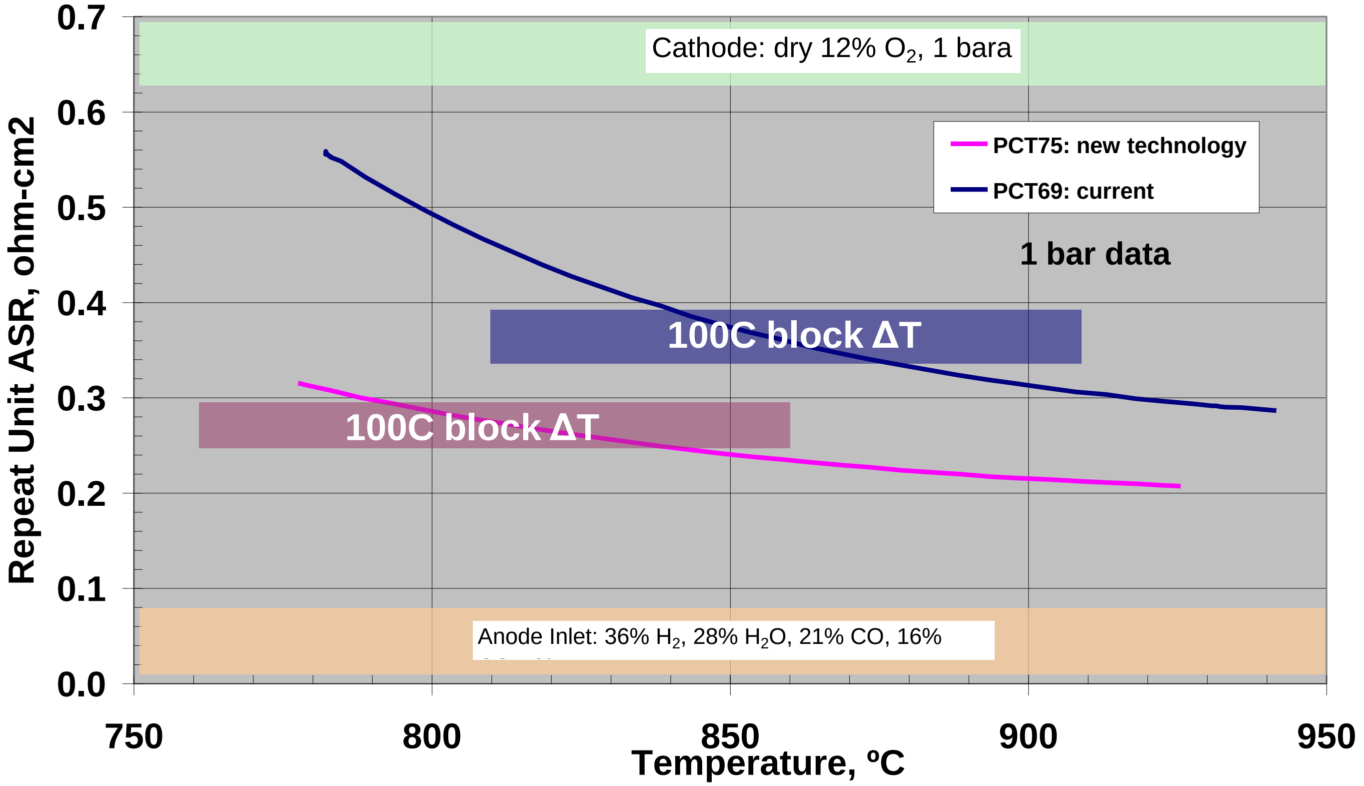
A New Cell-to-Cell Interconnection Materials Set Developed for Single Layer Anode Technology

- Interconnect ASR >0.2 ohm-cm² from materials incompatibility issue with anode
- Optimized formulation achieved typical 0.07 ohm-cm² range of ASR



Focus on reducing peak operating temperature to extend lifetimes

- Latest cell technology offers potential for lower degradation rates and improved system efficiency
- Lower ASR cell technology is entering full system durability screening



LG data

Outline

- System Relevant Block-Scale Testing
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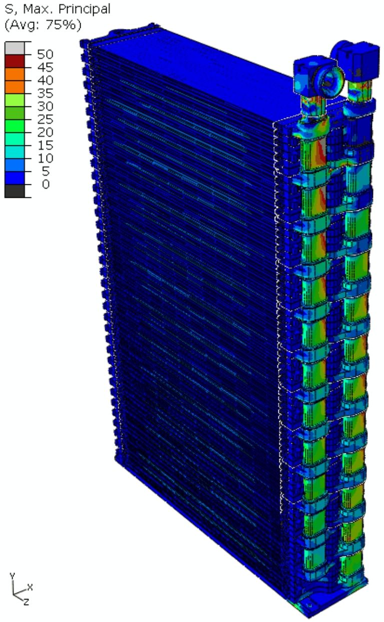
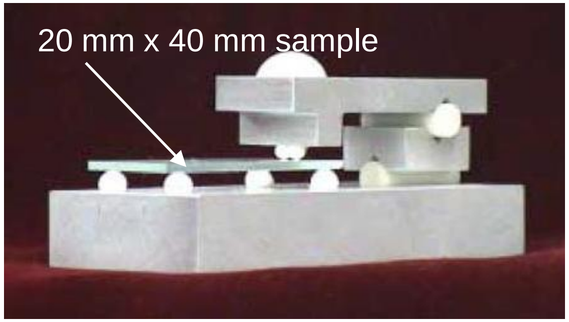
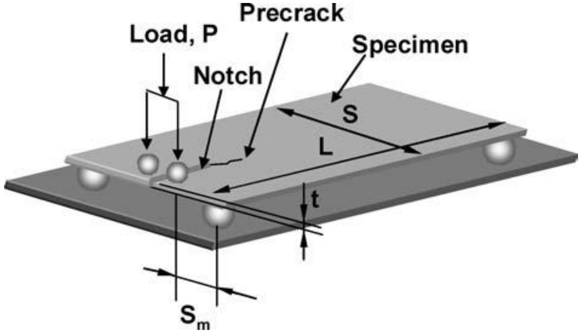
- **Reliability Methodology**

Infant Mortality and Time Dependent Reliability Considerations

- **Infant Mortality:**
  - **Thermal and stress analysis**
  - **Insure that design and system operational modes can accommodate the stack material**
  - **Material property database being generated**
- **Life-time Reliability**
  - **Time dependent, slow crack growth mechanisms being studied**



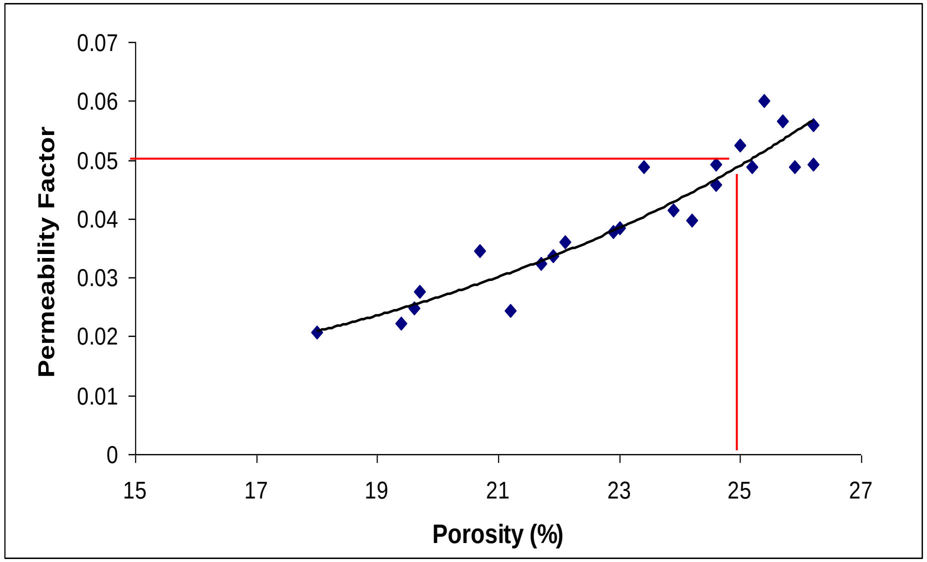

20 mm x 40 mm sample

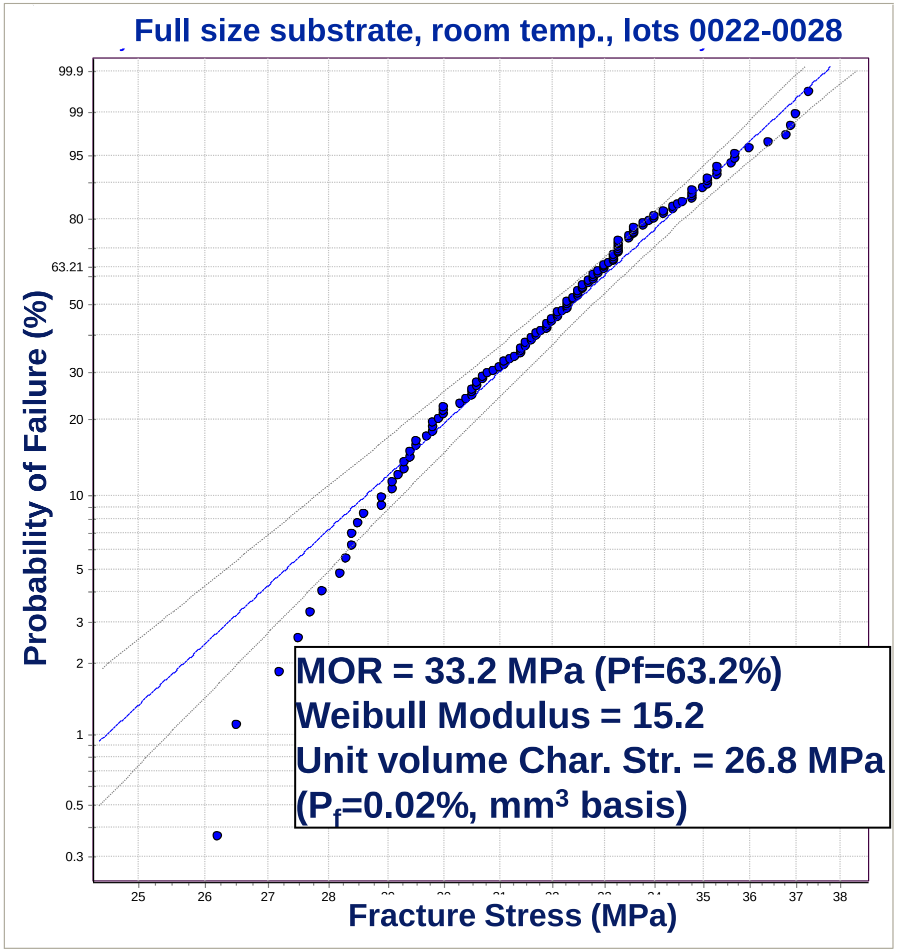


LG data

Strength specification met for higher porosity substrates

- Room temp. MOR >29 MPa (full-size substrate)
- Weibull modulus >10
- ~25% porosity for permeability factor spec. of 0.05 0.005



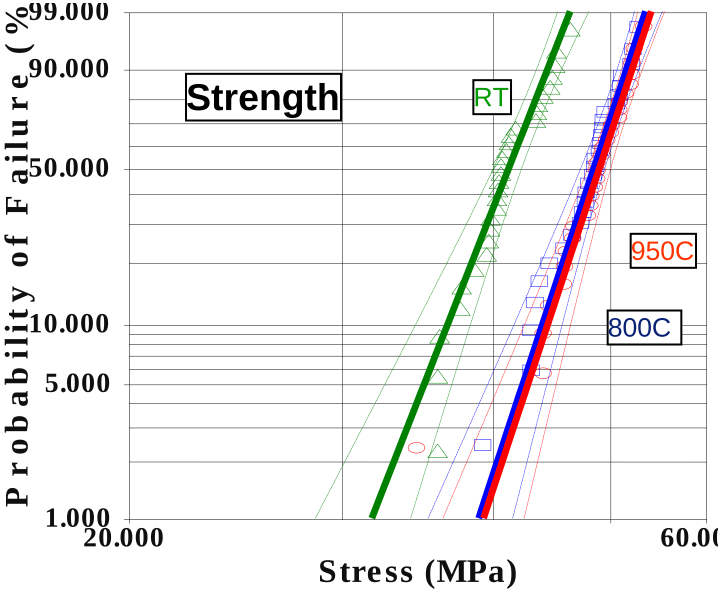

Full size substrate, room temp., lots 0022-0028

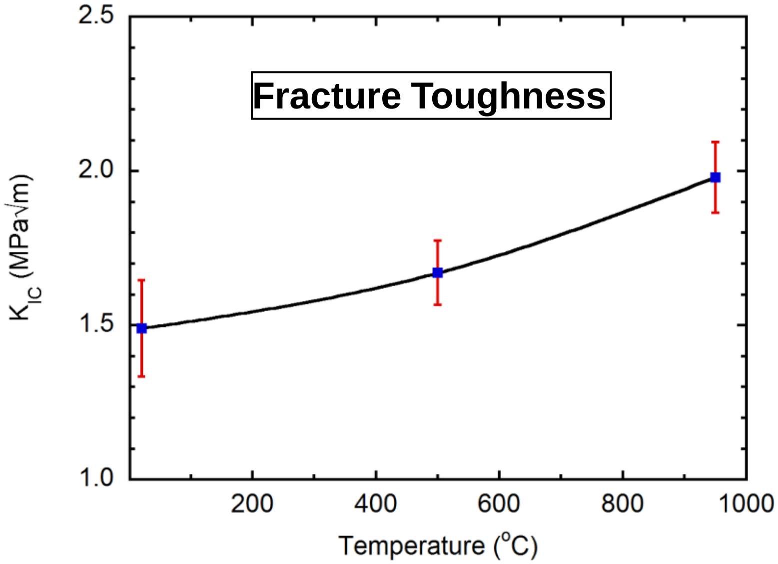
MOR = 33.2 MPa (Pf=63.2%)
Weibull Modulus = 15.2
Unit volume Char. Str. = 26.8 MPa
(P_f=0.02%, mm^3 basis)

LG data

MMA Substrate Strength and Toughness Increase with Temperature

- Substrate is $MgO+MgAl_2O_4$ (MMA)
- Improved strength and toughness at temperature benefits reliability





Test coupons from substrate edges

Temperature	Strength, MPa (Pf=63.2%)	Weibull Modulus
room temp.	42.3	16.2
800C	49.5	19.3
950C	50	19.2

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ORNL Performing Slow Crack Growth (SCG) Measurements of MMA Substrate

- **Thus far the MMA substrate is demonstrating reasonable SCG resistance**
- **Data in fuel environments with moisture content is most relevant**

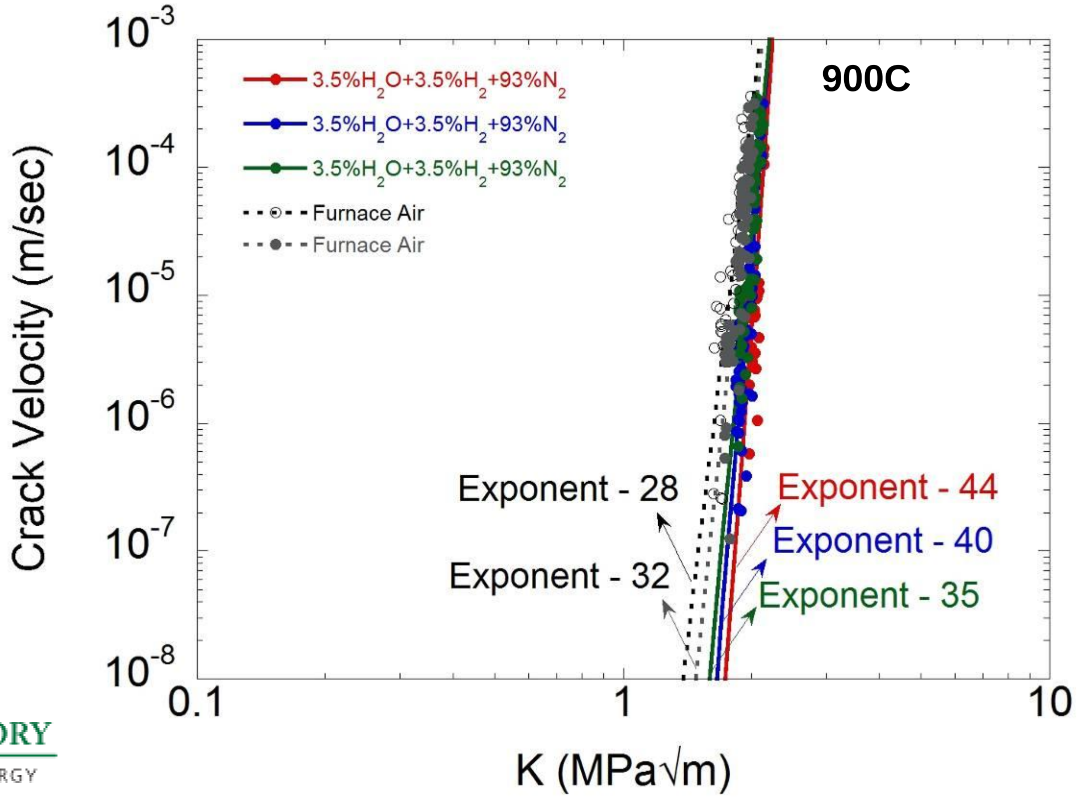
$v = AK_I^n$

v, crack velocity

K_I, stress intensity

A and n, *f*(mat'l, environ.)

n, slow crack growth exponent



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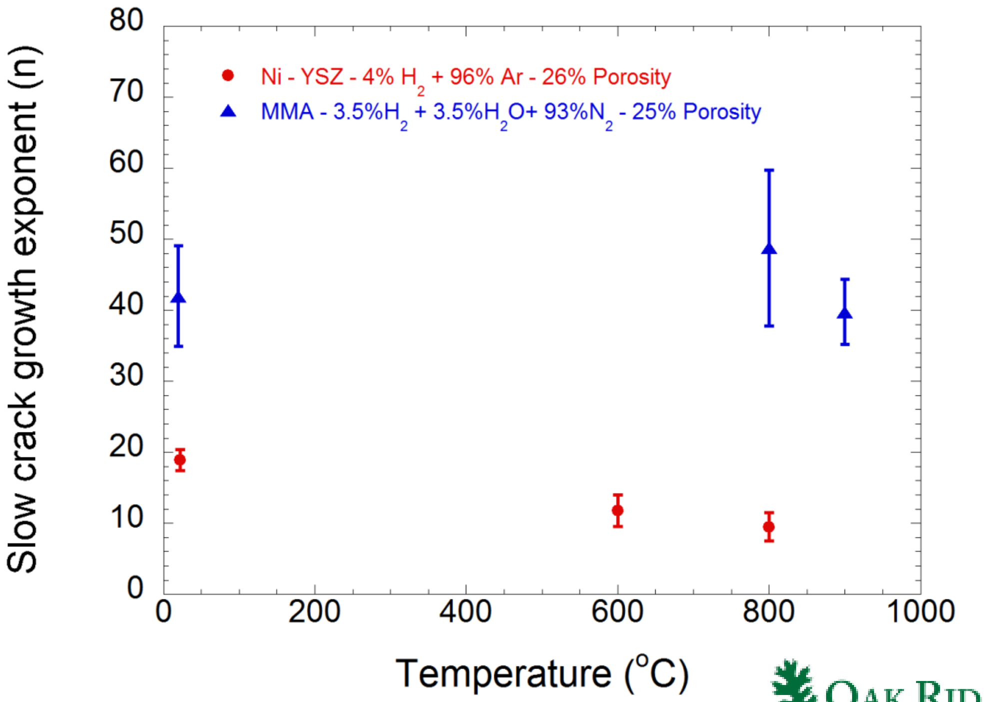
SCG Comparison of MMA and Ni:YSZ

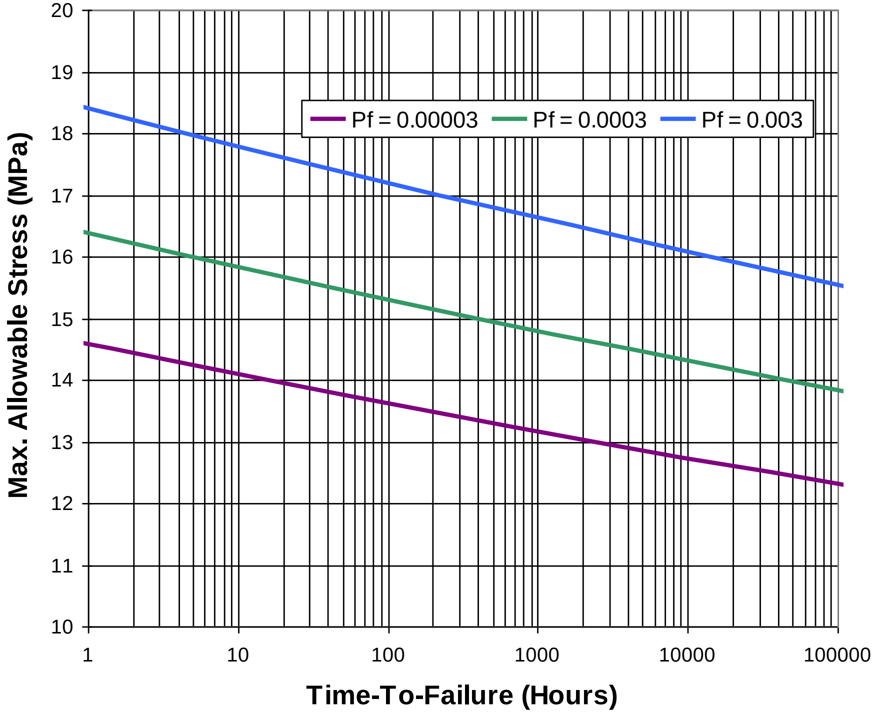
- ORNL had previously tested porous Ni:YSZ under Core Technology Program
- MMA substrate compares very favorably to other SOFC substrate materials
- Very limited SCG literature data for electrolytes (n from 8-25, air/900-1000C), none in high H_2O fuel
  - Compressive electrolyte residual stresses for anode- and MMA-supported may reduce risk. Electrolyte SCG a greater concern for electrolyte supported SOFC



SCG data combined with Weibull characteristics can allow lifetime predictions

- **Guides design allowable stresses for components to meet lifetimes (probabilistic)**
- **Consider P_f of 1 in 360 (0.003) for blocks (1 failed substrate within a 5 strip block)**

Example of calculations/predictions with SCG data. For illustrative purposes only



Relationships developed originally for glass components (Weiderhorn)

$$K_{Ii} = K_{IC}\left(\frac{\sigma}{\sigma_o}\right)\left[\frac{-V_E}{\ln\left(1-P_f\right)}\right]^{1/m}$$

$$t = \frac{2(K_{Ii}^{2-n} - K_{IC}^{2-n})}{(n-2)A\sigma^2Y^2}$$

Requires mat'l properties at operating condition:
K_{Ic}, fracture toughness
σ_o, characteristic Weibull strength
m, Weibull modulus
n, slow crack growth exponent
A, slow crack growth coefficient

Requires inputs of:
Y, geometric factor for crack orientation/loading
P_f, desired probability of failure for component
V_E, Volume of mat'l in component under stress
σ, stress level of elements within component

Conclusions

- **LGFCS established, combining LG and Rolls-Royce talents and resources to commercialize MW-scale IP-SOFC technology**
- **Stack degradation rates trending under the SECA Phase 2 target**
- **Next generation/optimized electrodes screened and entering long-term durability testing to advance to 5-year service life**
- **Current emphasis on ceramic materials database generation and stress analysis to progress understanding of reliability**

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