Update on the Rolls-Royce Coal-Based SECA Program

27th July 2010

Richard Goettler and Ted Ohrn

Outline

- FY2010 Highlights
- Rolls-Royce Fuel Cell Business
- Stack Technology
- IGFC System Design
- Substrate Requirements
- Cell Performance
- Cell and Stack Durability
- Next steps & Conclusions

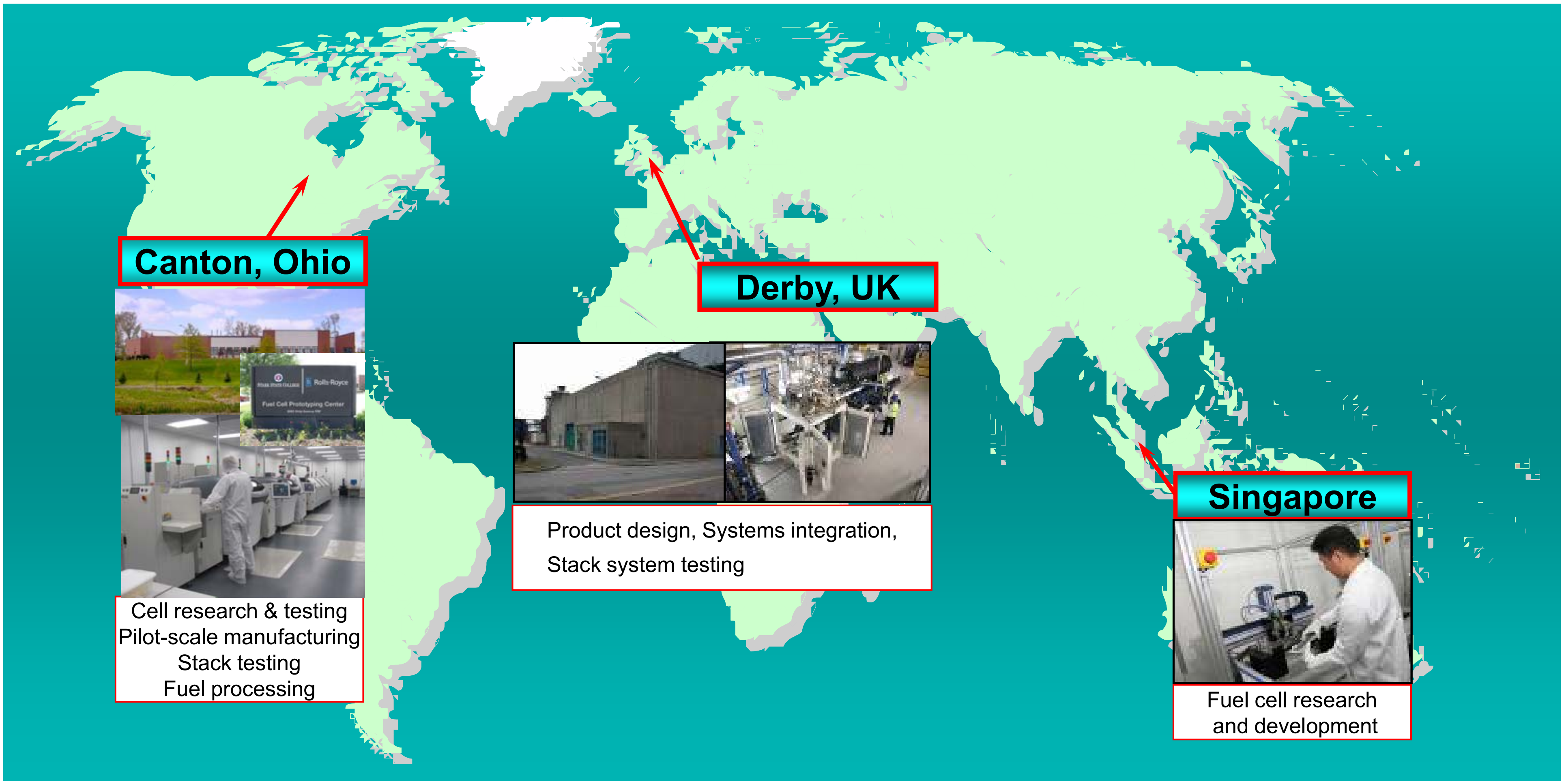
Highlights

- Cell and stack manufacturing capability established in Canton, Ohio
- Stack average repeat unit ASR reduced to 0.32 ohm-cm^2, technology demonstrated for further reductions
- Stack components optimized to meet 80% fuel utilization
- Reduced degradation mechanisms associated with interconnect and anode-side materials
- Addressed a cathode-moisture effect impacting ASR, and screened alternate cathodes for moisture tolerance
- Completed stack cost model

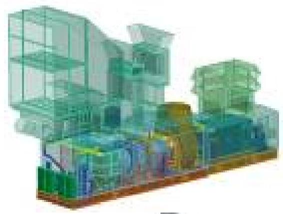
RRFCS SECA Program

- Start date: Sept. 2009 with pre-award activities
- Phase 1 extending through June 2011
  - 15 kW stack test
- Partners
  - ORNL, mechanical characterizations
  - PNNL, glass sealant studies
  - UCONN, metals chromium volatility
  - CWRU, detailed analytical studies

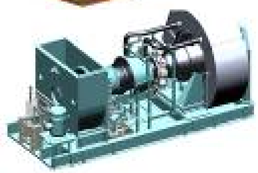
Rolls-Royce Fuel Cell Systems Limited
Locations



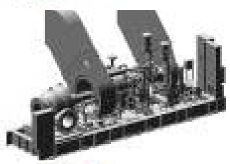
Rolls-Royce Energy Business



Trent 60 – 58MW



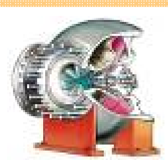
RB211 – 32MW



501 / Avon 5 – 14MW

Recips 1.2 – 8.5MW

Fuel Cells 1MW Market Entry – follow on can be larger

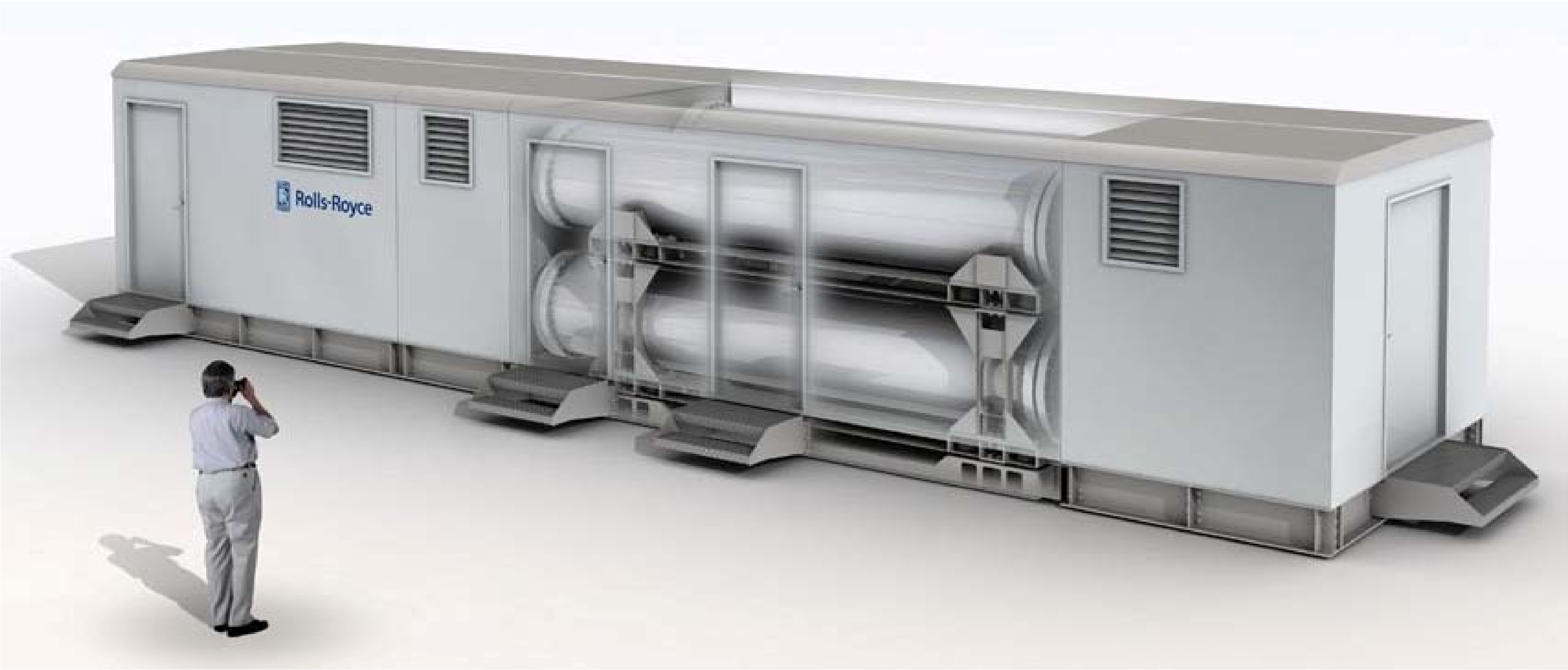


Compressors – 37MW

Rolls-Royce data

Rolls-Royce Fuel Cell Systems is creating…

- A cost competitive distributed energy solution
- Potential net-AC electrical efficiencies >60%
- Very low environmental impact, quick wins on air quality



Rolls-Royce data

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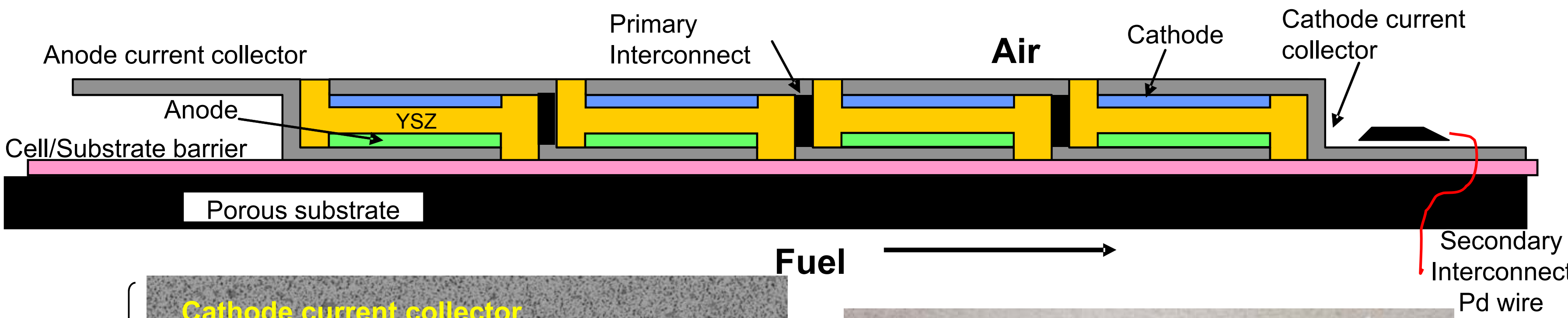
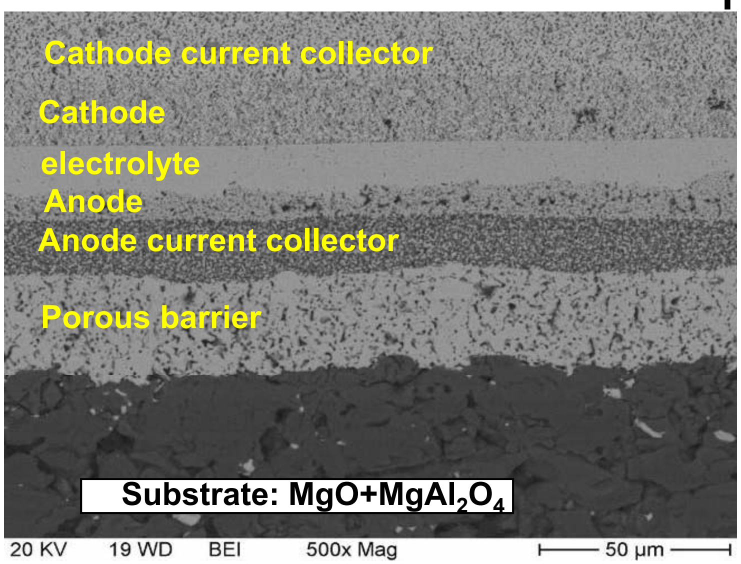
Rolls-Royce Integrated Planar Solid Oxide Fuel Cell



LSM-based

YSZ:ScSZ

Ni-based
cermets



- Integrated planar series arrangement – high voltage, low current
- Ceramic support material uses low cost $MgO+MgAl_2O_4$ powder, low cost extrusion
- Low-cost screen printing of cell active layers

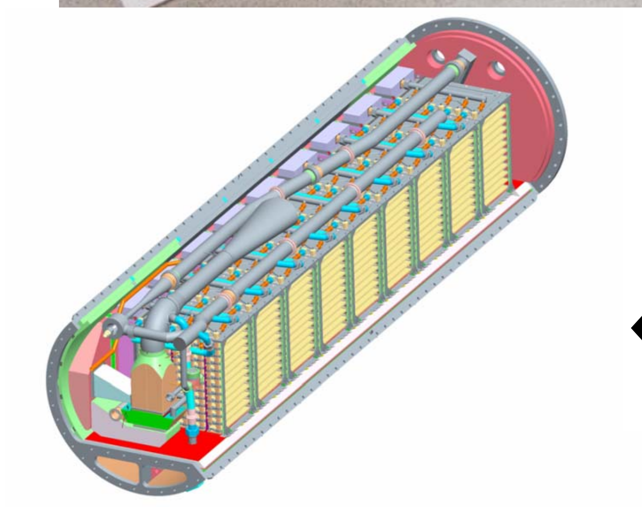
Current Stack Configuration

Tube assembly, 60W

Bundle assembly, ~350W

Block assembly, ~20kW

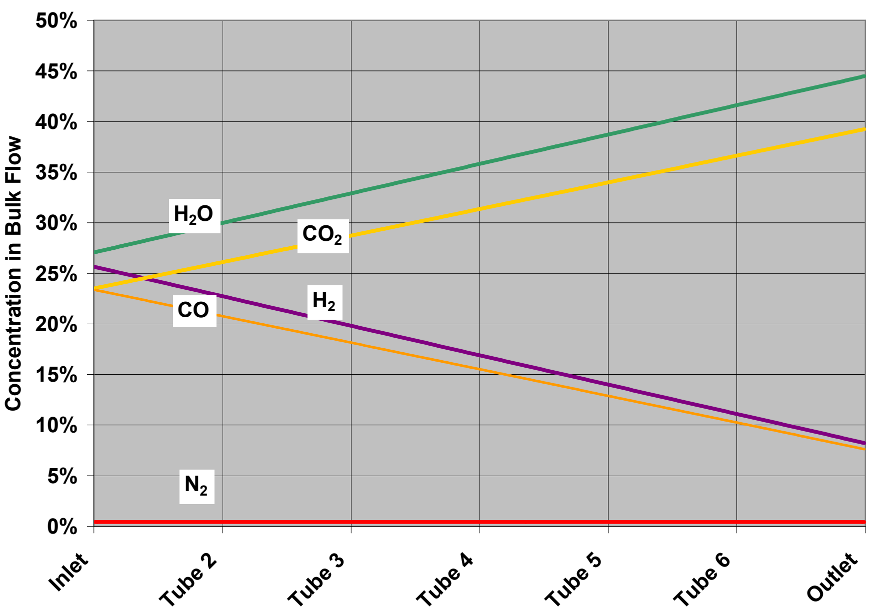
(5 strips of 12 parallel bundles)

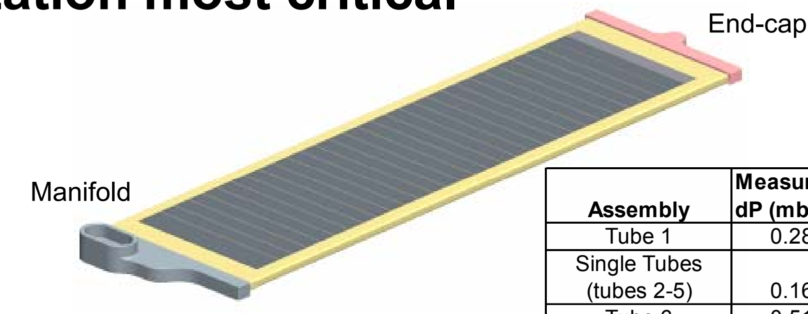


1MW System will be 250kW tiers with larger block sizing

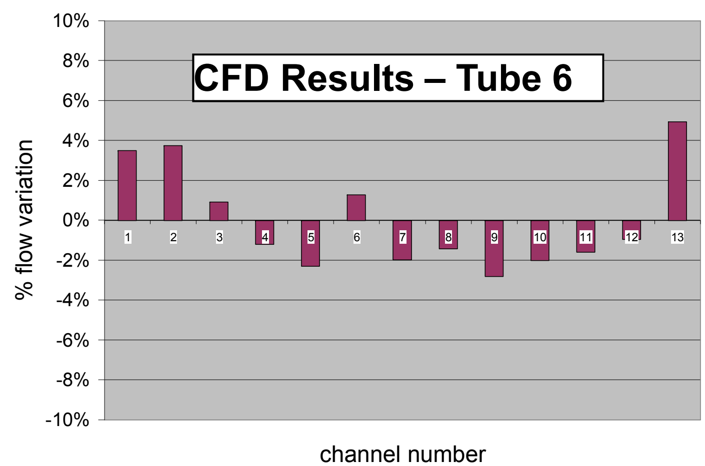
Stack Optimization for High U_f and Efficiency

- **Achieved improved flow distribution within bundles**
  - **Modified end-cap and manifold designs for pressure drop**
- **Tube 6 with higher fuel utilization most critical**



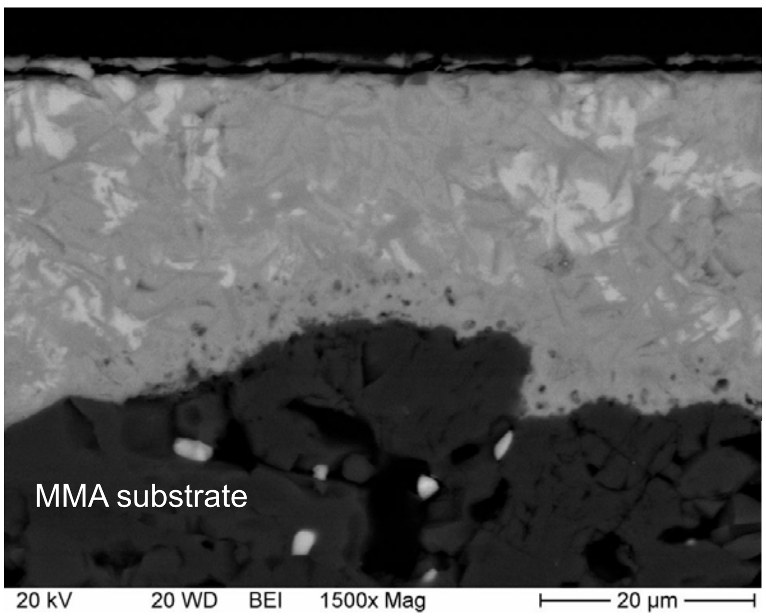


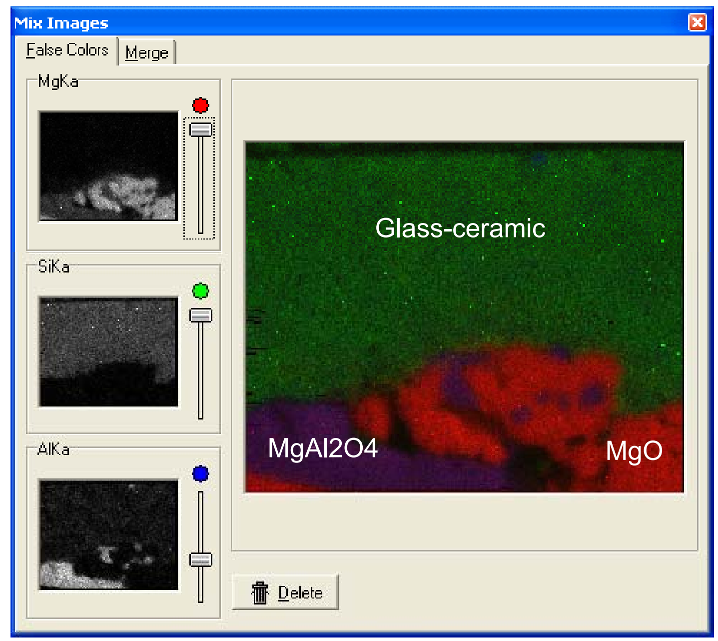
Assembly	Measured dP (mbar)	Modelled dP (mbar)
Tube 1	0.283	0.324
Single Tubes (tubes 2-5)	0.169	0.179
Tube 6	0.519	0.539



Glass-Substrate Interactions

- RRFCS has screened glass-ceramic sealants from several suppliers.
- Selected glass has provided adequate sealing and joining to dense MMA in 12,000 hour testing (limited cycling)
- Phase analysis of glass and interfaces underway at CWRU
- PNNL to suggest glasses for higher CTE substrates

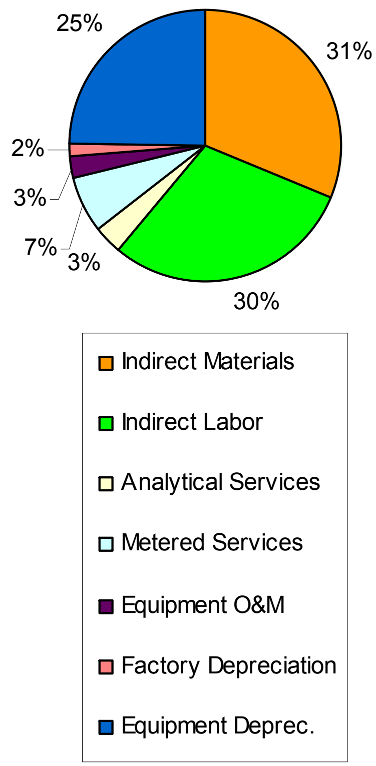


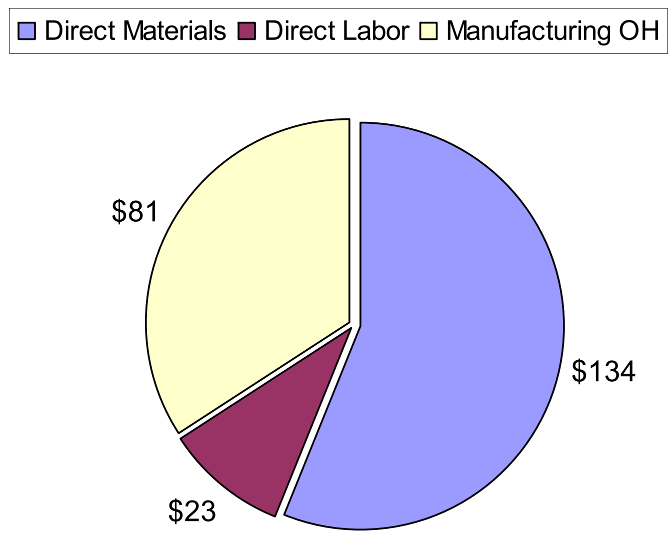


2100 hrs (900C+950C, 1 bar) + 1400 hrs (900C, 6.5 bar)

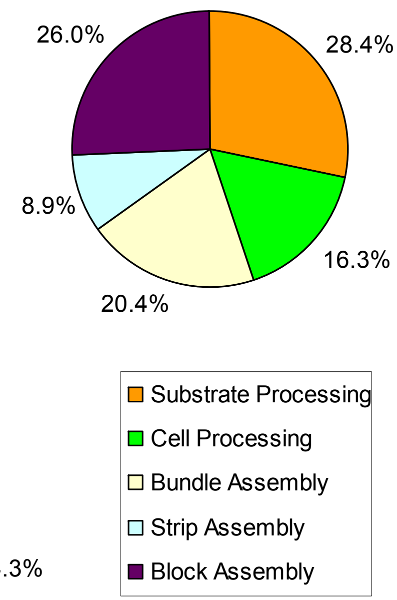
Distribution of Production Costs

Stack Cost Projected at $238/kW

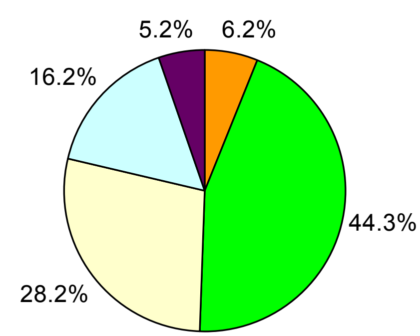




Direct Materials



Direct Labor



Metric	Value
Production Input (substrates/yr	5,168,095
Production Output (blocks/yr)	7,878
Production Line Yield	77%
Production Capacity (MW)	255

Canton Manufacturing Facilities

Print line matching that used within RRFCS since 2005
Approximately 50,000 active substrates produced at RRFCS

X-ray inspection of bundles

Assembly firing of strips

Rigs for QA testing of manufactured active substrates
(2 of 4 scheduled install Aug '10)

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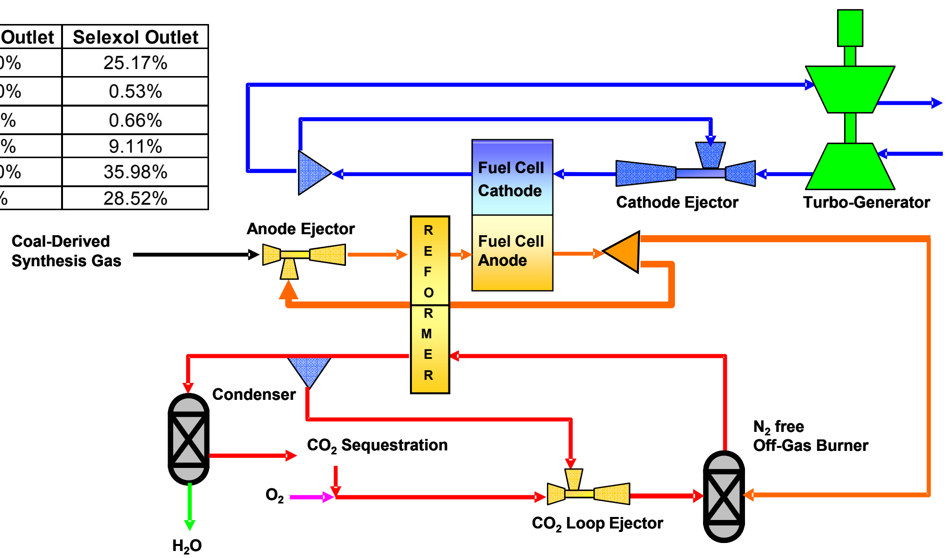
Selected SOFC cycle for IGFC Plant

- **Switched from warm gas clean-up (RTI) to cold clean-up (Selexol)**
  - **High steam content with warm clean-up limited anode loop to single pass**
  - **Dried gasifier syngas from Selexol allows anode recycle**
- **IGFC plant lay-out still under consideration**
  - **IGFC combined cycle design, stack/tier configuration, turbo-generator size, tier cluster arrangement**

Species	Gasifier Outlet	Selexol Outlet
H_2	15.50%	25.17%
H_2O	41.40%	0.53%
N_2	0.30%	0.66%
CO	4.80%	9.11%
CO_2	20.00%	35.98%
CH4	18%	28.52%

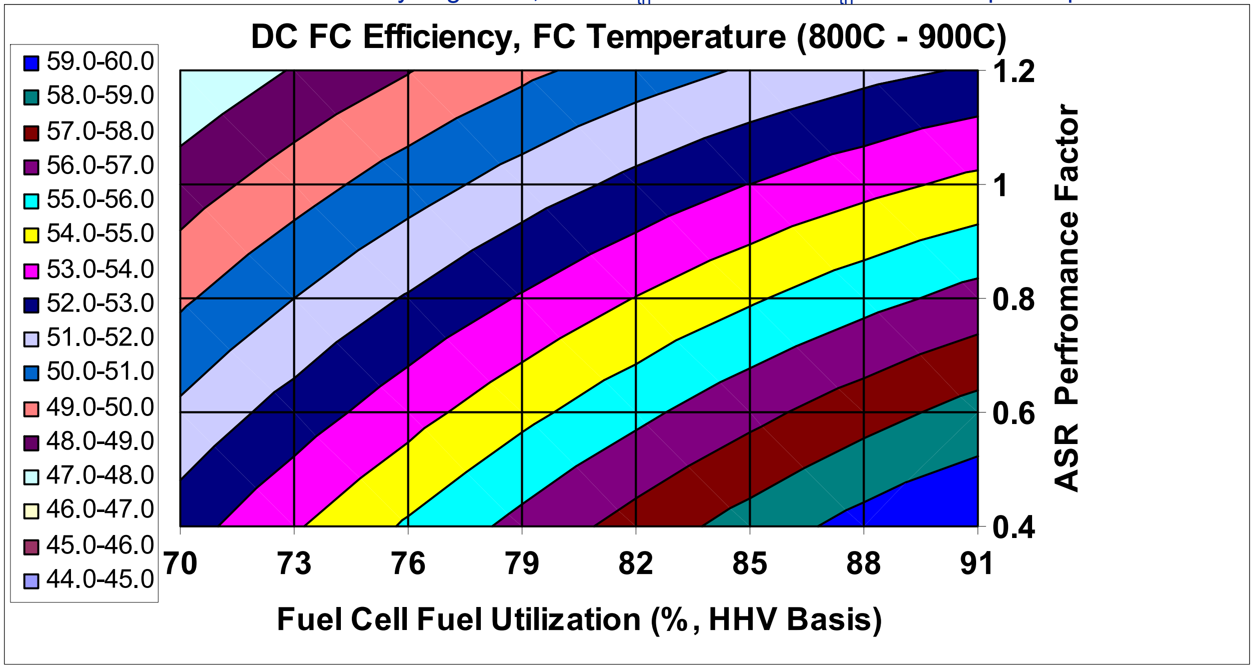


Stack Outlet Compositions for 80% Fuel Utilization (HHV basis)

	Original Cycle	Revised Cycle
H_2	7.5%	8.1%
H_2O	60.7%	44.6%
N_2	0.4%	0.4%
CO	3.7%	7.7%
CO_2	27.7%	39.2%
Outlet Flow	6.00 nlpm	9.38 nlpm
Outlet Flammables	11.2%	15.8%

Model Predictions (DC SOFC Efficiency)

Assumes 90% efficiency of gasifier, 600 kW_{th} coal → 540 kW_{th} to fuel cell power plant



- **Performance Factor of One Represents the Current State of the Technology (Stack ASR 0.32 ohm-cm^2)**

Fuel Utilization	SOFC DC Efficiency	
	540 kW_{th} HHV to SOFC	600 kW_{th} HHV coal feed
80%	51.6%	46.4%
82%	52.3%	47.1%
85%	53.0%	47.7%

Cycle Comparisons for Higher SOFC DC Efficiency

Stack Temperature 800C to 900C, 0.4 amps/cm^2, Overall Fuel Utilization 82%, Fuel Cell Performance Factor = 1 (except case 4)					
			SOFC DC Efficiency		
Case	Name	Change	540 kW_{th} to SOFC	600 kW_{th} coal feed	Comment
1	Dried Coal Syngas	Baseline	52.3	47.1	Low Efficiency Relative to NG Cycle
2	Dried Coal Syngas with no CO2	no CO2	54.0	48.6	Requires two-stage CO2 removal
3	Case 1 with High P	P=25 bara	55.7	50.1	Potential methanation issue at higher pressure
4	Case 3 with	0.8 Performance Factor	57.5	51.8	Dried Coal Syngas Cycle approaches NG Dry Cycle Performance at Higher Pressure, 20% lower ASR
5	NG Dry Cycle	Baseline	57.5	na	Estimated Currently Acheivable Performance for Dry NG Cycle at 6.4 bara

- **Achieving higher system efficiency requires combination of:**
  - **Reduced average stack ASR <0.26 ohm-cm^2**
  - **Reduced SOFC cost to increase active surface area, higher voltage operation**
  - **Demonstration of long-term durability at high U_f conditions**

- **DOE study predicts significant power from oxy-combustor expander**
  - **Need to further explore IGFC cycles combined with RRFCS SOFC modules**

Case 3 Assumptions

Nernst Potential	0.89 V
Operating Voltage	0.84 V
Fuel Utilization (w/ recycle)	85%

warm gas clean-up (RTI)

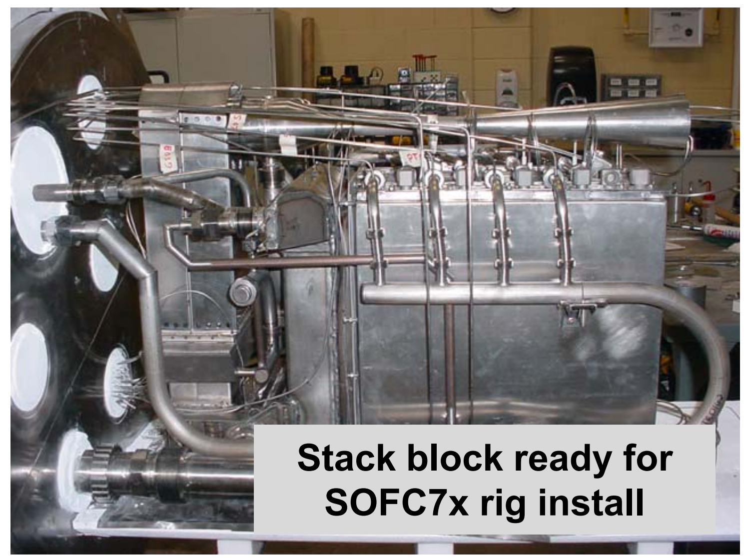
	kW	Efficiency Contribution
Thermal Input	1,025,091	
Fuel Cell	473,388	46.2%
Expander Power	13,947	1.4%
Oxy-combustor expander	154,537	15.1%
Cathode compressor-expander	10,359	1.0%
Auxiliary (less CO2 compression)	-38,523	-3.8%
CO2 compression	-34,305	-3.3%
Total	579,403	56.5%

E.Grol and J. Wimer, “Systems Analysis of an Integrated Gasification Fuel Cell Combined Cycle, Volume 1: Technical Assessment”, Report DOE/NETL-40/080609 Aug. (2009)

Stack Block Test Rigs

- **Three pressure vessels in UK for natural gas cycle testing at prototypic conditions**
  - **Support from UK TSB**
  - **Commissioned in 2009**
    - **Cumulative test time ~2200 hours**
    - **First duration test of ~1000 hr completed in 2010**
      - **Block analysis/inspection in progress**
- **SECA test stand builds upon UK experience**

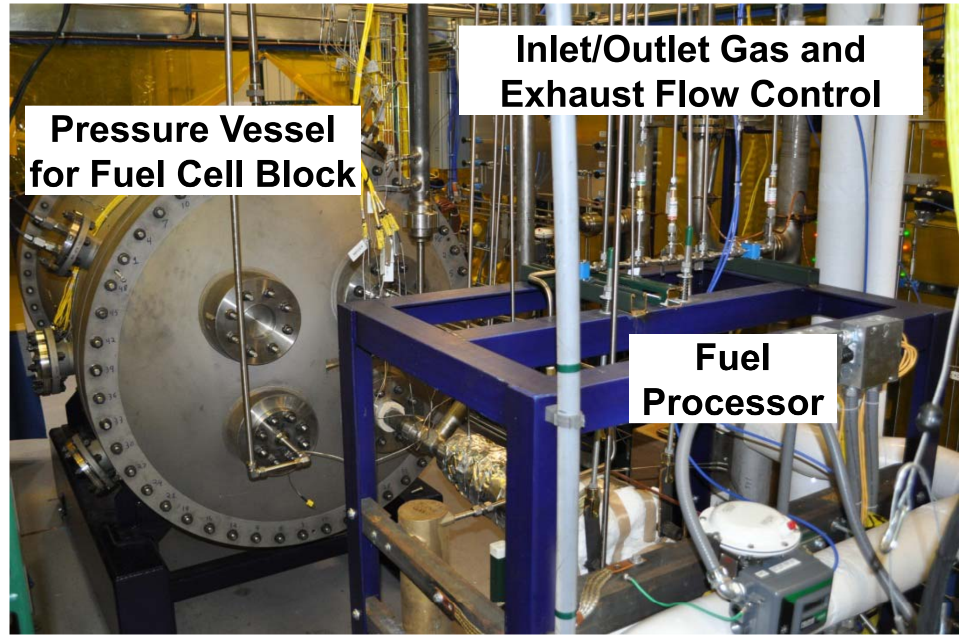
SOFC7x Test Stands (3) hold single-block



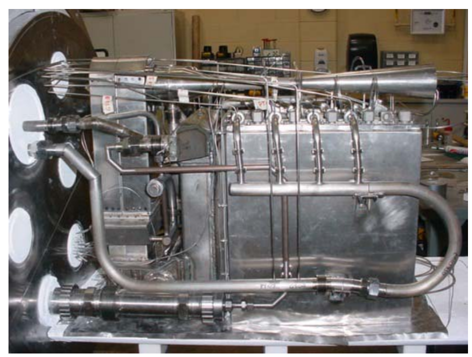
Stack block ready for SOFC7x rig install

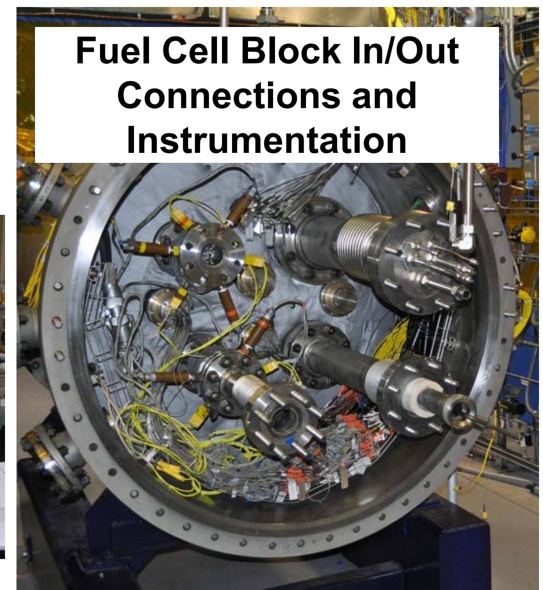
SECA Stack Block Test Stand (SBTS)

- SBTS build completed
  - RRFCS capital+Ohio Third Frontier Funds
- External CPOX reactor provides stack anode-gas composition from pipeline natural gas
- Commissioning in progress
  - Mechanical to prove balance of facility functionality and control (complete 2010-Q4)
  - Electrical (Complete 2011-Q2)
- SECA 5000 hr durability to follow



SECA Commissioning Test Block





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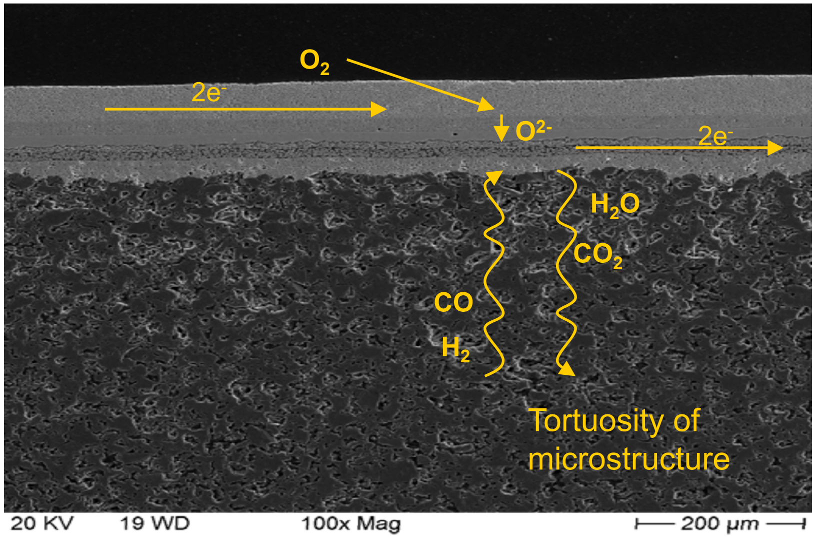
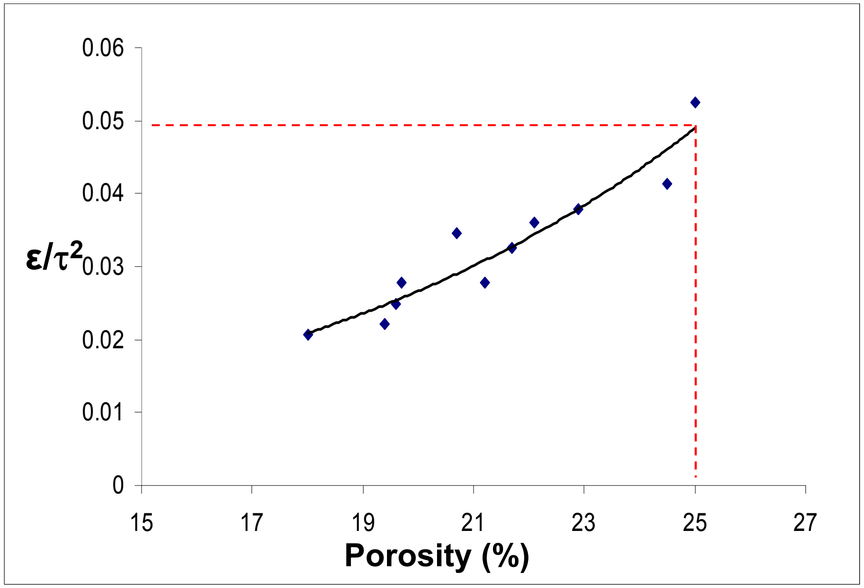
Tube Permeability Control for High U_f and Efficiency

- **Sufficient tube permeability is required to transport fuel to the cell and remove larger, slower diffusing H_2O product species**
- **Low permeability → high ASR**
- **Methodology defined for determining key substrate characteristics from permeability measurements**
  - **Porosity/tortuosity² (ε/τ^2)**
  - **Mean pore radius**

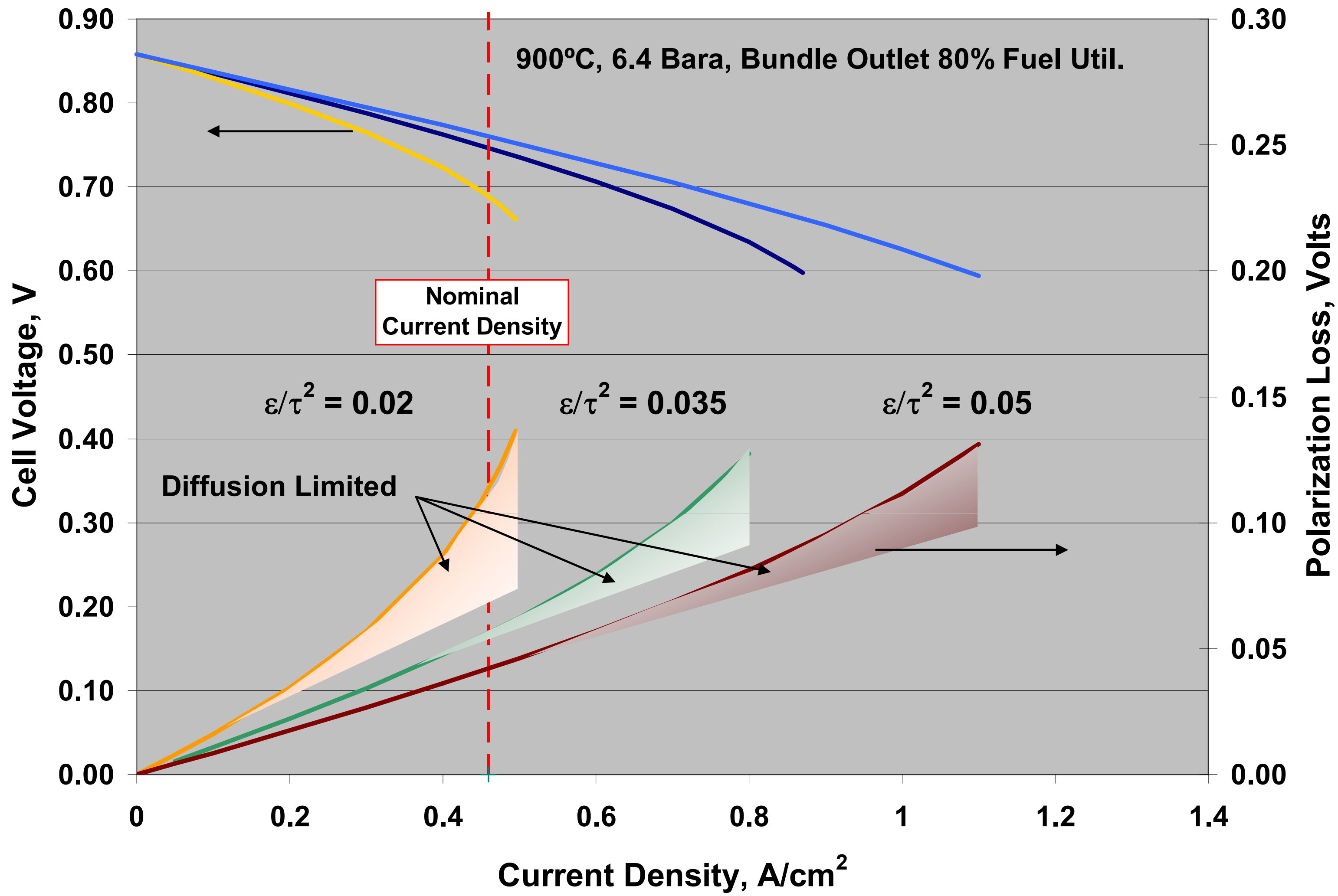


Permeability Characterization of Substrates

- Rig developed for measuring permeability factor (ε/τ^2) and m.p.r.
  - Rig located at substrate vendor
- Microstructural engineering to shift ε/τ^2 versus porosity trends



Electrochemical model developed that guides requirements for tube permeability

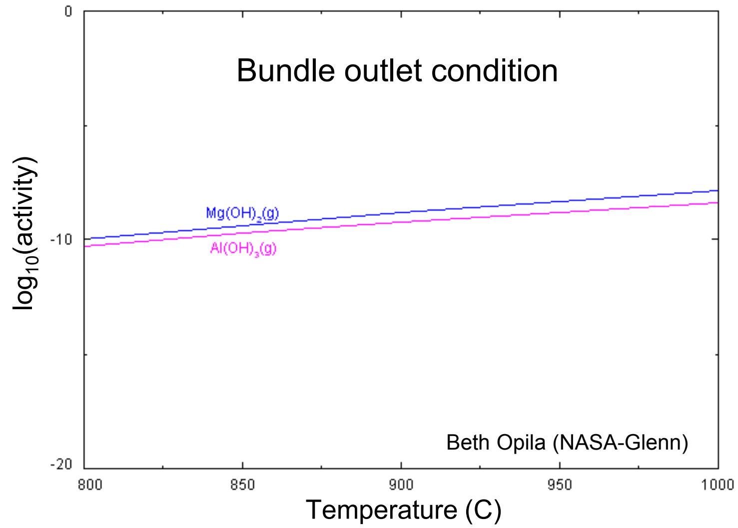


Rolls-Royce data

Thermodynamic Calculations and Post-Test Support MMA Substrate Selection

Reaction	Dependency	Le Chatelier
MMA		
$MgO + H_2O \rightarrow Mg(OH)_2$	$p_{Mg(OH)2}$ α p_{H2O}	No shift
$Al_2O_3 + 3H_2O \rightarrow 2Al(OH)_3$	$p_{Al(OH)3}$ α $p^{3/2}_{H2O}$	⟶

Low Al_20_3 activity: low content and reacted as $MgAl_2O_4$

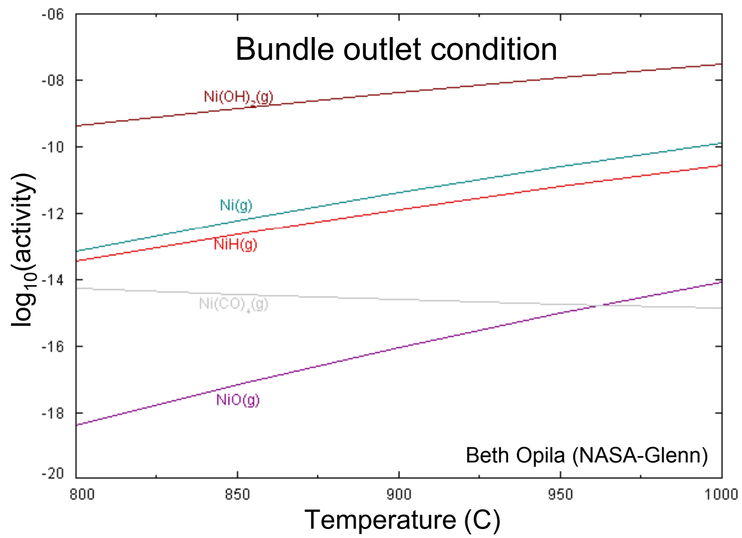


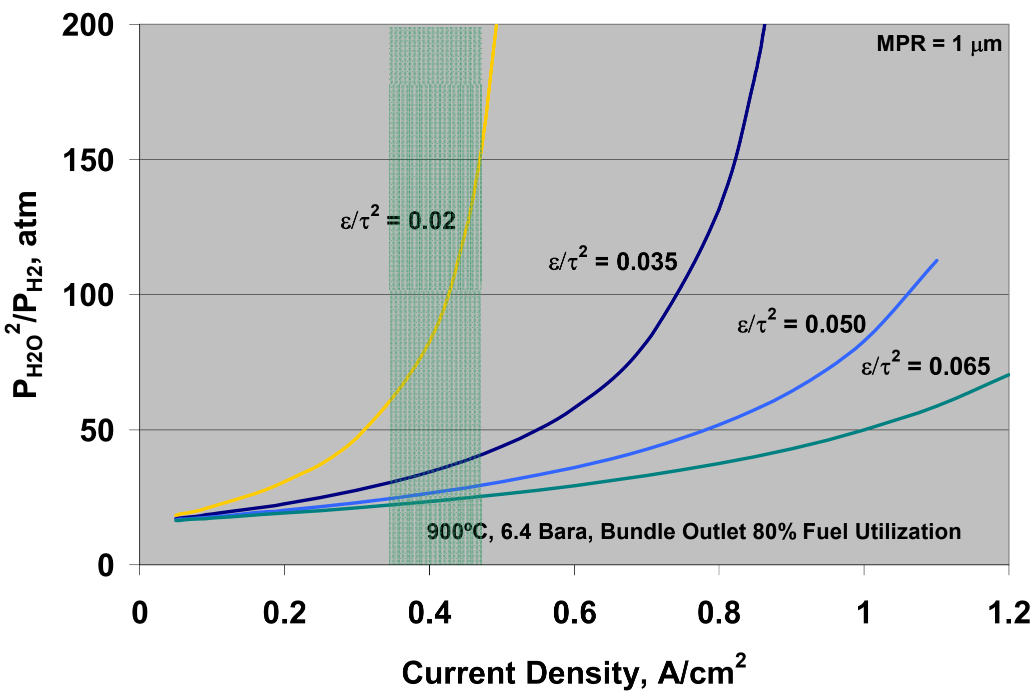
Equilibrium calculation indicates MgO loss <0.01%/40K hours

Influences on Anode Volatility

Reaction	Dependency	Le Chatelier
Anode Material $Ni + 2H_2O \rightarrow Ni(OH)_2 + H_2$	$p_{Ni(OH)2} \propto p^2_{H2O}/p_{H2}$	No shift

- System pressure doesn't adversely impact equilibrium
- Lowering system temperature reduces partial pressures
- Tube permeability important variable to manage Ni volatility





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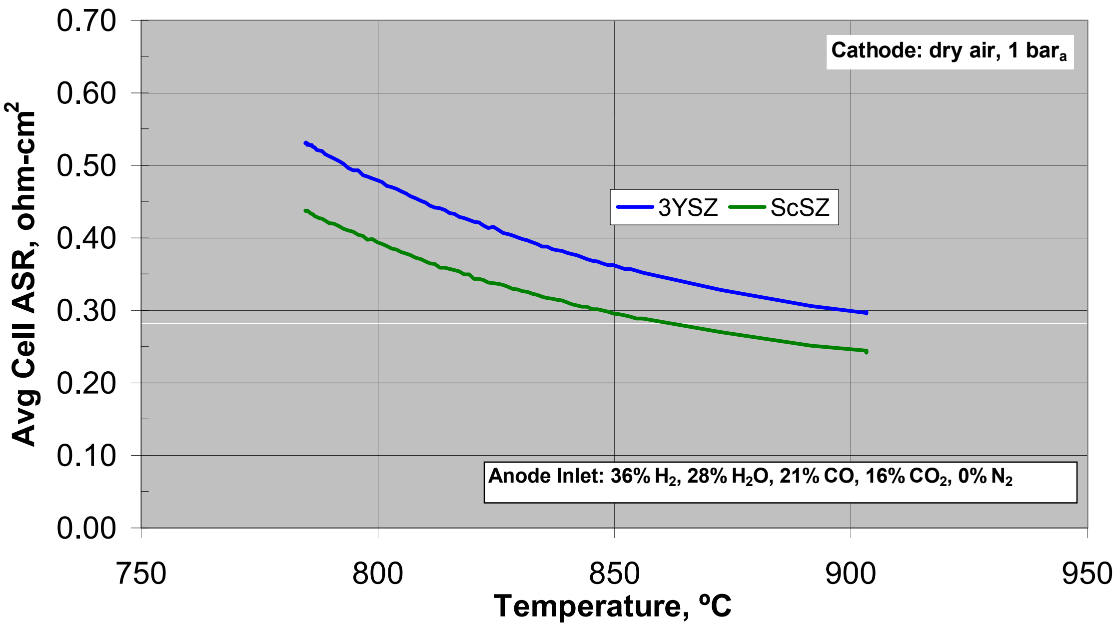
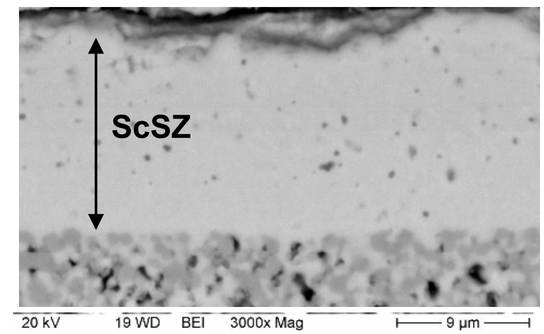
Switch to ScSZ Electrolyte for ASR Reduction

- Manufacturability demonstrated on pilot line
- Average stack ASR reduction ~0.06 ohm-cm^2

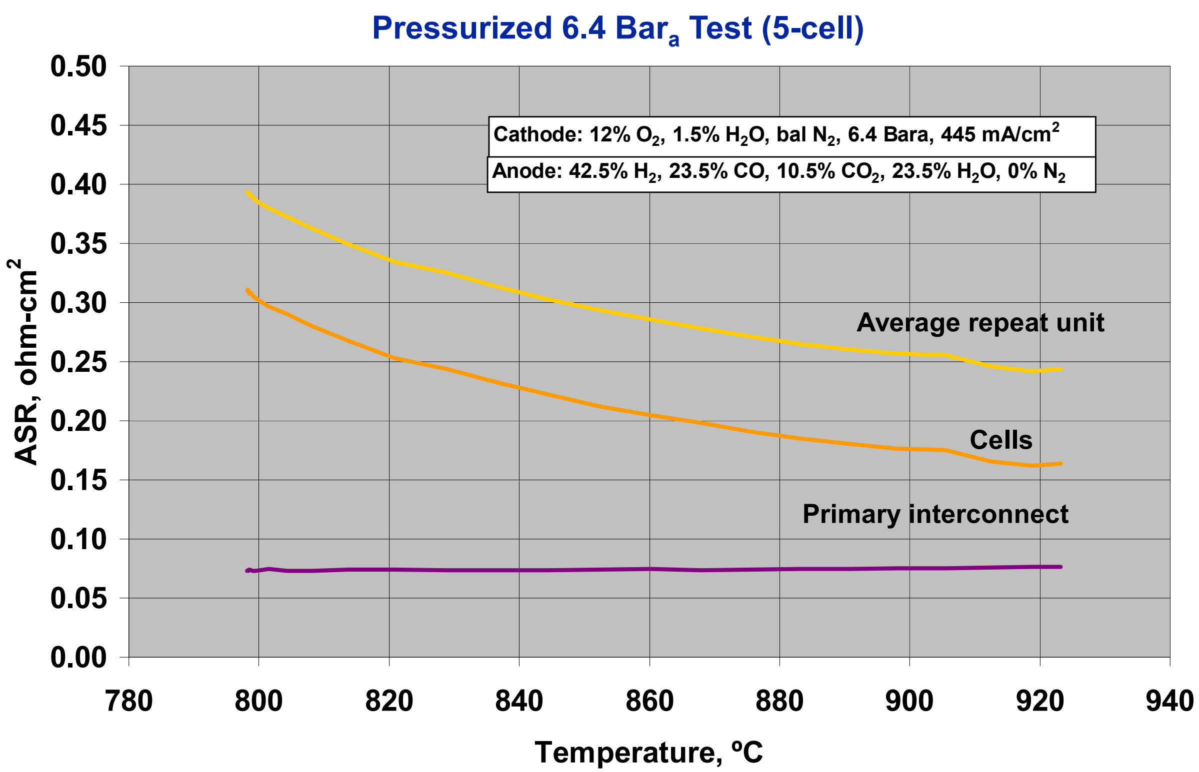




Ink qualified that achieves high density constrained sintering

Cell ASR Status – Full System Conditions

- Epsilon technology with ScSZ showing 0.32 ohm-cm^2
  - Integrated average ASR (800ºC-920ºC stack operation)
  - Further ASR reduction being achieved through interconnect modification and cathode improvement

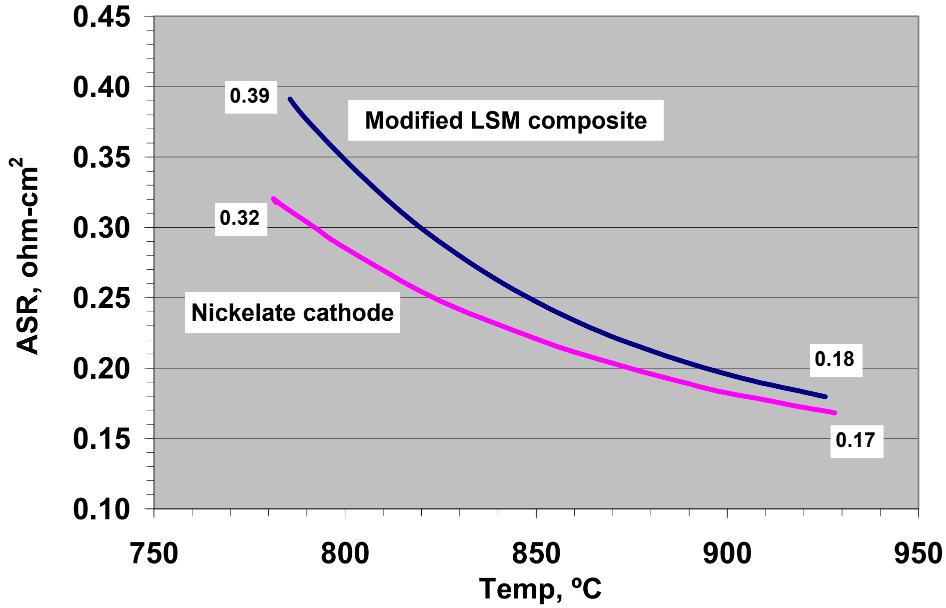


Rolls-Royce data

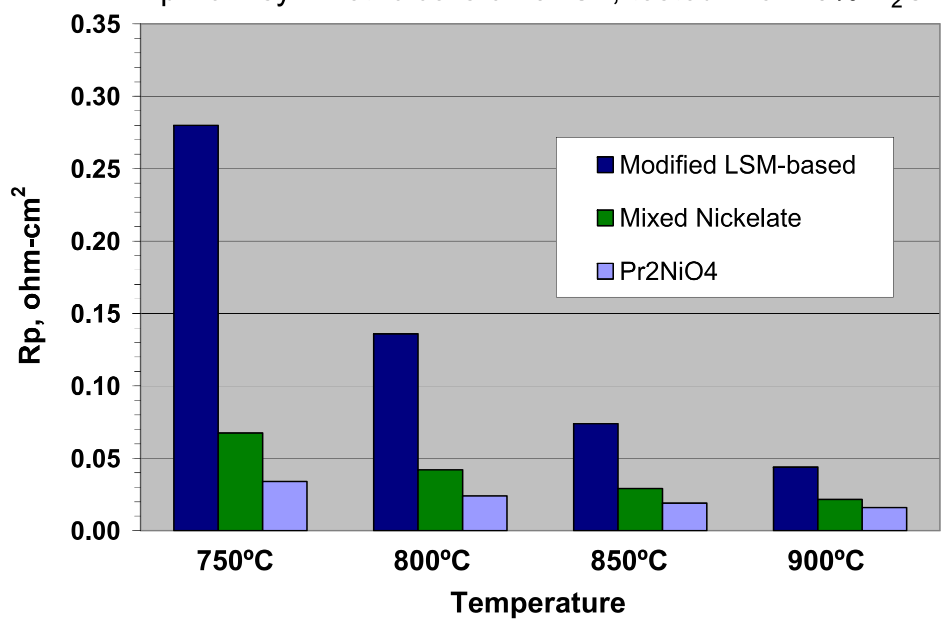
Longer-term Cathode Improvement: Alternative Cathode Family

- **Ruddlesden-Popper nickelates: $Ln_{n+1}Ni_nO_{3n+1}$**
- **A-site modification improves phase stability**

Single cell test articles use ScSZ electrolyte



Rp from symmetric cells on 5YSZ, tested in air+3% H_2O

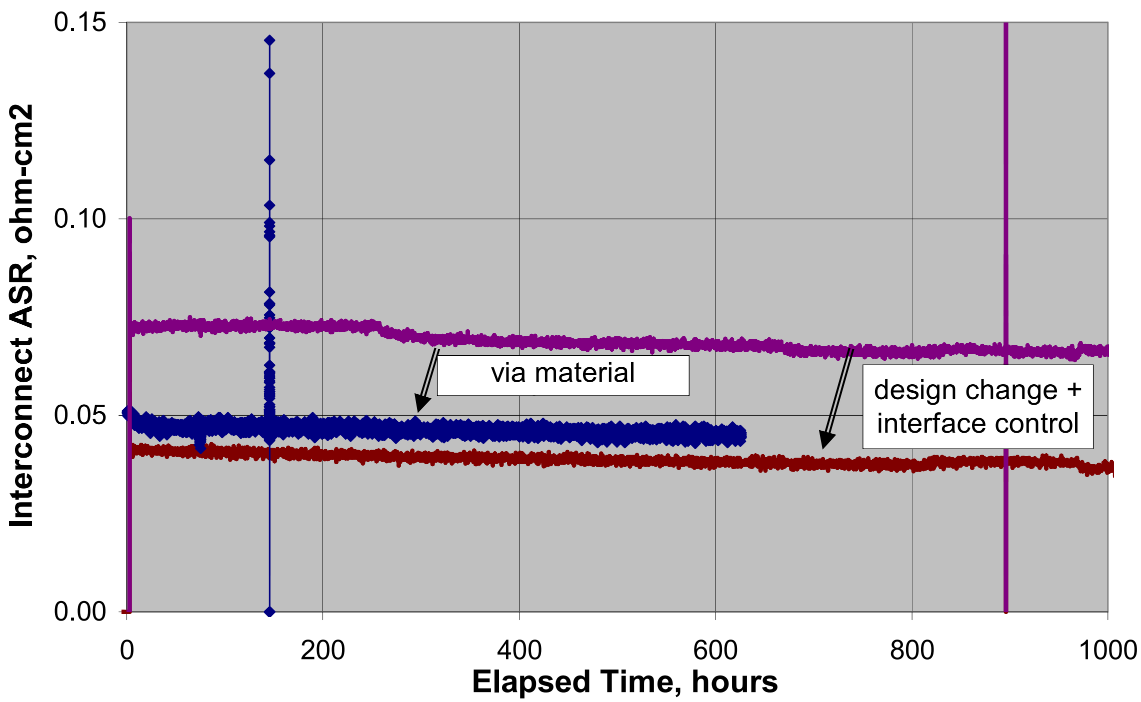


Testing at 1 bar_a

Primary Interconnect ASR Reduction

- **ASR reduction through via design and material modification, and interfacial resistance control**

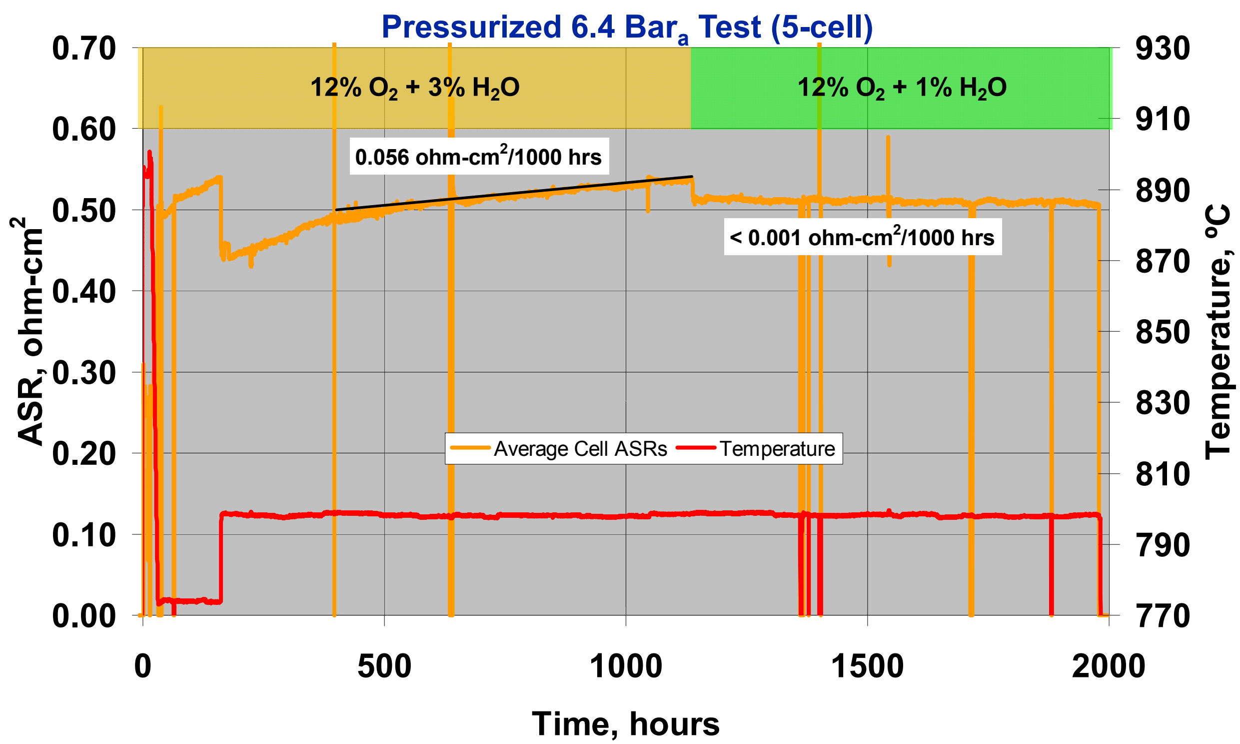
Via-based interconnect design



Rolls-Royce data

Cathode Steam Tolerance at 800ºC

- **Ambient humidity causes ASR degradation at low temperatures**
  - **Similar results recently reported by Riseo DTU**
- **Determining maximum allowable moisture levels and minimum operating temperature**
- **Objective: match of cell technology with system stack ΔT and ASR requirements**



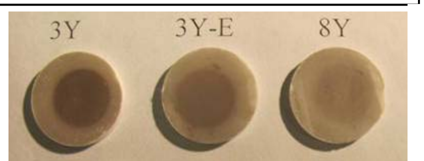
A. Hagen et.al., Effect of Humidity in Air on Performance and Long-Term Durability of SOFCS," ECS Transactions, 25(2) 439-446 (2009)

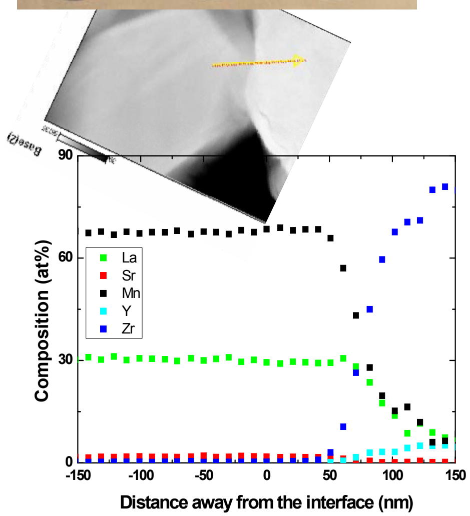
J. Nielsen et. al., "Effect of Cathode Gas Humidification on Performance and Durability of Solid Oxide Fuel Cells," Solid State Ionics, 181 517-24 (2010).

Ionic Phase Change as Root Cause?

- **Significant La and Mn diffuse into YSZ**
- **Explored how Mn plus steam may affect YSZ phase stability**
  - **In dry environment Mn is 2+ in YSZ, and promotes cathodic oxygen exchange[1]. No significant valence change observed with mositure exposure (174 hours, 775C, 4% moisture)**
  - **No phase change of Mn-diffused 3YSZ electrolyte**

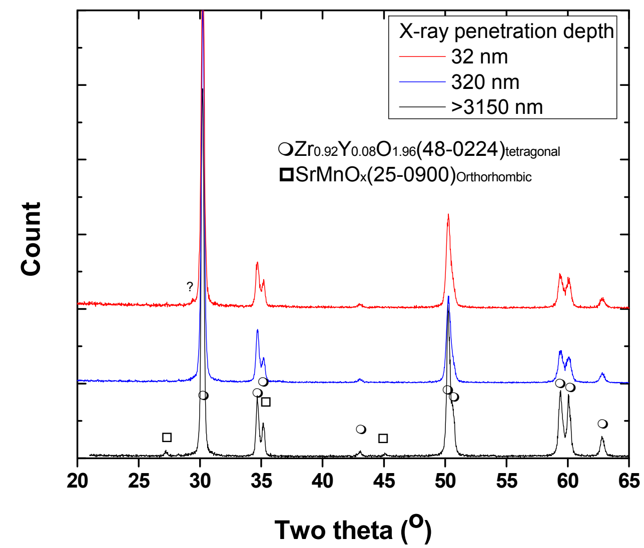
various electrolytes after contact with LSM 1150C/1 hr





Backhaus-Ricoult et.al., Solid State Ionics 177 (2006) 2195-2200.

Electrolyte shows only cub./tetra. after moisture ageing



<u>Mn Valence in 3YSZ not significantly changed (CWRU, ex-situ XPS)</u>

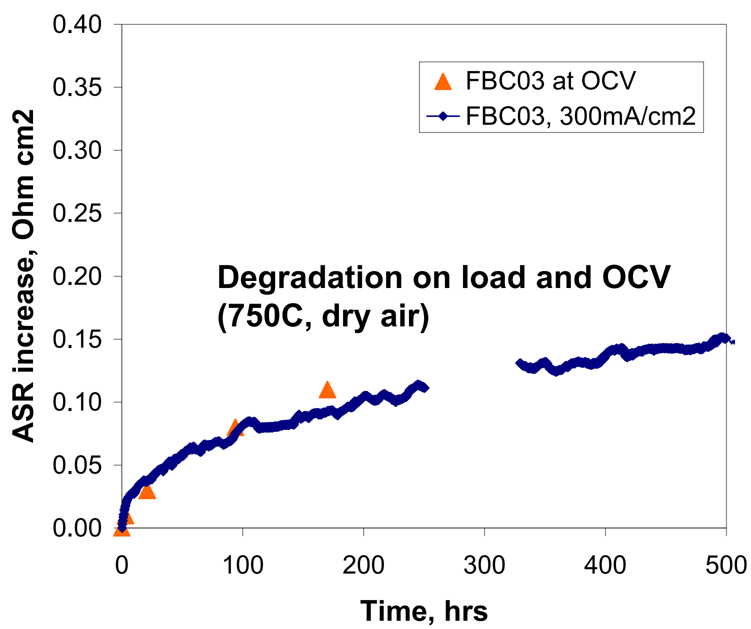
As-sintered (1150C): 2.23

174 hrs 775C/4% steam: 2.06

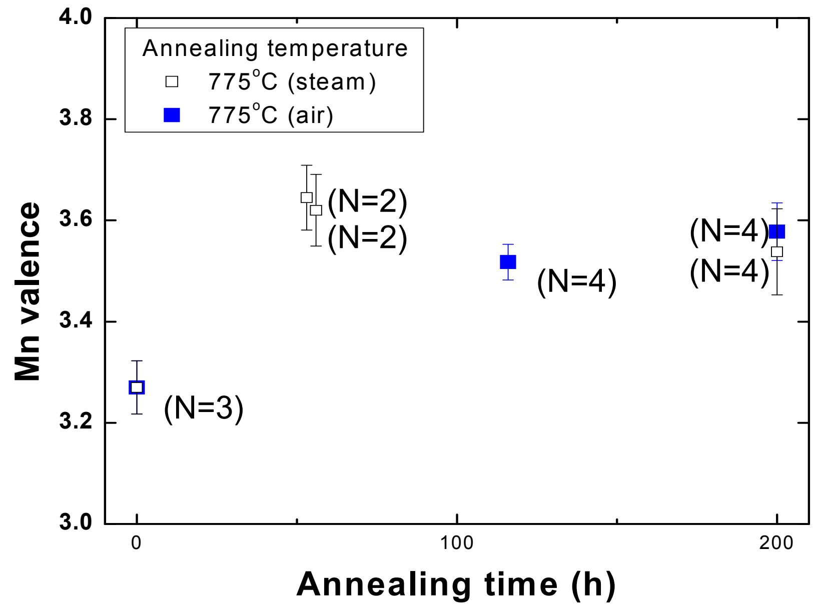
CWRU Investigating LSM Surface Chemistry Changes (ex-situ)

- Mn valence changes with temperature, no clear effect of steam
- Root cause of steam effect still not understood

ASR of button cell at 750C, Cr-free test rig



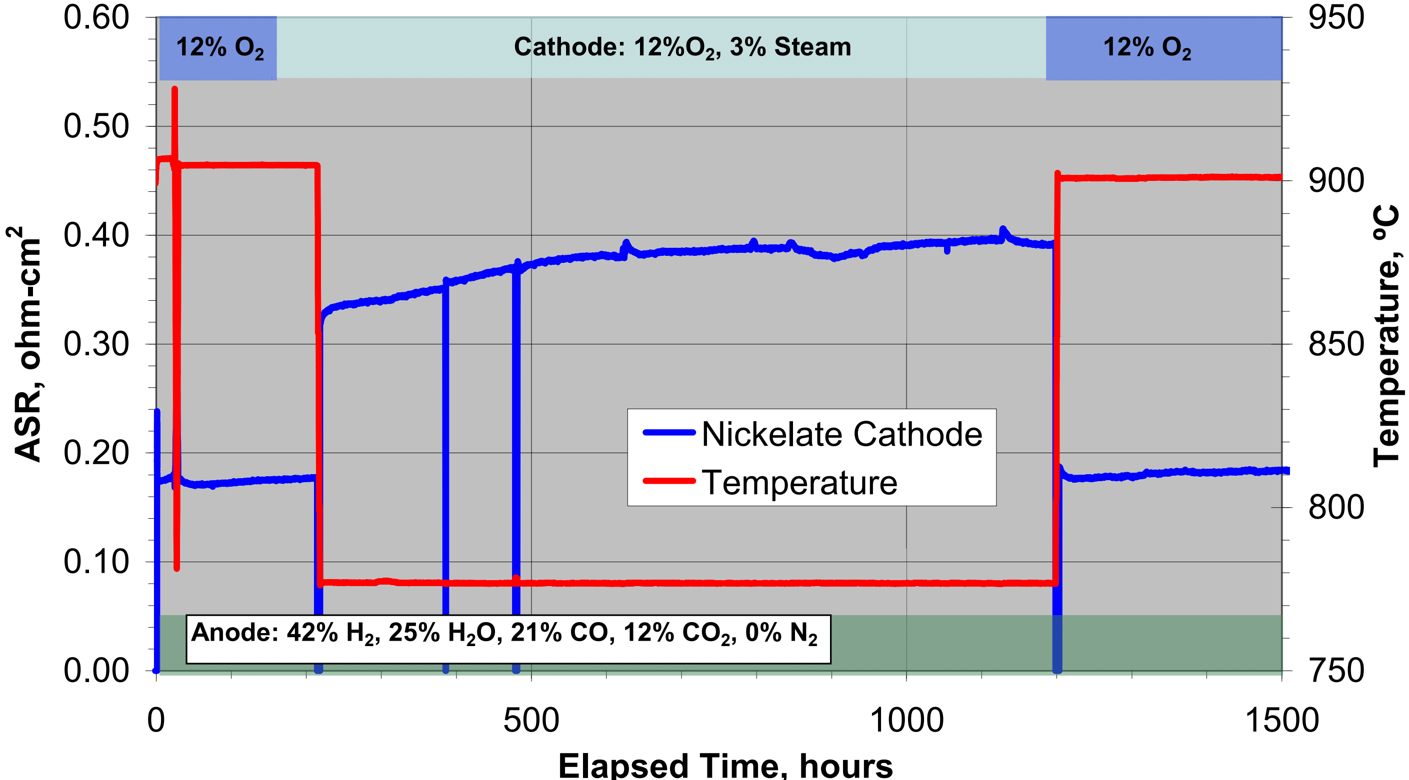
No significant valence change wet versus dry condition (XPS measurements)



Rolls-Royce data

Nickelate Showing Encouraging Steam Tolerance

- ASR on 3% steam levels off at 775C
- Could allow system peak temperature of <900C
- LSM and nickelate cathodes show recovery at 900C



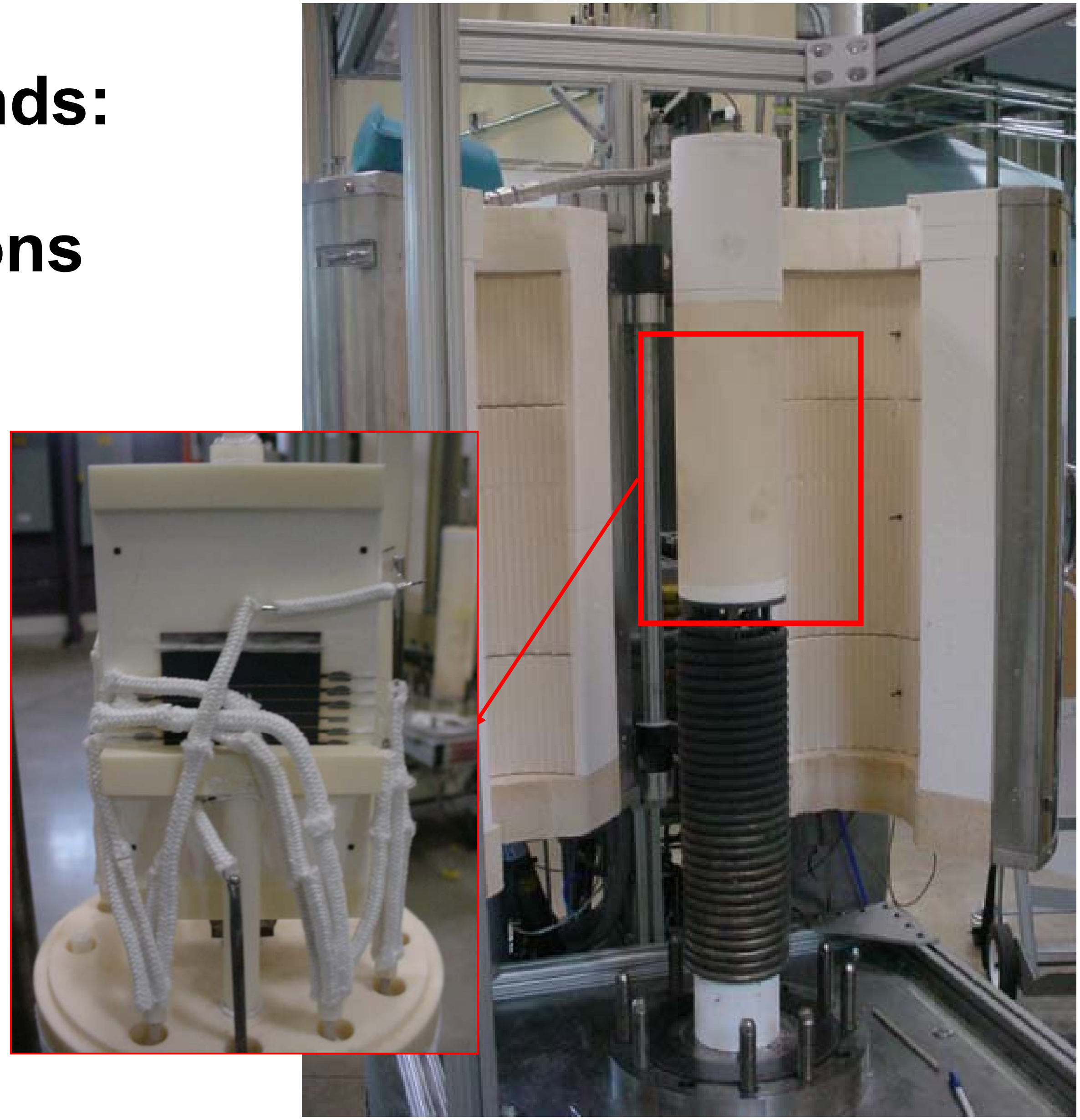
Rolls-Royce data

Outline

- FY2010 Highlights
- Rolls-Royce Fuel Cell Business
- Stack Technology
- IGFC System Design
- Substrate Requirements
- Cell Performance
- **Cell and Stack Durability**
- Next steps & Conclusions

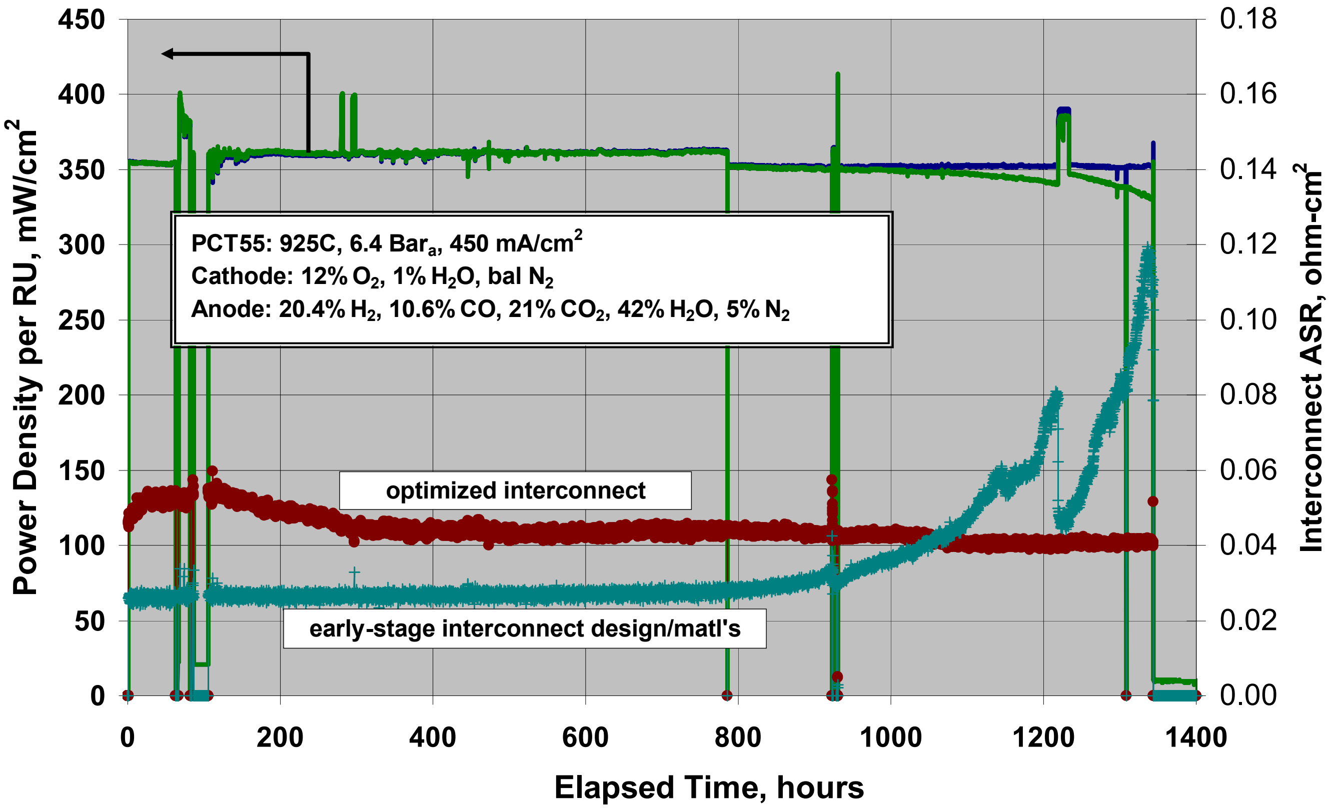
Pressure Test Stands: Well Controlled Boundary Conditions

- Pressure
- Temperature
- Current/Voltage
- Composition



Interconnect Degradation Mitigated

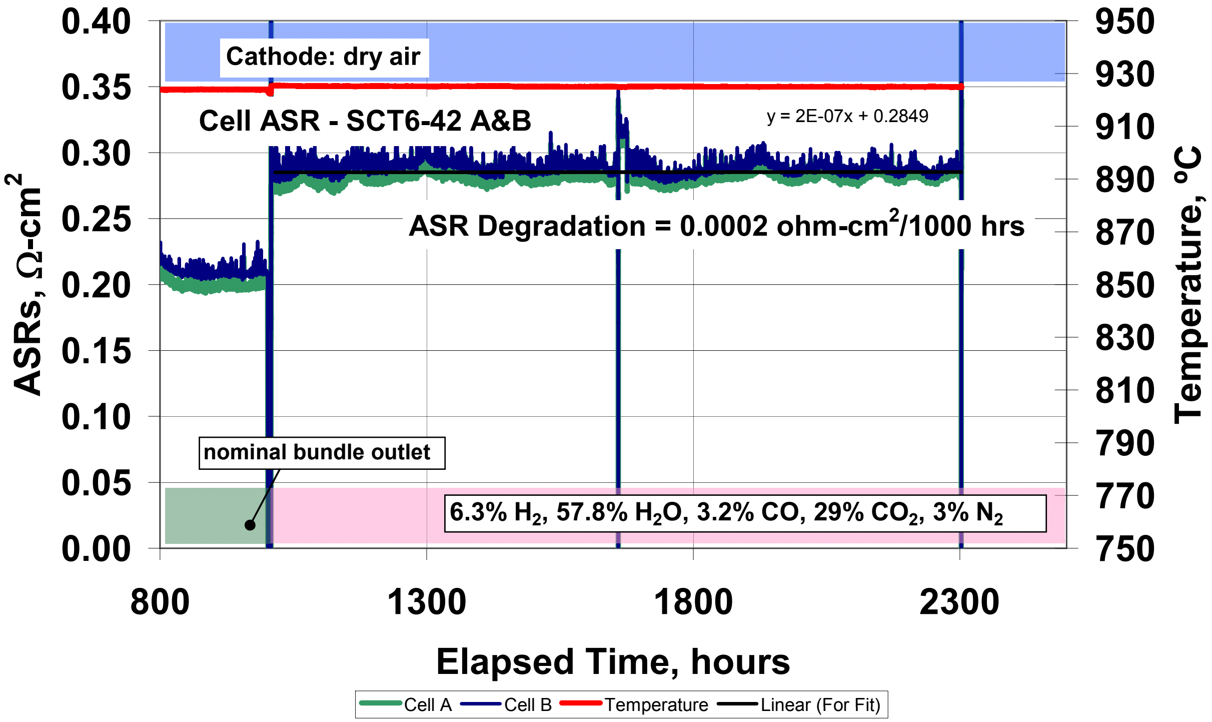
- **Observed accelerating degradation at >1000 hrs peak stack temperature and fuel utilization**
- **Material migration issues resolved, confirmed by EDS**



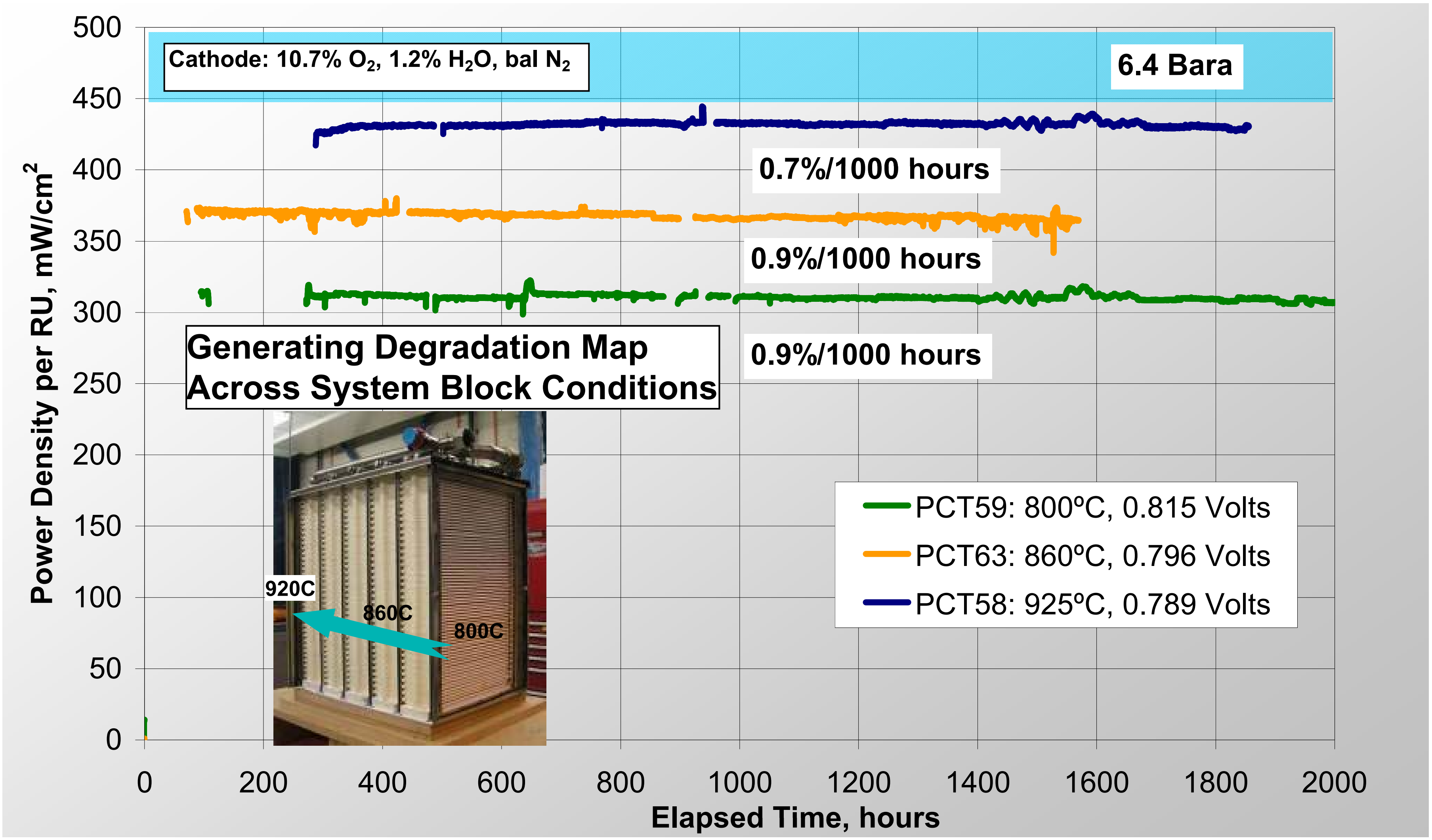
Rolls-Royce data

Anode-side Durability Testing

- **Testing at peak temperature and extreme U_f (~90%)**
- **Higher permeability substrates enhance durability**
  - **Low ε/τ^2 can't achieve design current, exhibit high degradation**
- **Challenges for long-term commercial operation remain anode coarsening and migration**



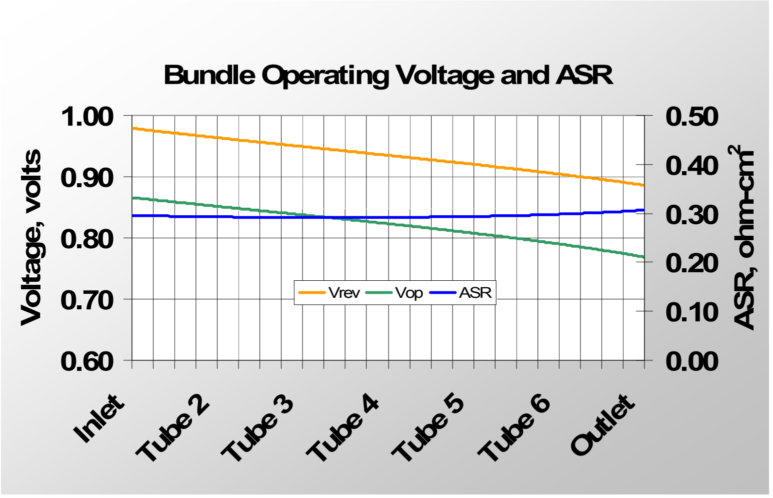
5-Cell Pressurized Durability

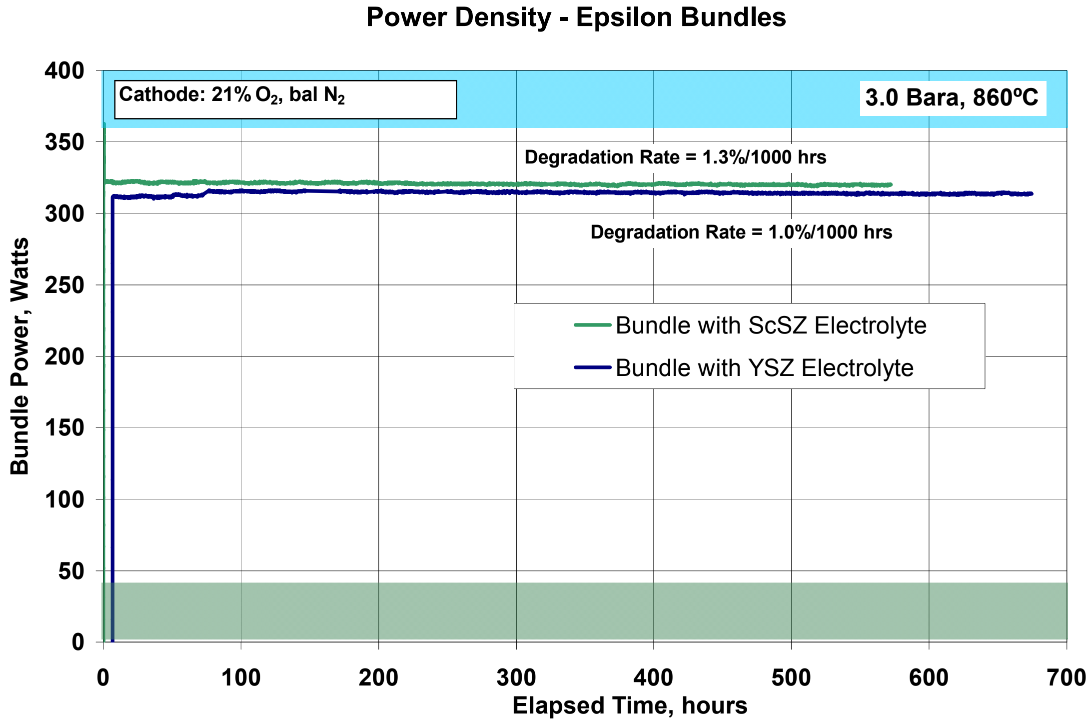


Rolls-Royce data

Bundle Durability Testing

- Test rig requires 3 bar_a to meet IGFC system P_{O2}
  - New bundle rig to be operational in Canton in Sept for full system conditions

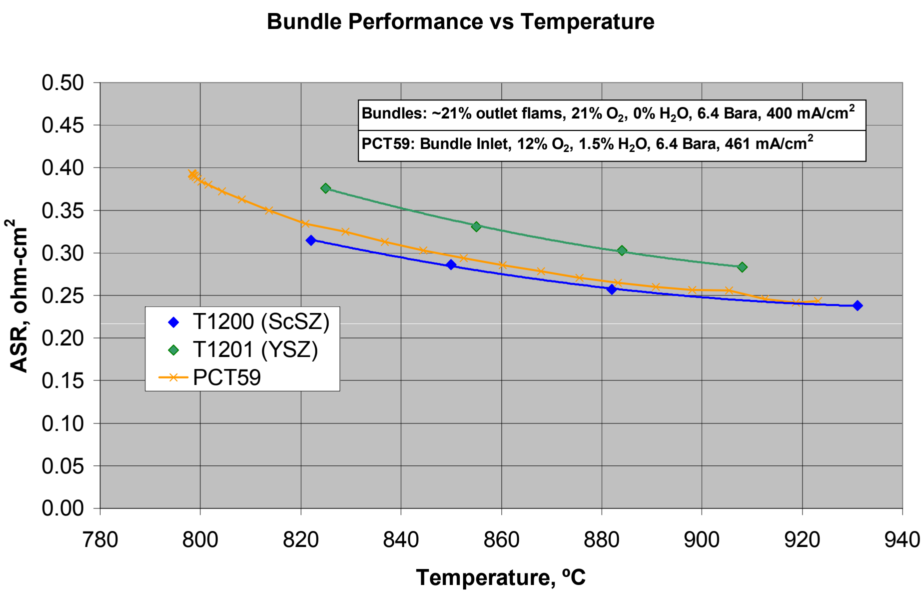


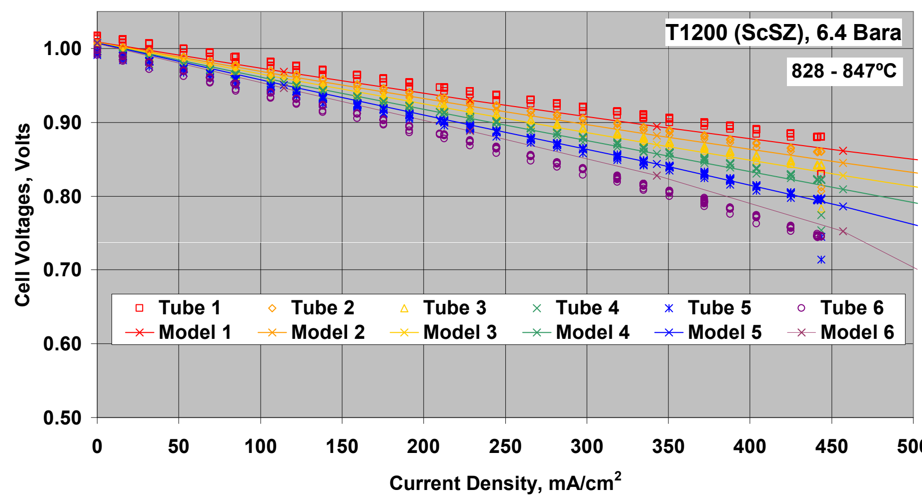


Rolls-Royce data

Bundle Performance

- Bundle data closely matches 5-cell data at equivalent fuel utilization test conditions
- Tube 6 in bundle does not show diffusional resistance at design point current (~400 mA/cm^2) and 80% fuel utilization





Summary

- Significant progress lowering ASR to improve efficiency and reduce operating temperatures
- Full-scale printing and stack assembly of latest technology underway on recently commissioned Canton, Ohio pilot line
- New substrate specifications and stack manifolding developed to allow achievement of high fuel utilization
- SECA target degradation rates being achieved in 5-cell and bundle tests
- Stack test rig undergoing commissioning with metric stack test initiating 2Q 2010

Acknowledgements

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