LG Fuel Cell Systems Program and Technology Update

DOE 17th Annual SOFC Review, 19 July 2016

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Contracts

Work performed by LG Fuel Cell Systems under DOE contracts:

- **DE-FE0012077: SECA Coal-Based Systems LGFCS**
- **DE-FE0023337:Improved Reliability of SOFC Systems**
- **DE-FE0026098: Advanced Materials and Manufacturing**

Outline

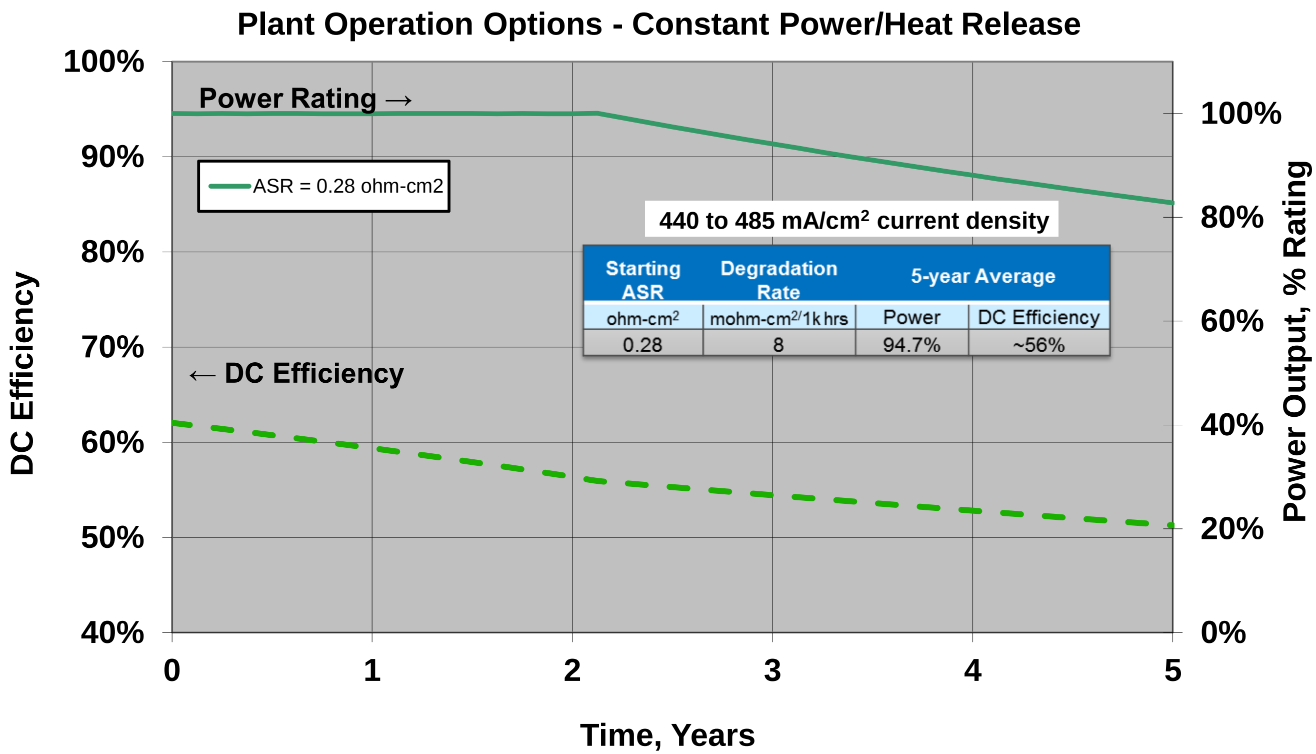
- Performance Improvement
- Cost Reduction
- Durability
- Block Testing
- Advanced Materials and Manufacturing
- Summary

Outline

- Performance Improvement
  - Fuel cell system operation strategy
  - ASR improvement for longer service life and cost reduction
- Cost reduction
- Durability
- Block Testing
- Advanced Materials and Manufacturing
- LGFCS Program

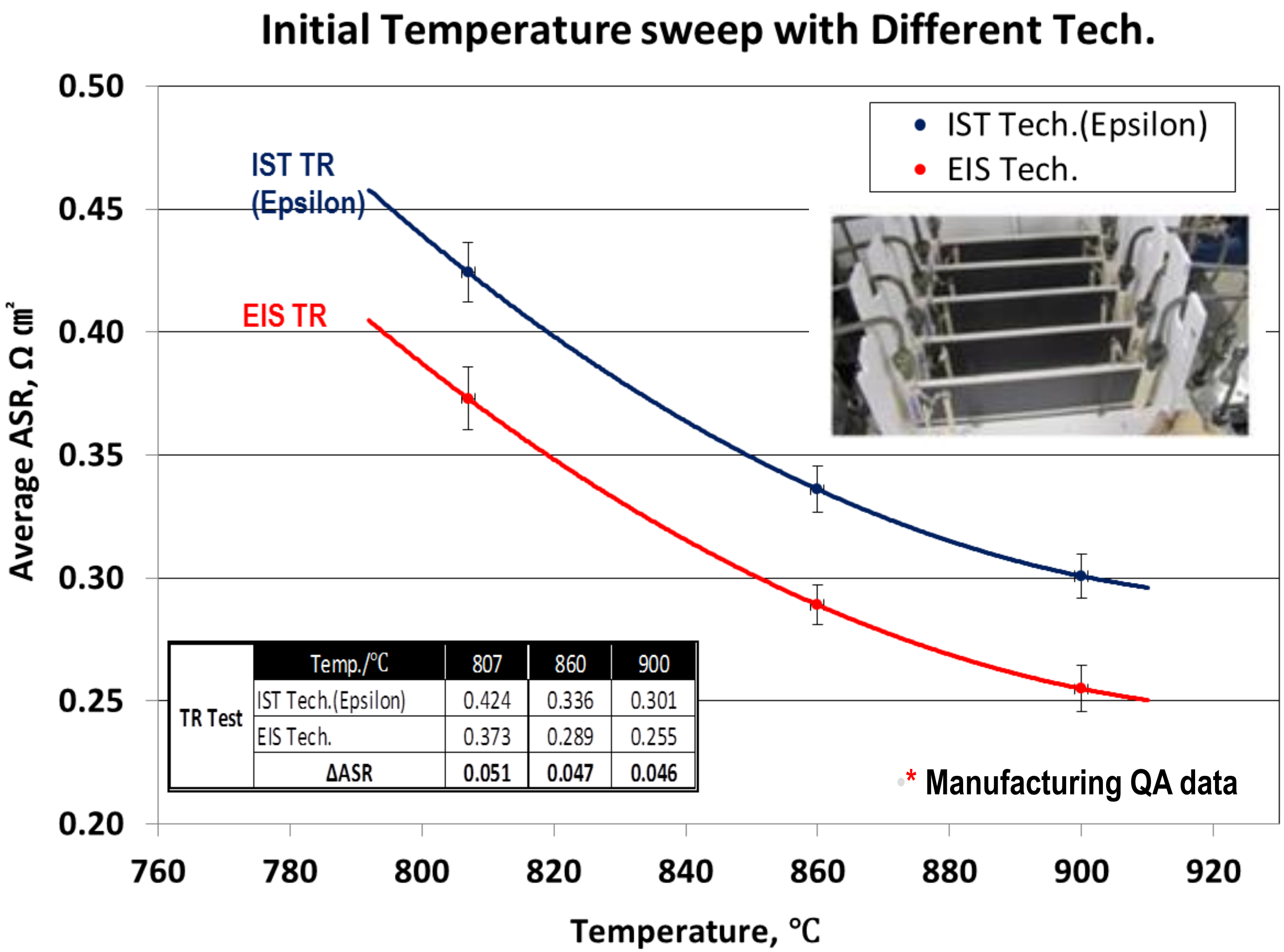
Plant Operation Options Based on Stack Performance

- **Initial ASR and ASR degradation rate are key metrics for benchmarking cell technology**
- **System design must be able to operate over a wide range of ASR (starting to end-of-life) while maintaining specified stack temperature range**
- **Operation based on current technology developed to date**



ASR Reduction Achievements

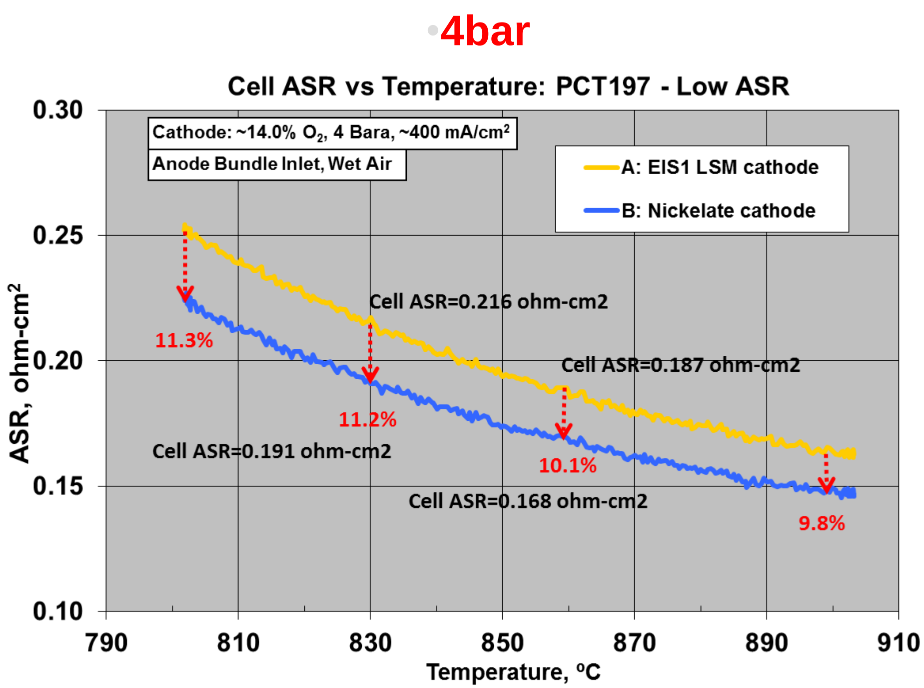
- **EIS Tech. provide ASR benefit (0.04~0.05 Ω㎠) compared with IST Tech.**



	Temp./℃	807	860	900
TR Test	IST Tech.(Epsilon)	0.424	0.336	0.301
	EIS Tech.	0.373	0.289	0.255
	ΔASR	0.051	0.047	0.046

Additional ASR Reduction Achieved using Nickelate Cathodes

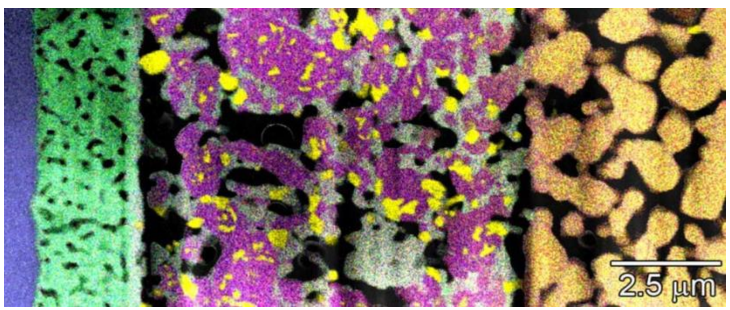
- **Candidate nickelate cathodes have ~0.02 Ohm cm^2 lower cell ASR at 860C, 4bar**



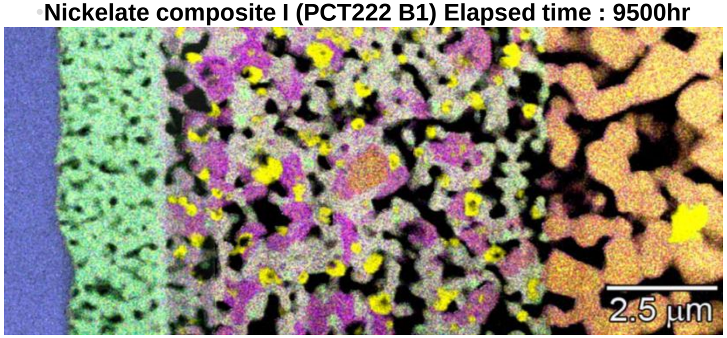
Current Status for Nickelates

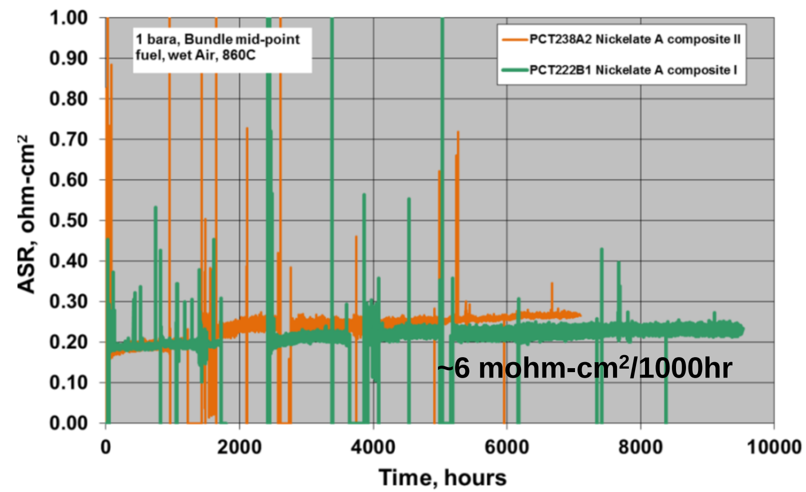
- Difficult to achieve complete phase stability
- But, still promising durability even with multiple phases present
- Recent further improvements in degree of phase instability

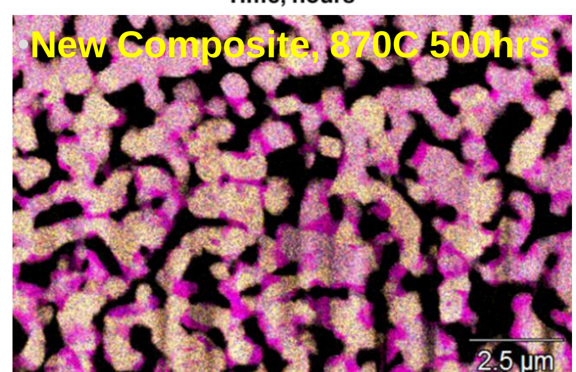
Nickelate composite II (PCT238 A2) Elapsed time : 7200hr



Nickelate composite I (PCT222 B1) Elapsed time : 9500hr





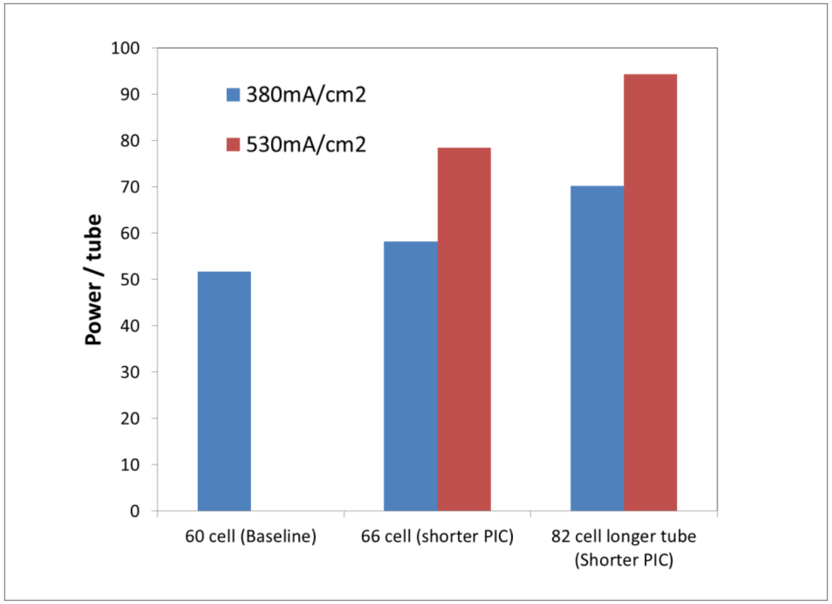


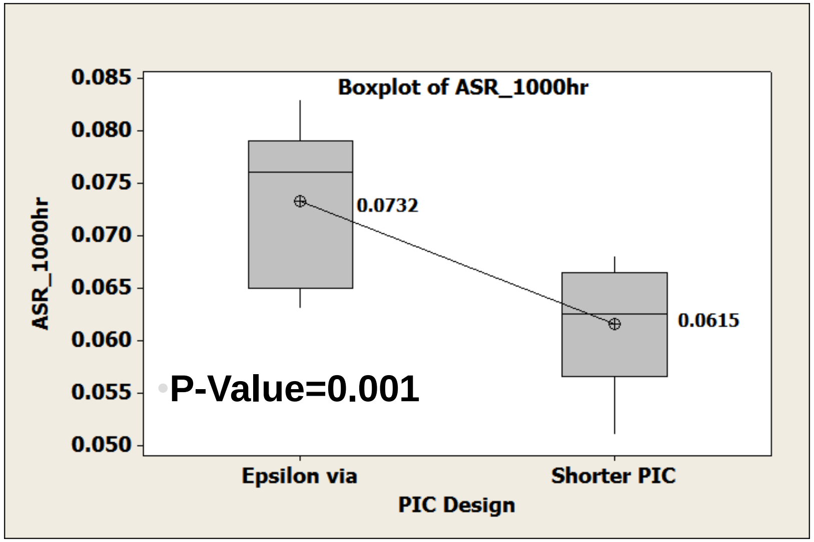
Outline

- Performance improvement
- Cost reduction
  - Cell and stack design changes
  - Current density
  - System simplification for cost reduction
- Durability
- Block Testing
- Advanced Materials and Manufacturing
- LGFCS Program

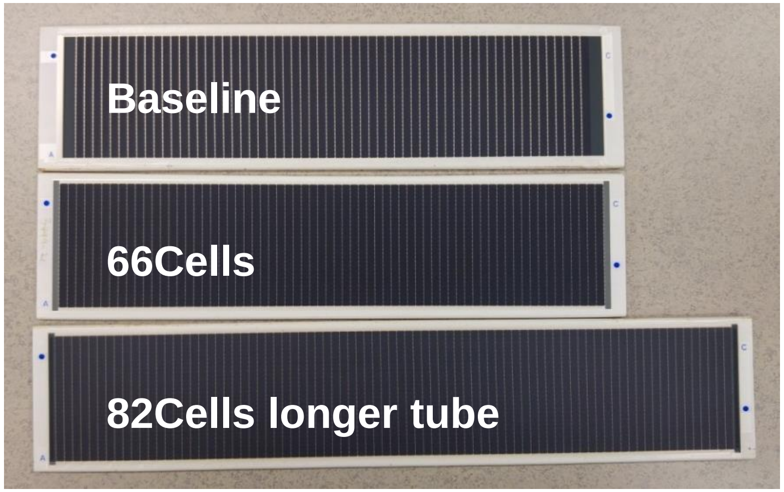
Cell & Tube Design Options for ASR Reduction & Power Increase

- Smaller PIC dimension has lower ASR contribution
- Power increased using longer tube (~100W/tube)





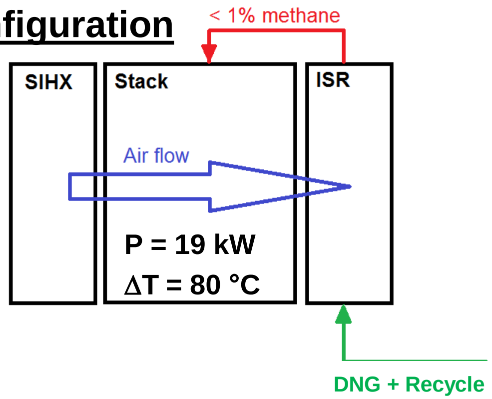
PIC ASR reduction: 0.012 Ohm cm2 (PCT)



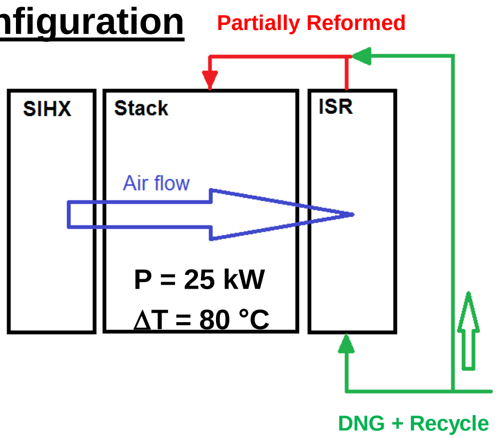
In-Block Reforming Enables Higher Power Density

- **In Block Reforming reduces stack DT to allow higher power density for the same air flow**
- **Single tube mapping tests showed no evidence of performance loss with various levels of IBR**
- **Low ASR enables higher current density while maintaining efficiency**

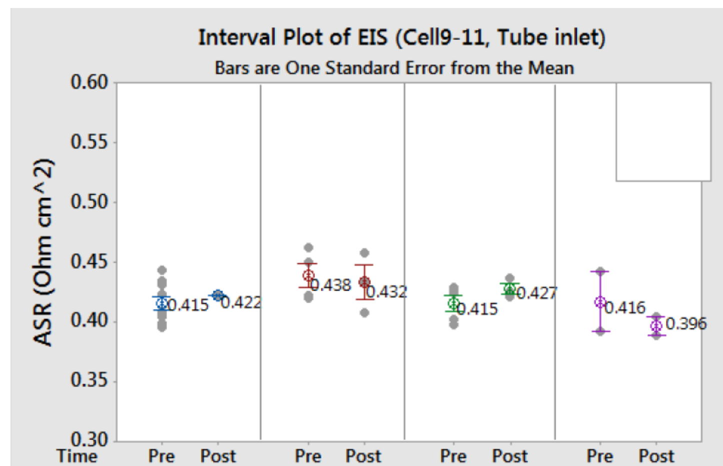
IST configuration



IBR configuration

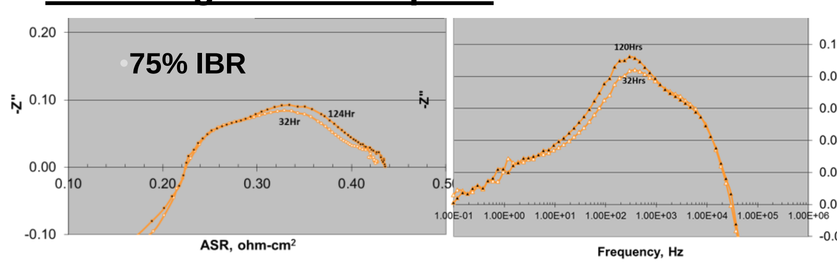


Cell performance



Increasing % IBR ⟹

No change in anode peak



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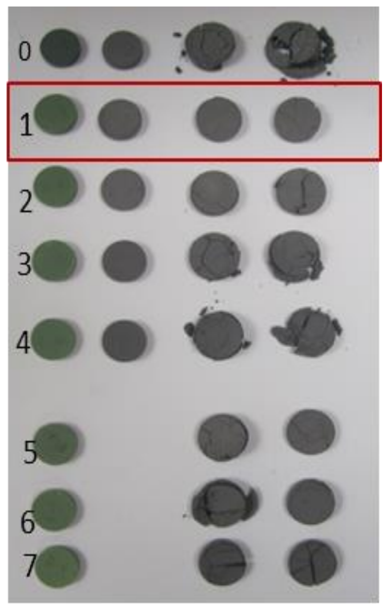
Anode Protection System Simplification for Cost Reduction

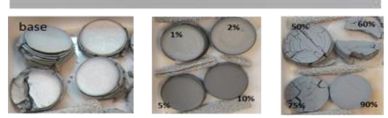
- Operational scheme results in anode redox
- A minimal number of redox cycles required for product
- cost reduction by 75% from early design of Anode Protection Unit

- Early system designs utilized a separate subsystem for system scale APG generation

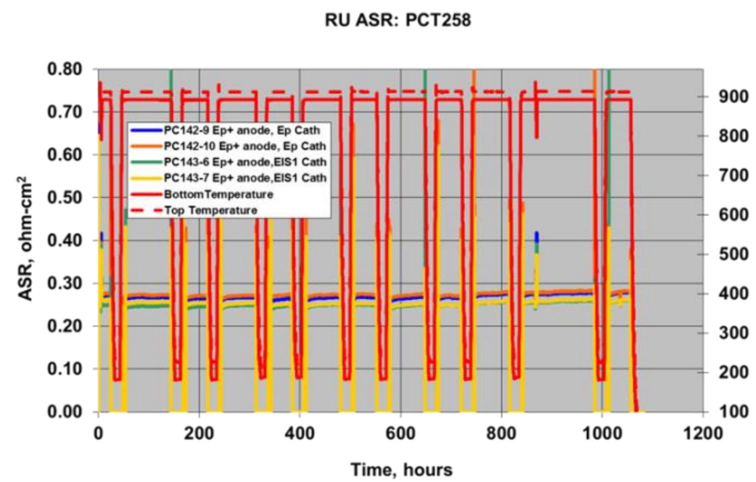
Catalytic Anode Protection Gas System

- Pellet Redox
- Exposure to air for 2 hrs at 900C
- 5 cycles





A) Additive A B) Additive B C) Additive V

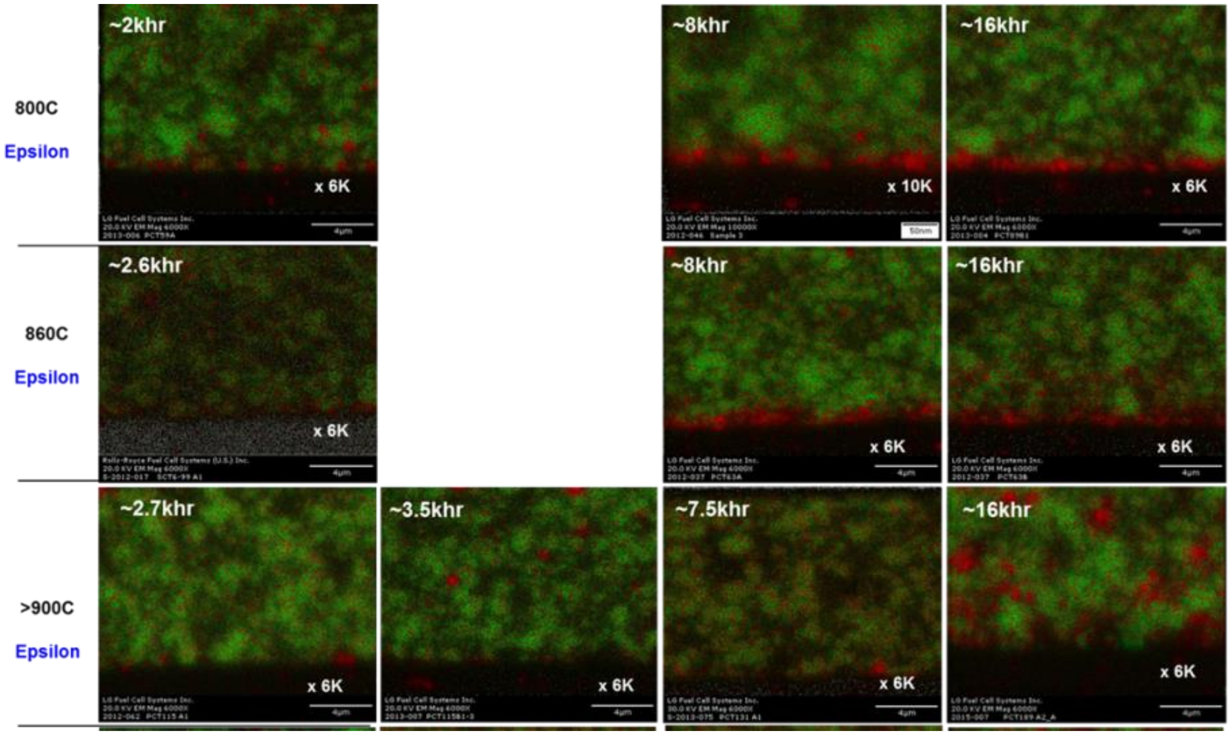


Outline

- Performance improvement
- Cost reduction
- Durability
  - Cathode
  - Anode
  - PIC
  - Degradation rate
- Block Testing
- Advanced Materials and Manufacturing
- LGFCS Program

MnOx Accumulation, Redistribution Status of Understanding, Solutions

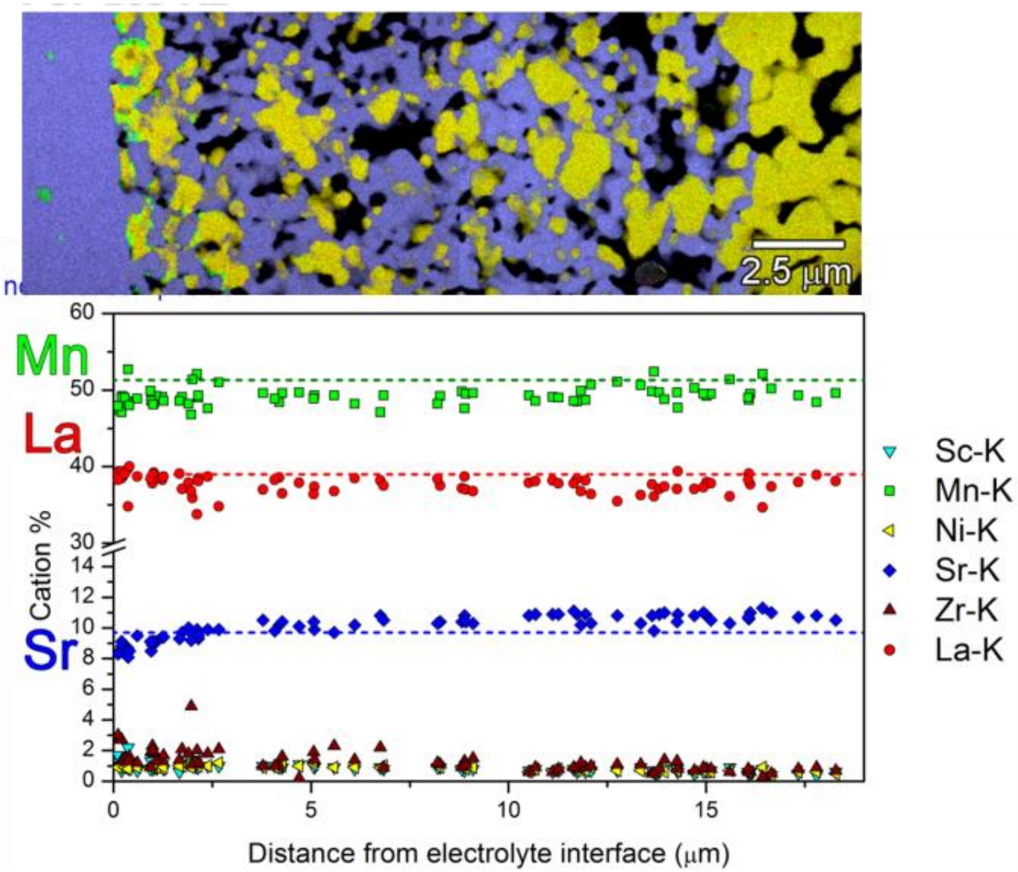
- Mn enrichment greater at low temperature



MnOx Accumulation, Redistribution Status of Understanding, Solutions

- Mn enrichment greater at low temperature

- MnOx source appears to be from throughout the cathode and CCC layers. No significant localized LSM stochiometry change
  - Even 5% A-site deficient CCC has free-MnOx as-fabricated.



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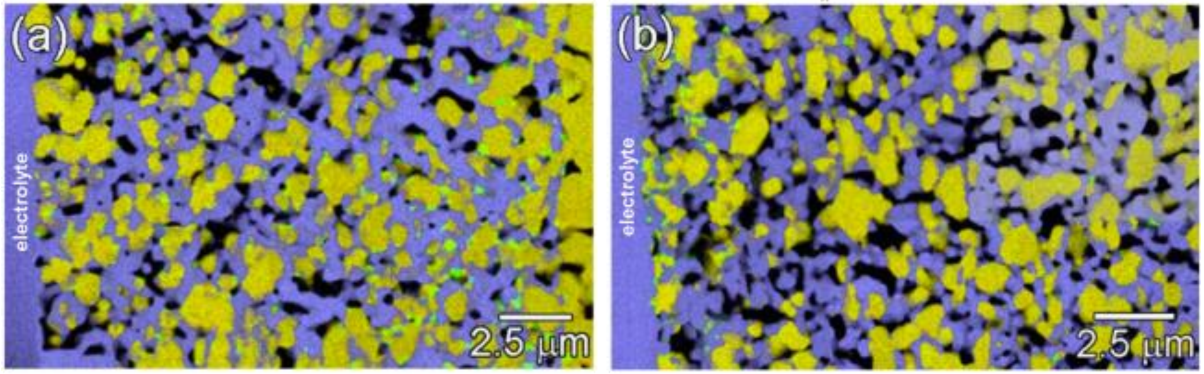
- MnOx source appears to be from throughout the cathode and CCC layers. No significant localized LSM stochiometry change
  - Even 5% A-site deficient CCC has free-MnOx as-fabricated.
- **Localized at interface (driving force?)**
  - **Overpotential and/or pO2**

Reference cell w/o current load
- MnO_x at cathode/CCC interface

Active cell with current load
- MnO_x at electrolyte
- MnO_x elimination from bulk cathode



- **Tested ~5000 hrs at 925°C and 4 bar**

Mn
LSM

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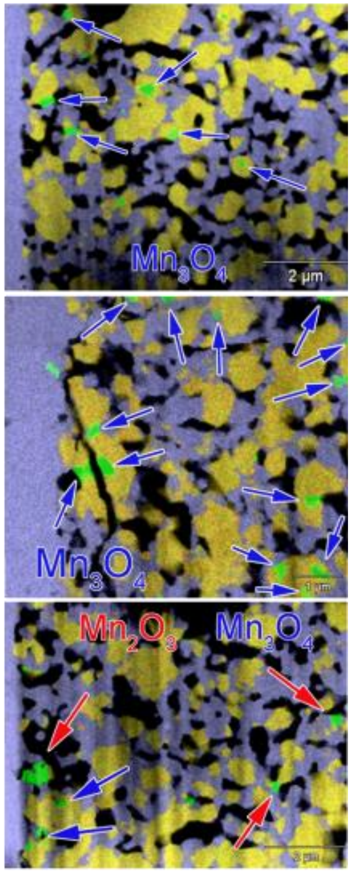
  - Even 5% A-site deficient CCC has free-MnOx as-fabricated.
- Localized at interface (driving force?)
  - Overpotential and/or pO2
- **Mn valence along interface**
  - **Using EELS**



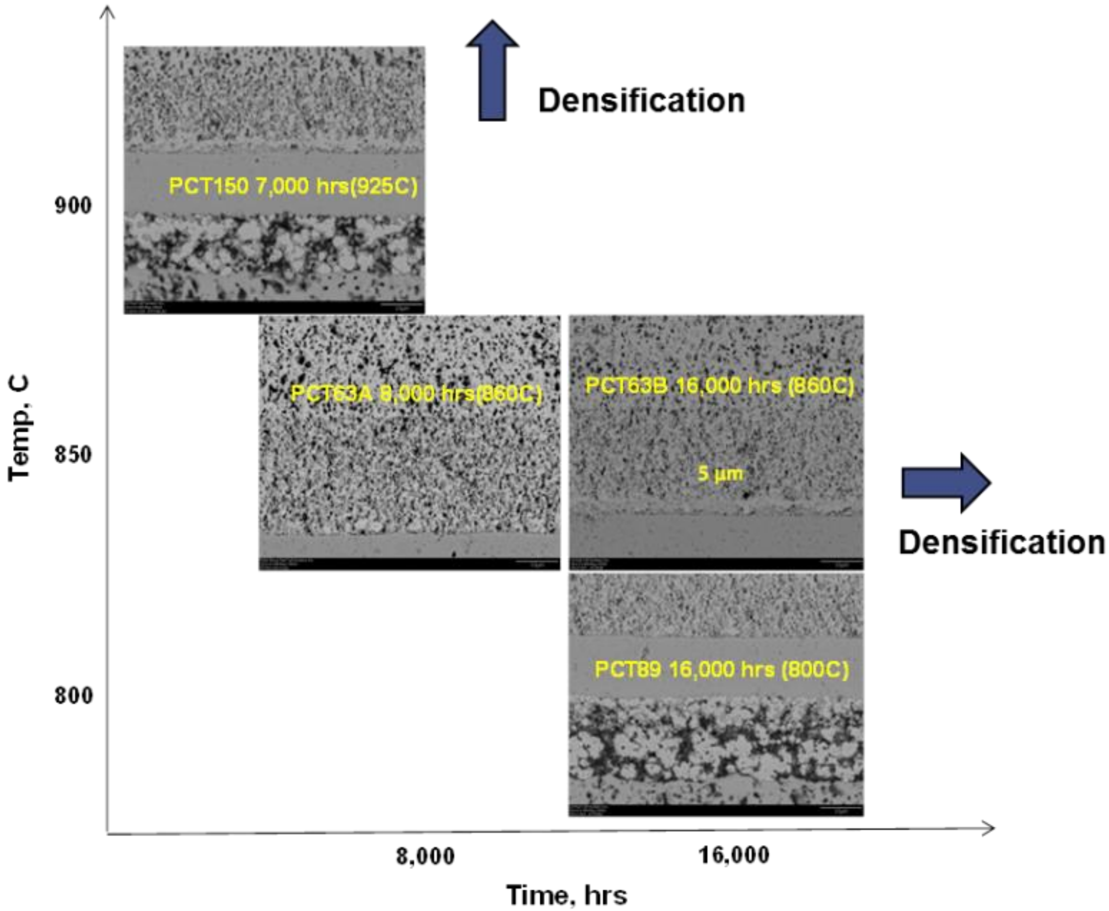
As fired

900C

800

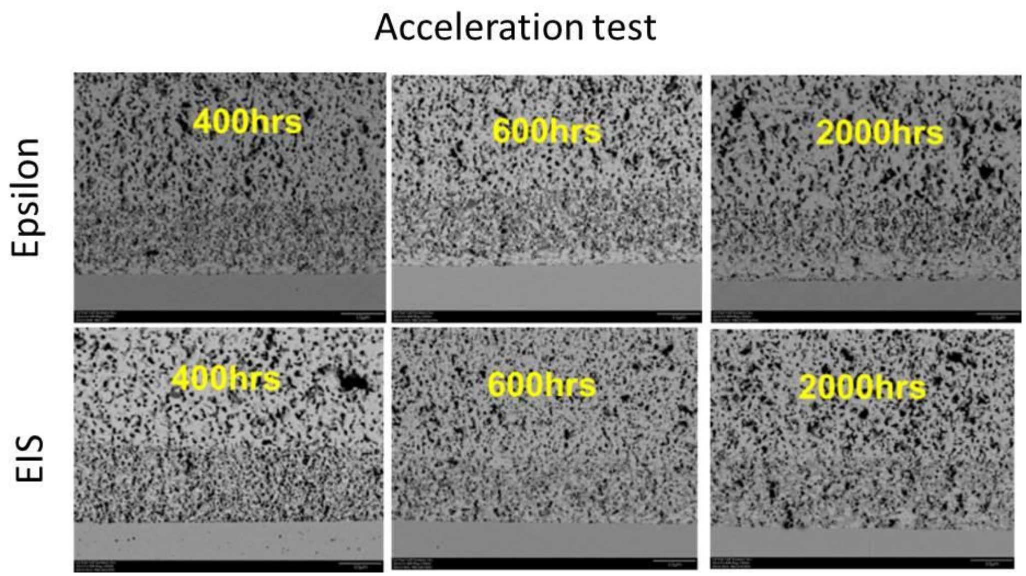
Cathode Densification – Status of Understanding, Solutions

- **Densification greater at high temperature**



Cathode Densification – Status of Understanding, Solutions

- Densification greater at high temperature
- Densification is greatest under localized low pO2 if kinetics are high
  - Pressurized SOFC benefit higher pO2
- **Degree of A-site deficiency influences densification**



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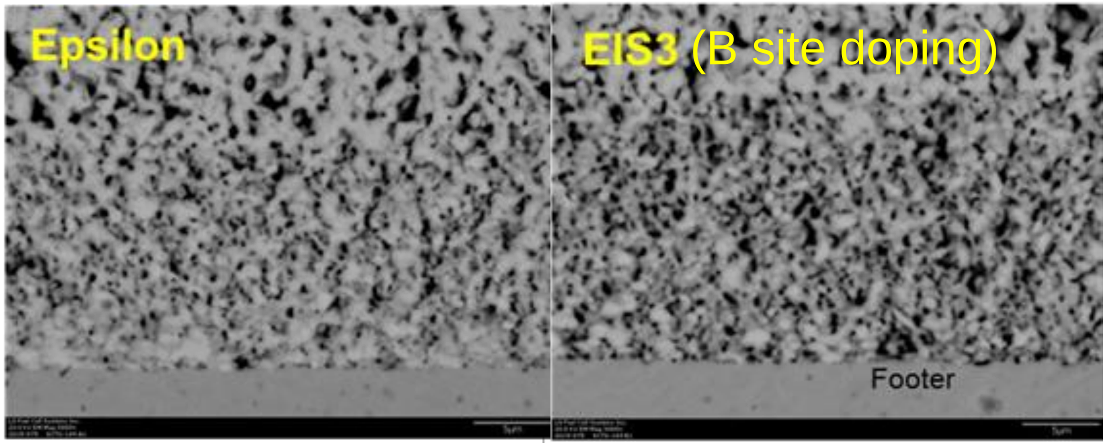
- Degree of A-site deficiency influences densification
- **B-site dopant selection can reduce densification**

Acceleration test 1000hr



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- Densification is greatest under localized low pO2 if kinetics are high
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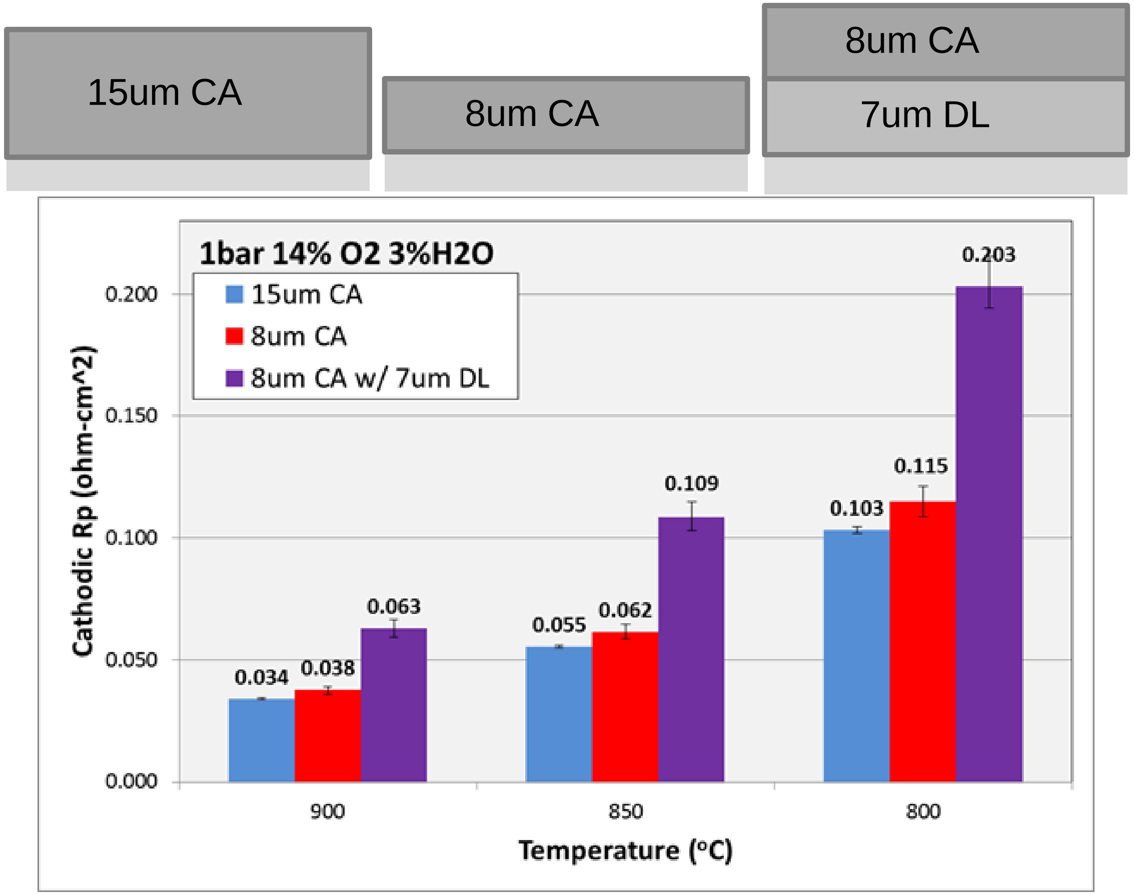
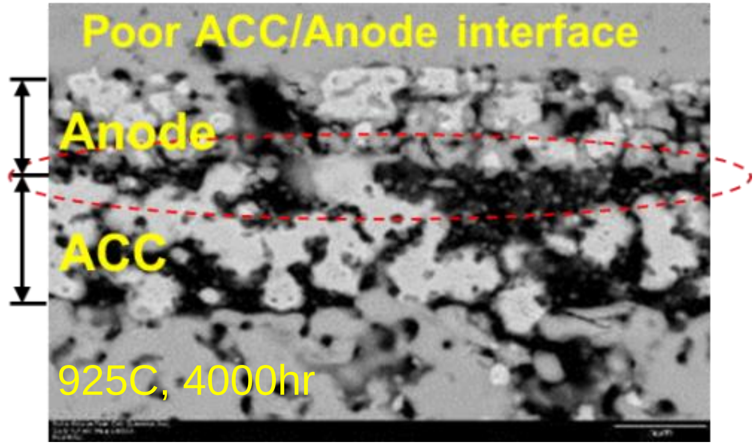
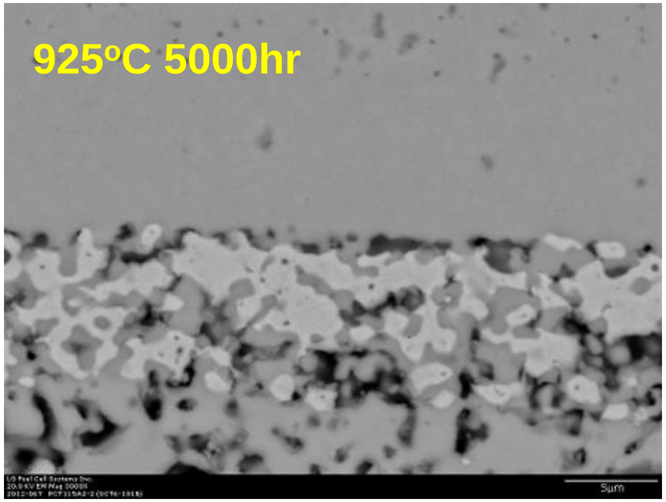
- Degree of A-site deficiency influences densification
- B-site dopant selection can reduce densification
- **Densification increases Rp**



Anode Degradation– Status of Understanding, Solutions

- **Bilayer anode+ACC versus single layer**
  - **Avoidance of interfaces resistance**



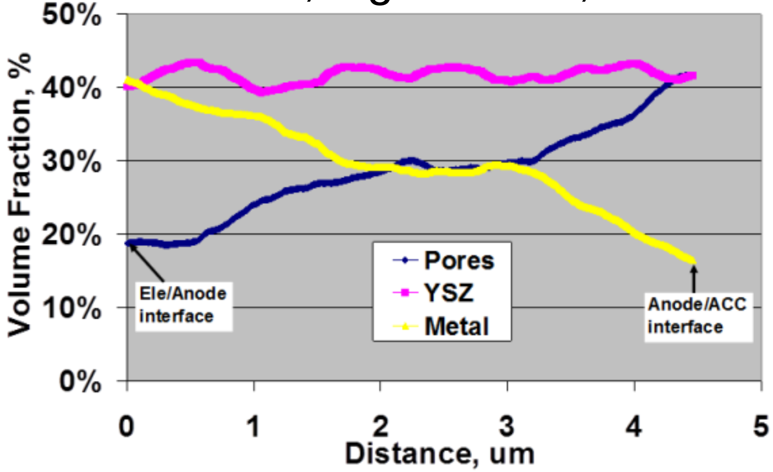


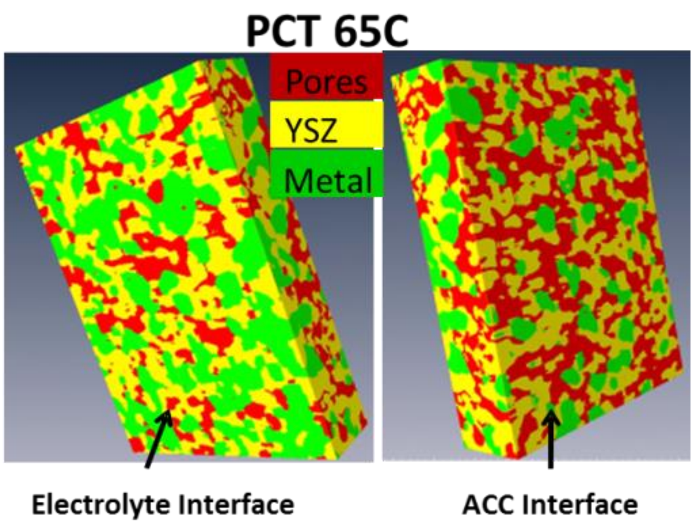
Anode Degradation– Status of Understanding, Solutions

- Bilayer anode+ACC versus single layer
  - Avoidance of interfaces resistance

- **Ni accumulation along interface at high temp and higher Uf**

925C, high steam ,4000Hr





Anode Degradation– Status of Understanding, Solutions

- Bilayer anode+ACC versus single layer
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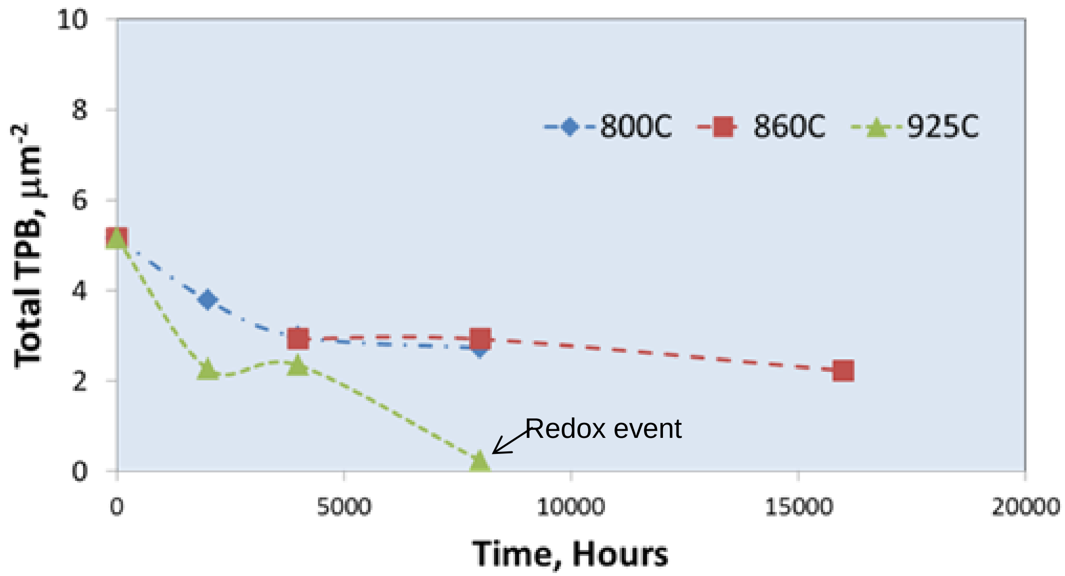
- Ni accumulation along interface at high temp and higher Uf
- **Loss of TPB**



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Anode Degradation– Status of Understanding, Solutions

- Bilayer anode+ACC versus single layer
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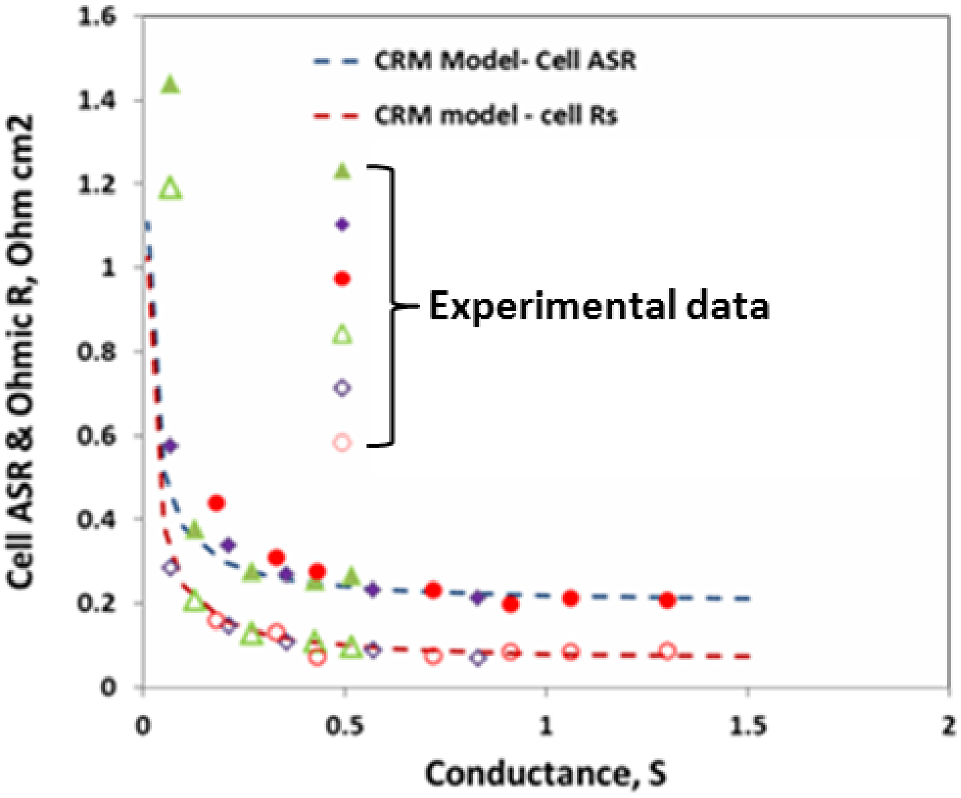
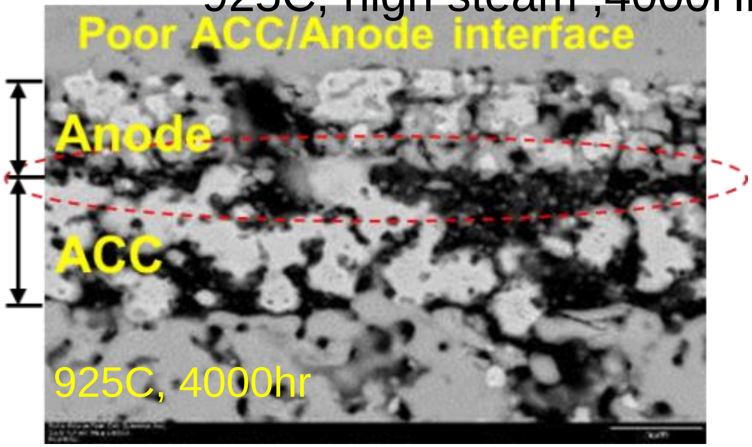
- Loss of TPB
- **Anode-side conductivity retention important for durability**

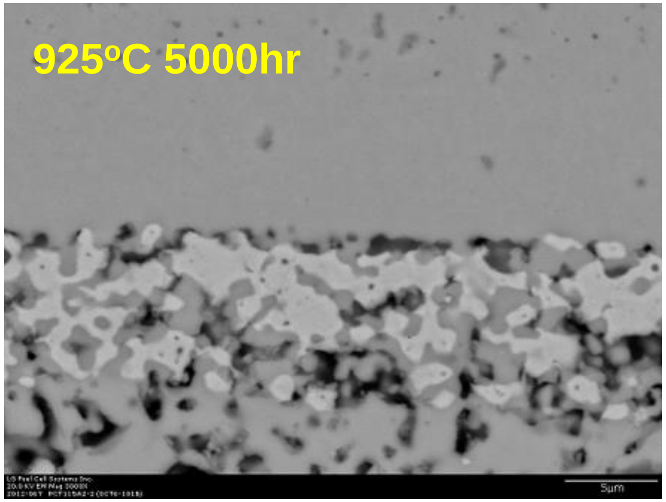


Anode Degradation– Status of Understanding, Solutions

- Bilayer anode+ACC versus single layer
  - Avoidance of interfaces resistance
- Ni accumulation along interface at high temp and higher Uf
- Loss of TPB
- Anode-side conductivity retention important for durability
- **Mn penetration through Electrolyte was not observed thus far (16000hrs)**

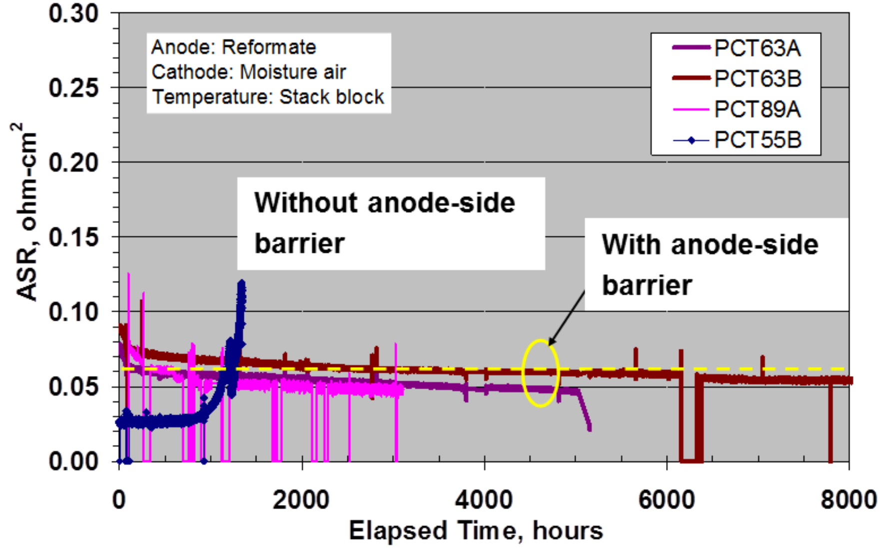
925C, high steam ,4000Hr



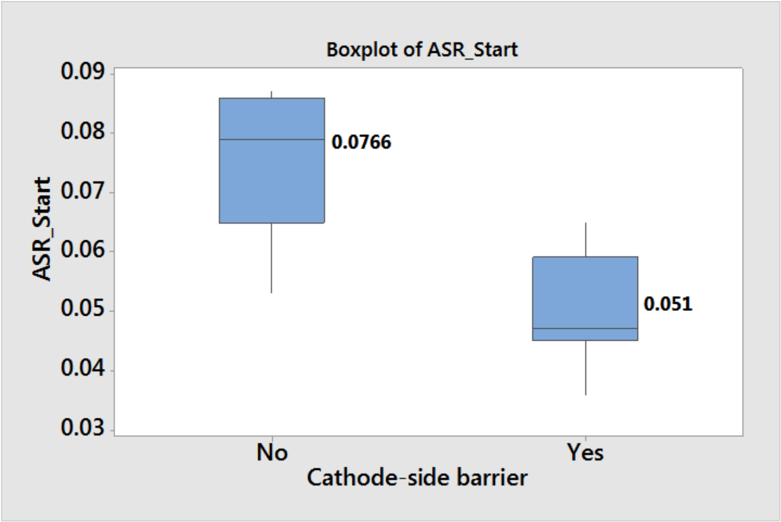


Primary Interconnect Degradation– Status of Understanding, Solutions

- Anode-side barrier layers were applied to primary interconnect region to improve durability

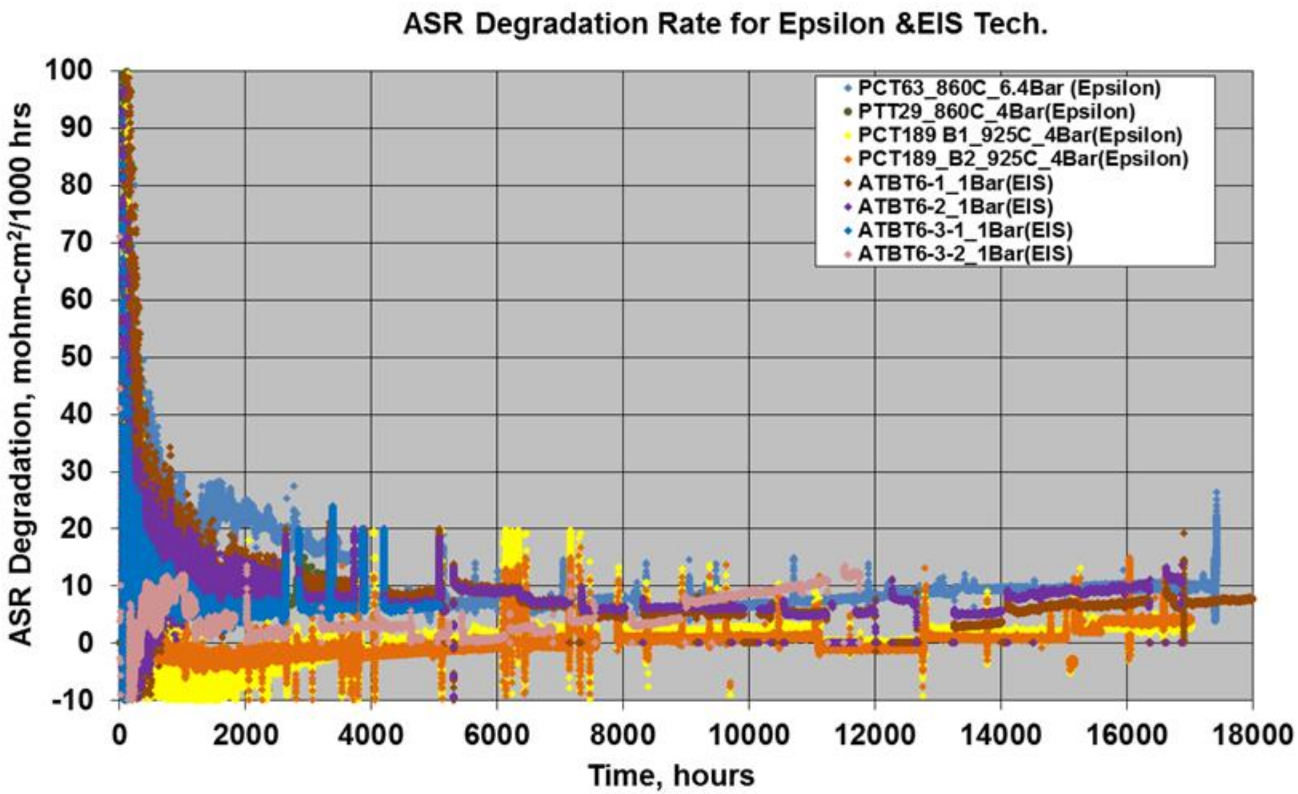


- Cathode side barrier layers further improving interface quality
  - Lower initial ASR
  - Improved long term durability



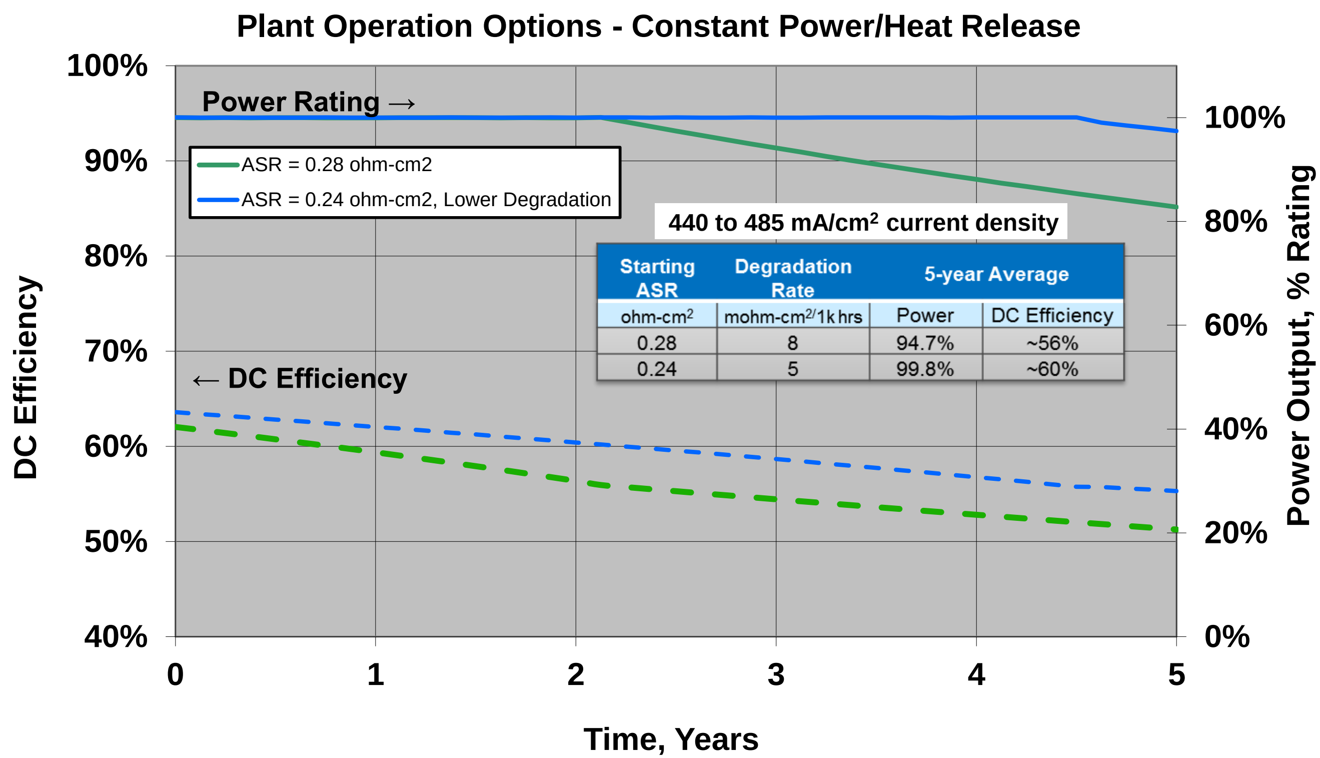
Durability Trends: 3-10 mohm-cm²/1000 hrs

- **New cathode bundle test (ATBT6) at 1 bar demonstrated < 7 mohm-cm²/1k hrs over 2 year test**
- **Subscale cells (PCT189) demonstrated < 3mohm-cm²/1k hrs over 2 year test**
  - **Correspond to 0.10~0.15%/1000hr power degradation rate**



Plant Life Improved with Lower ASR and Degradation Rate

- Reduction of degradation rate from 8 to 5 mohm-cm^2/1k hrs with ASR of 0.24 ohm-cm^2 permits nearly constant power operation over 5 year life
  - ASR reduction using lower cathode Rp + Shorter PIC + thin wall substrates > 0.04 Ohm cm^2
- Average efficiency also significantly higher

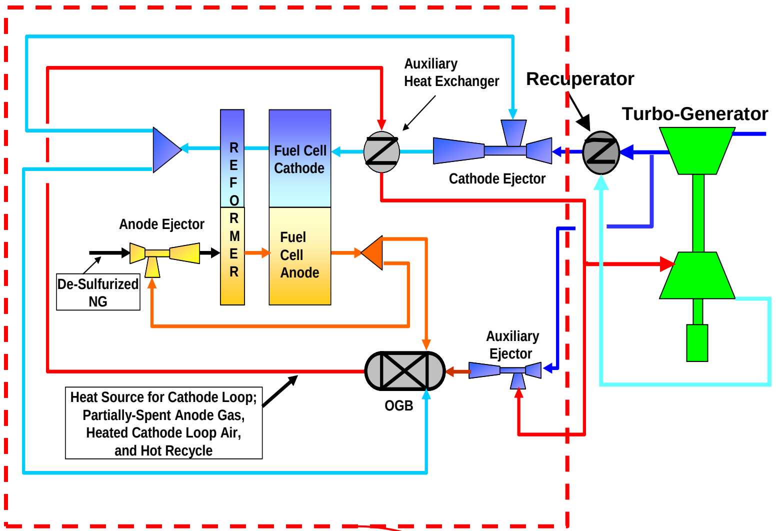


Starting ASR	Degradation Rate	5-year Average	
ohm-cm^2	mohm-cm^2/1k hrs	Power	DC Efficiency
0.28	8	94.7%	~56%
0.24	5	99.8%	~60%

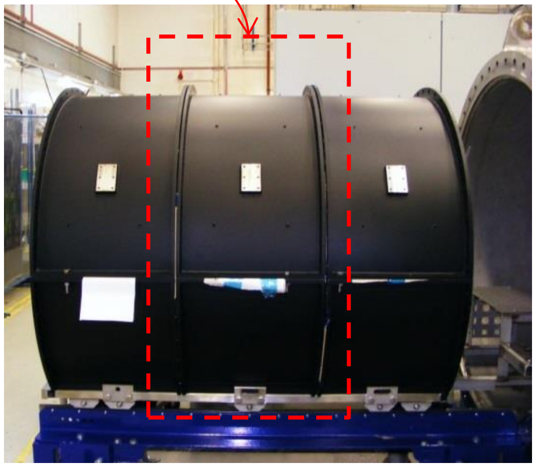
Outline

- Performance improvement
- Cost reduction
- Durability
- **Block Testing**
  - **Block Test T1418 & T1315**
  - **IBR Block Test T1506**
- Advanced Materials and Manufacturing
- LGFCS Program

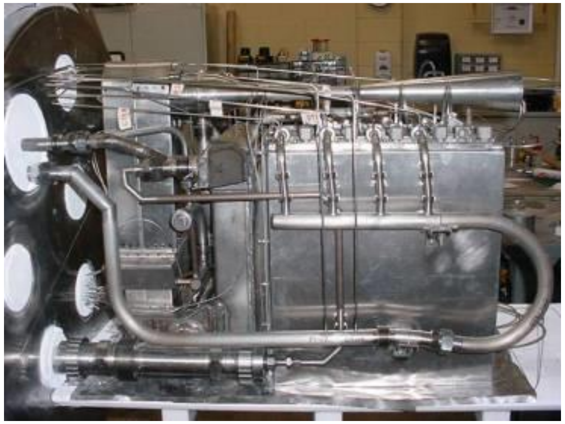
Block Testing Matching Product Cycle, Components and Operating Conditions



Integrated block Design for product (T1506)



Initial design of block testing rigs
Representative of cycle and components
Not packaged for product (T13xx, T14xx)



T1418: First Block Test of EIS Technology

Test Identification

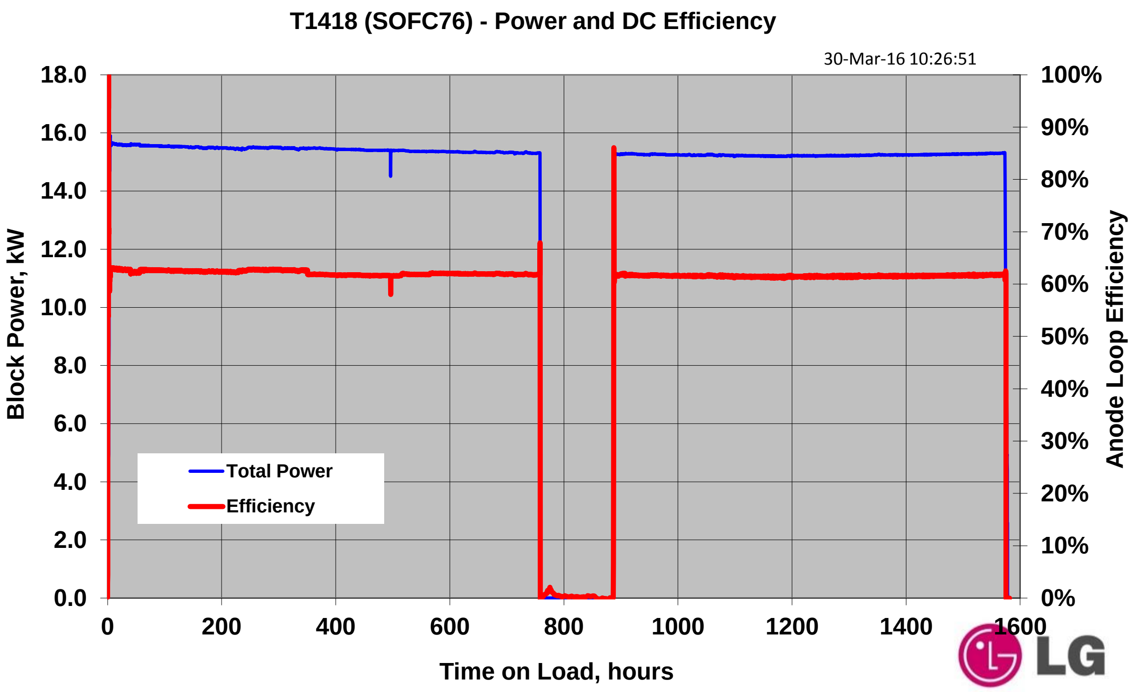
- Strip 1 – EIS1 cathode & lower ASR interconnect
- Strips 2-4 IST (Epsilon) standard strips

Test Objectives

- Test 5000 hours with power degradation < 0.75%/1000 hrs

Results

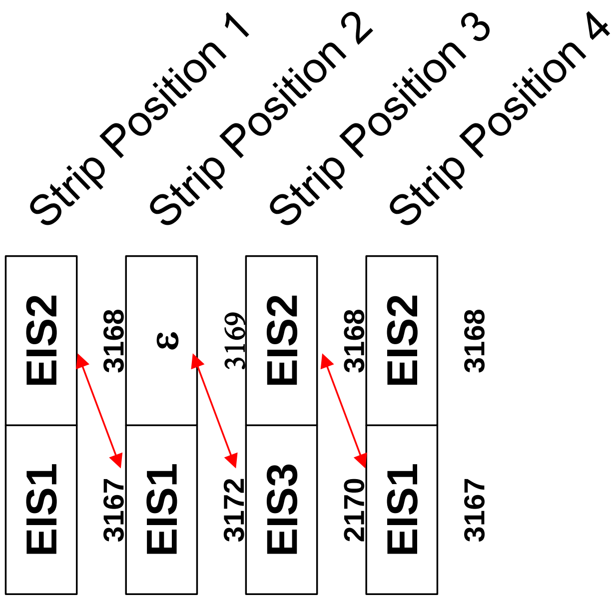
- 1.30% Power Degradation/1khrs
  - 0.30 ohm-cm^2 ASR at 1500 hours was as expected
- Average DC Efficiency ~ 62%
- Completed 1450 hours on load
  - Test run short due to BOP issues
  - Decision to convert rig to IB standard



T1315: EIS Cathode Screening Block Test

Test Identification

- 4 different cathode configurations
  - Standard IST (epsilon)
  - 3 EIS candidates
- Lower ASR interconnect
- IST (Epsilon) standard anode

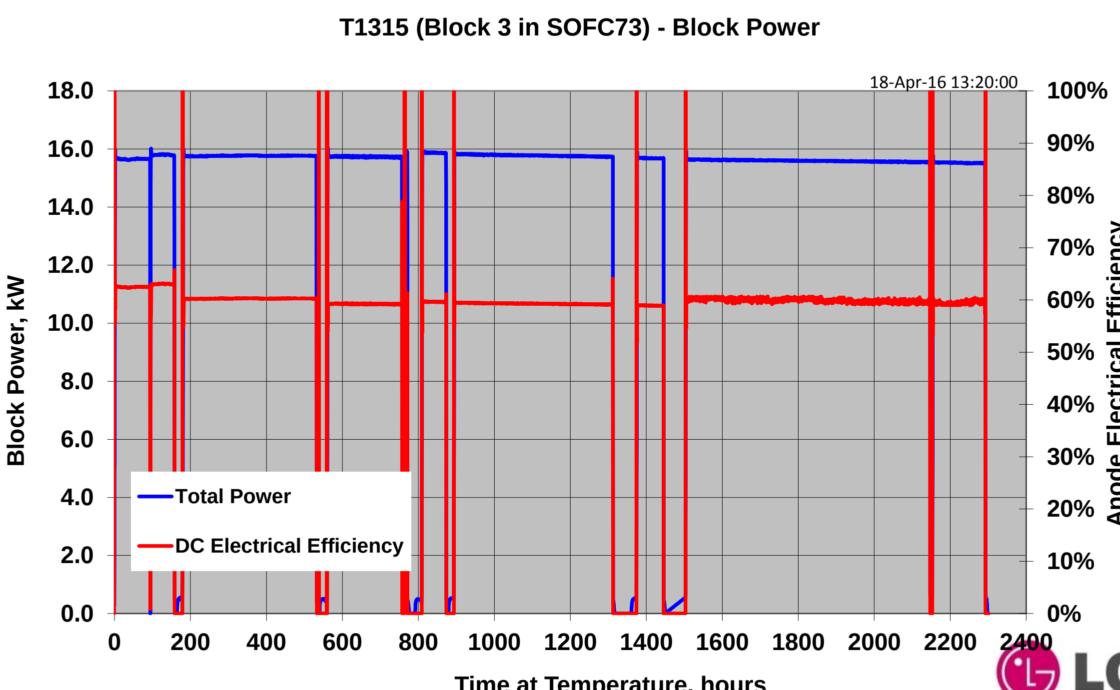


Test Objective

- Test 2000 hours with power degradation < 1.5%/1000 hrs

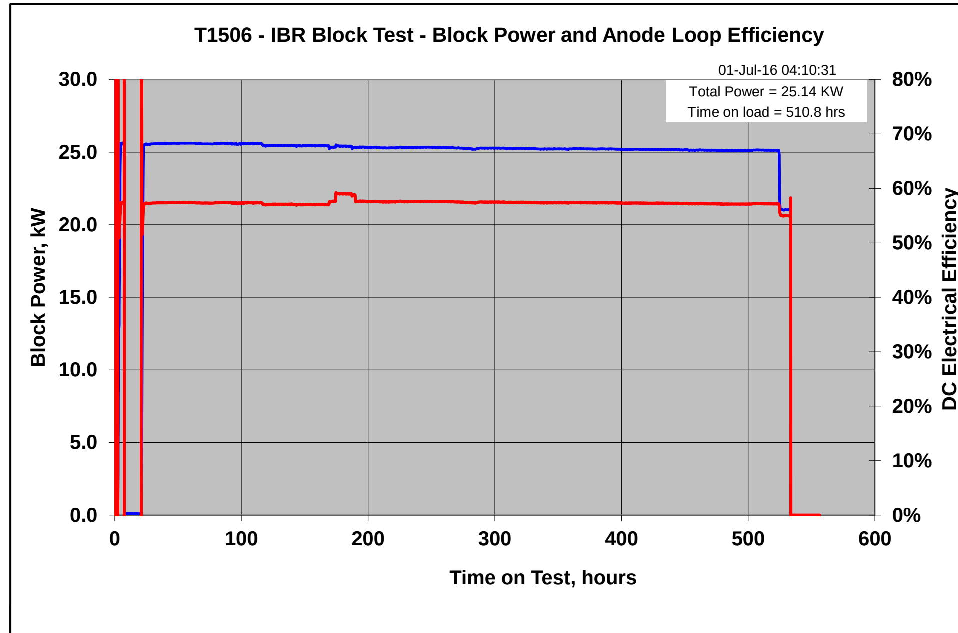
Results

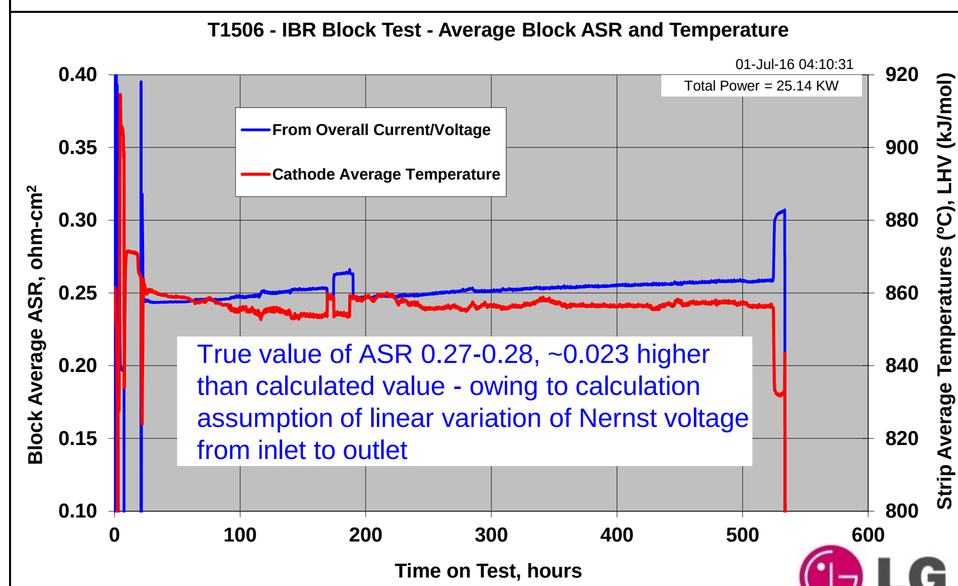
- 0.78% Power Degradation/1khrs
- Average DC Efficiency ~ 60%
- Completed 2049 hours on load

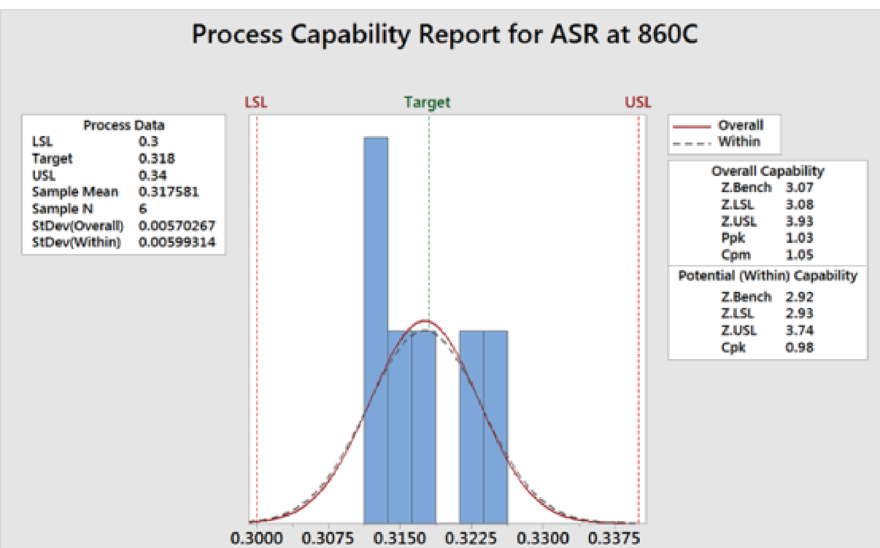


T1506: Demonstration of In-Block Reforming

- Initial power 25.6 kW
  - Highest single block power
- Test duration 511 hours on load
- Lowest block ASR tested
- Achieved <80°C dT
- Strip Technology
  - EIS1 Cathode
  - Lower ASR interconnect

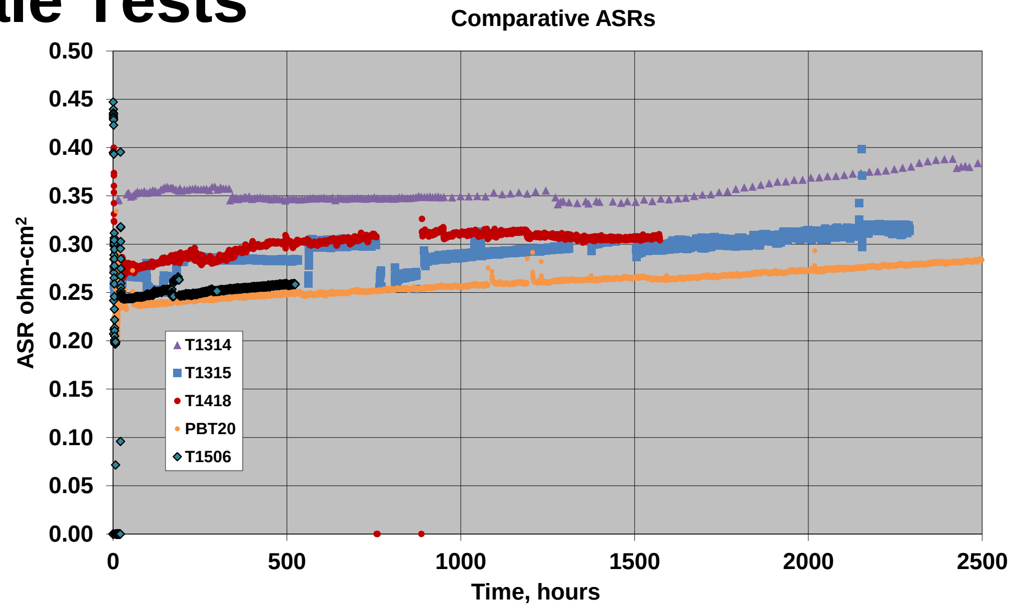




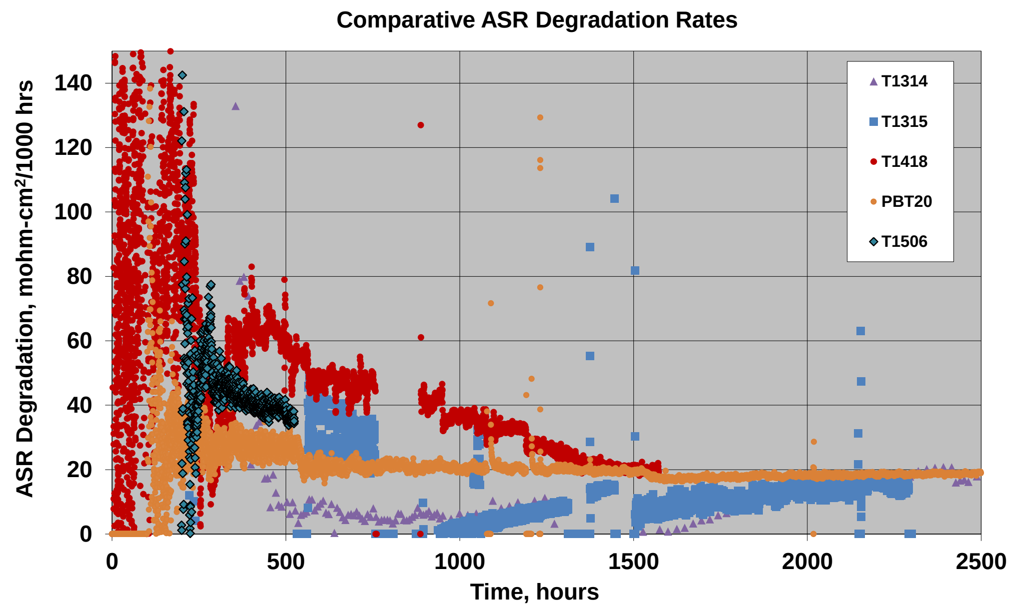


IBR Block Performance:
Within Range of Sub-scale Tests

- **Improved block ASR from T1314 to T1315/T1418**
- **Excellent correlation from bundle PBT20 to block T1506**



- **ASR degradation rates tend to converge after longer test periods**



Block Performance Summary

Parameter	T1314	T1418	T1315	T1506
Initial Power (Normalized for 5 strips)	18.8 kW	19.5 kW	19.7 kW	25.6 kW
Starting ASR (ohm-cm^2)	0.35	0.28	0.28	0.27 [Note 1]
Current Density (mA/cm^2)	380	380	380	530
Fuel (@ 75 – 80% Uf)	Bottled CH_4	PNG	Bottled CH_4	PNG
Power Degradation (per 1000hrs)	1.2%	1.3%	0.78%	Note 2
Duration (hours)	3040	1450	2049	520 [Note 3]
Cell Technology	Pre-Eps	Eps, EIS	EIS	EIS + IBR

Note 1: Accounting for non-linear Nernst voltage
Note 2: Power Degradation rate given once test accumulates >1000hrs of test time
Note 3: Still under test

Outline

- Performance improvement
- Cost reduction
- Durability
- Block Testing
- **Advanced Materials and Manufacturing**
  - **Task 2.0**
  - **Task 3.0**
- LGFCS Program

Advanced Materials and Manufacturing

- Task 2.0: Identify Candidate Components
  - Cathode and Anode Ejectors
  - Cathode and Anode Pipework
- Task 3.1: Identify Materials
  - Anode Ejector (low temp.) - continue using SS 310/316
  - Auxiliary Ejector (high temperature) materials considered
    - H120, RA330, AFA25, 601, and 230
- Task 3.2 Identify Processes

• additive manufacturing (AM)	• spin forming
• metal injection molding (MIM)	• lost wax casting
• hot isostatic pressing (HIP)	• other processes

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Advanced Materials Project Status Summary

- **Key Findings**
  - **Five candidate alloys identified based on material requirements**
  - **Preliminary cost study suggests ~50% reduction for aux. ejector**
  - **Metal Injection Molded (MIM) coupling fitting cost ~$8 & $9 at 50 MW quantities**
    - **Estimated 77% - 89% cost reduction vs low-volume machined component**
- **Lessons Learned**
  - **Additive Manufacturing Process is only cost effective for the complex nozzle assembly**
  - **Other manufacturing processes are being explored**
    - **spin forming**
    - **lost wax casting**

Summary

- **Significant progress made regarding performance improvements and durability. There is a better understanding on how to increase the life of the LGFCS fuel cell. These improvements will have a direct impact on reducing costs.**
- **Block testing, though challenging, has shown that ASR tracks across multiple scales. Improvements in cell technology and system performance allowed for LGFCS's best block test to date.**
- **The advanced materials and manufacturing project continues to support material selection and cost reduction of critical components.**

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