LG Fuel Cell Systems Program and Technology Update

DOE 18th Annual SOFC Review, June 2017

Cris DeBellis and Amit Pandey

Outline

- **LG Fuel Cell Systems Inc.**
  - **Introduction** (Cris DeBellis)

- **DE-FE0023337: Improved Reliability of SOFC Systems**
  - **Integrated system test** (Cris DeBellis**)**
    - **System description, test results, lessons learned**
  - **Improved fuel cell stack** (Amit Pandey)
    - **Reliability, durability and cost reduction**

- **DE-FE0026098: Advanced Materials and Manufacturing**
  - **Program objectives and activities** (Amit Pandey)

LG Fuel Cell Systems

Canton, Ohio

- Business HQ and leadership
- Cell & Stack development
- Fuel processor development
- System integration
- Control software development
- Prototype Manufacturing & Testing

Derby, UK

- Technology leadership
- System modeling & analysis
- Generator module design
- Turbo Generator design
- Rolls-Royce Technical Support

Seoul, Korea

- Manufacturing Tech development
- LG Technical Support

Foundational Value of LG and Rolls-Royce Joint Venture

Rolls-Royce Fuel Cells

- **FC Technology**
- **Fuel Processing**
- **System Engineering**
- **Design & Modeling**
- **Scaled Testing**
- **Years of know-how**

Rolls-Royce Group

- **Turbine & compressor**
- **Aero-thermal expertise**
- **High-temp Materials**
- **Power Electronics**
- **System Integration**

LG Group

- **Process Development**
- **Volume Manufacturing**
- **Design for Manufacturing**
- **Supply-Chain Development**
- **Electronics and Controls**

Transitioning to Entry into Service

Commercial Phase

- Growth of product in North America
- Expand breath of applications

EIS Phase

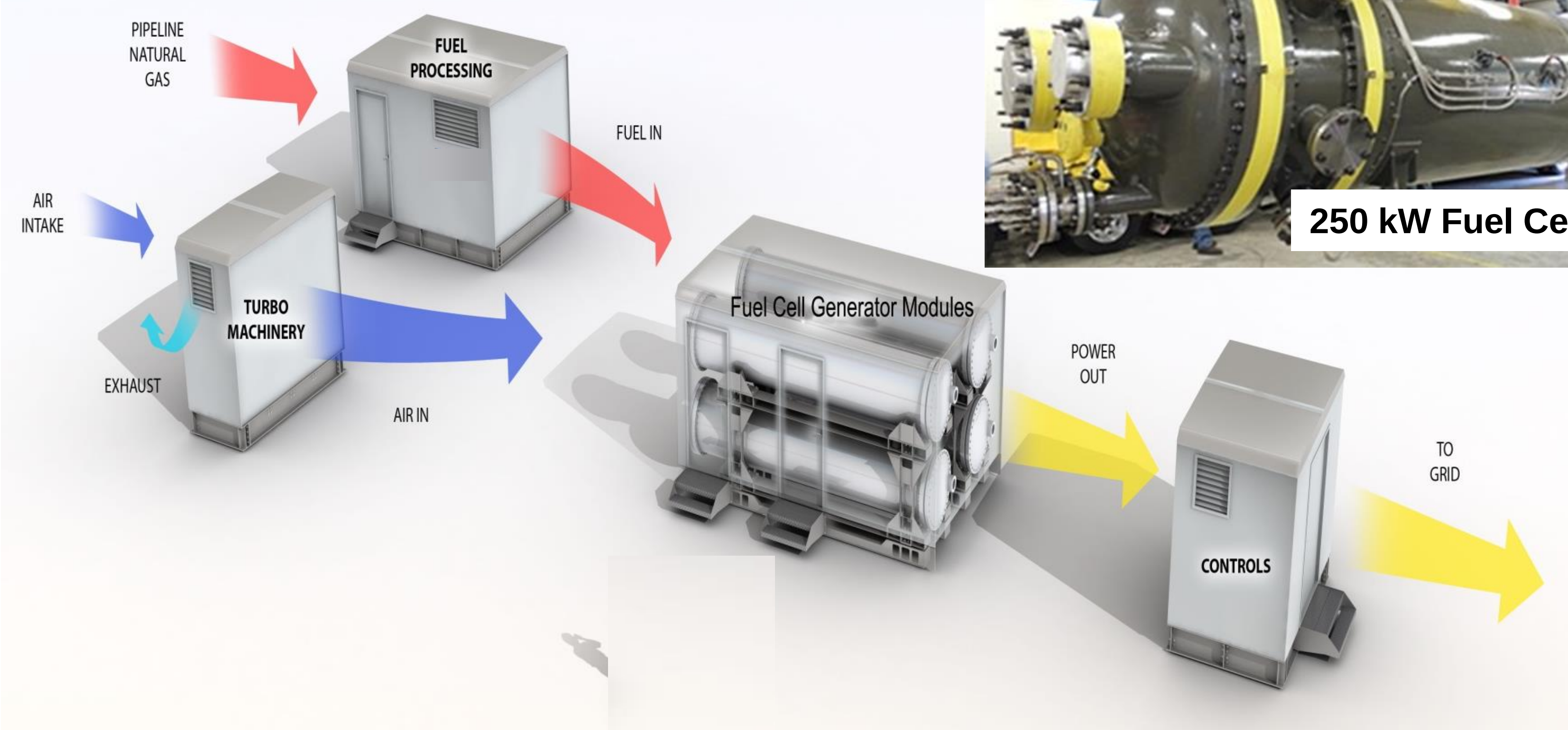
- Drive cost and performance improvements
- Validation of key new technologies
- Field trials at “friendly” locations
- Build robust supply chain

R&D Phase

- Design, Build and Demonstrated 200 kW Class Integrated system
- Completed over 2000 hours at efficiencies in the 60% range
- Developed key components and subsystems
- Established core fuel cell technologies

Targeting 1MW Power System

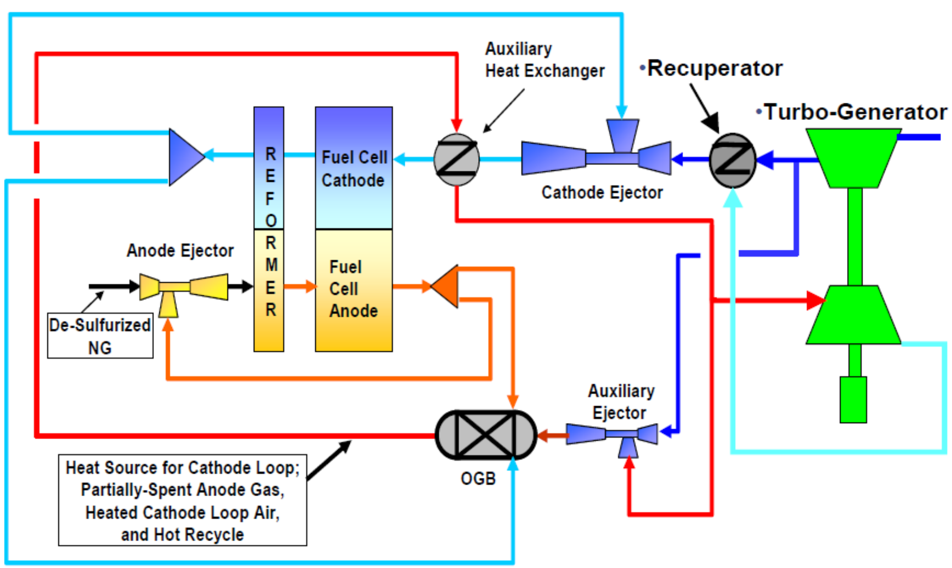
- **Nominal 1MW SOFC System scalable from 250 kW to >20 MW**
- **High availability for base load operation on natural gas**



250 kW Fuel Cell Vessel

LGFCS System Description

- **Pressurization to improve power density and performance**
- **Anode recycle to allow for internal natural gas reforming**
- **Cathode recycle to minimize components' size and cost**
- **Ejectors to drive recycle loops**
- **Combustion products confined in small volumes**



Integrated System Test Phase 1

- Phase 1: IST, June 2015
- Pipeline NG to grid AC
- 200kW-class SOFC system
- Demonstrated functionality of integrated subsystems:
  - Fuel processing
  - Pressurized SOFC vessel
  - Turbo generator assembly
  - Power electronics
  - Controls and safety system
- ASR similar at scales ranging from:
  - Penta (5 cells)
  - Bundle (360 cells)
  - Strip (4320 cells)
  - System (259,200 cells)

- Over 575 hours of operation
  - multiple startups and shutdowns
- Over 200 hours on load
  - 200 kW AC Power
  - DC Efficiency ~60%

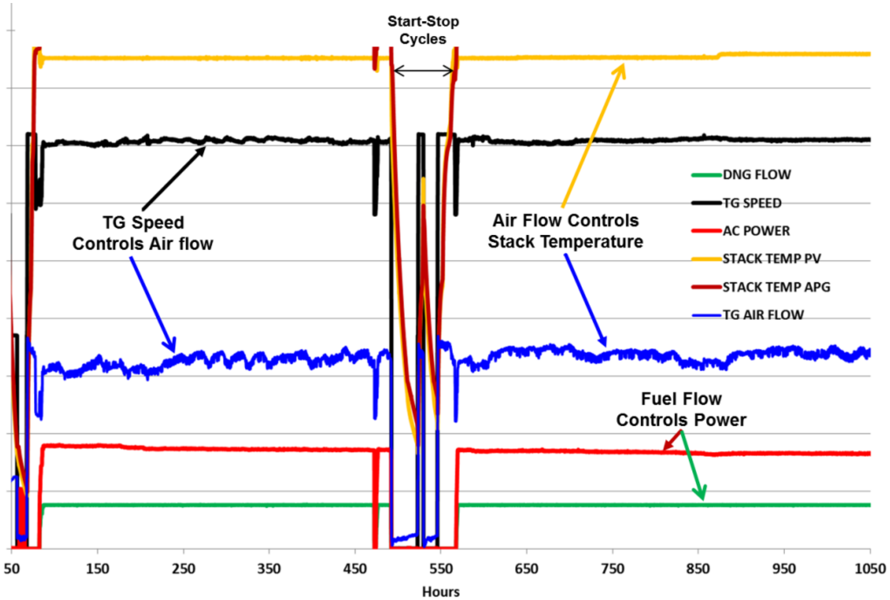
Lessons Learned

- Secondary Interconnect improvements for manufacturing and assembly
- Metallic component corrosion issues
- Performance loss due to high chrome release from corrosive components
- Vessel power feed through failure due to moisture accumulation during cold weather
- Balance of plant emergent behaviors
  - Frozen supply lines despite heat tracing
  - Communication power supply failure
  - Periodic blockage of control valve

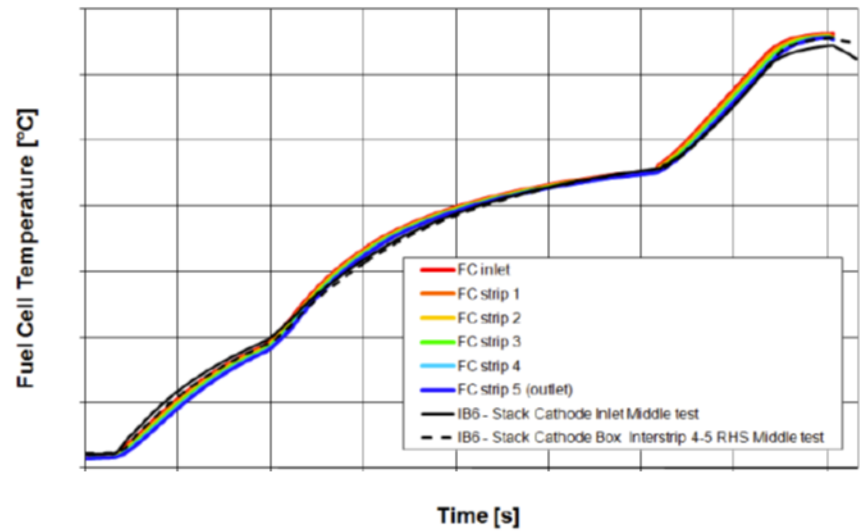
Integrated System Test Phase 2

- Phase 2: Prototype A
- October 2016
- Pipeline NG to grid AC
- 200kW-class SOFC system
- Successful on load operation for over 1000 hours
- Successful completion of test requirements including
  - Emissions testing
  - EMI Testing
  - Unmanned operation
- Over 1490 hours of operation
  - multiple startups and shutdowns
- Over 1190 hours on load
  - 180kW AC Power

Performance and Analysis

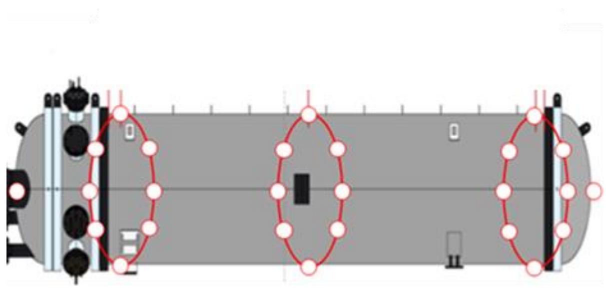


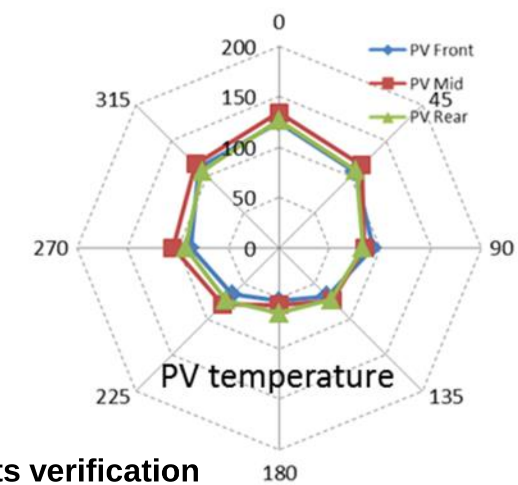
Extensive data set for design/control validation



Data used to benchmark design/performance tools

TCs location on PV





Environmental effects verification

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Integrated System Test Summary

- Over 2000 hours of systems testing including
  - Automated control/safety system
  - Multiple starts, stops, hot idle, emergency stops
- Over 1300 hours on load
- Identify and correct emergent behavior for improved reliability
- Future Improvements identified to reduce corrosion, chrome and cost
- Entry Into Service demonstration planned

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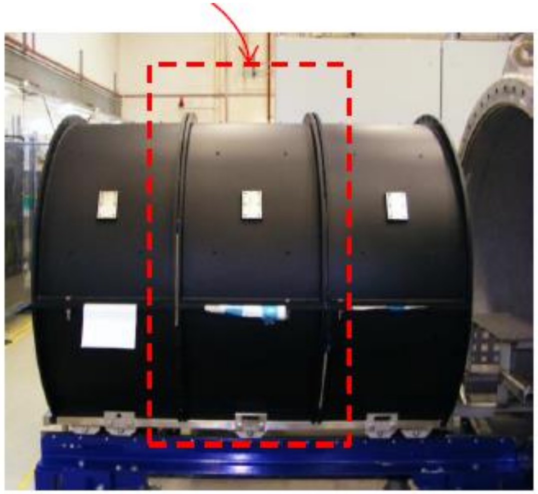
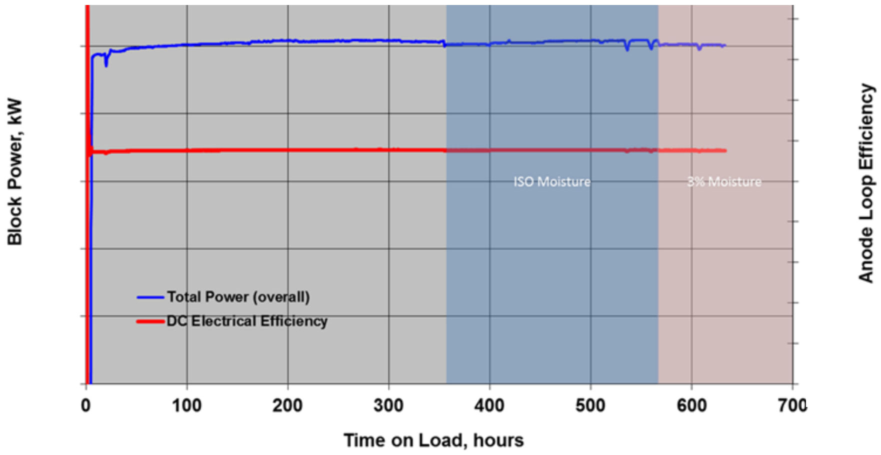
Block Test For Proving Reliability

- **Lessons learned and improvements implemented in block test**
  - **In Block Reforming**
  - **Cr mitigation**
  - **High current density**
  - **Remove corrosive elements**
  - **Match system environment**
    - **moisture (1-3%)**
- **Precursor to entry into service**



Integrated Block Test



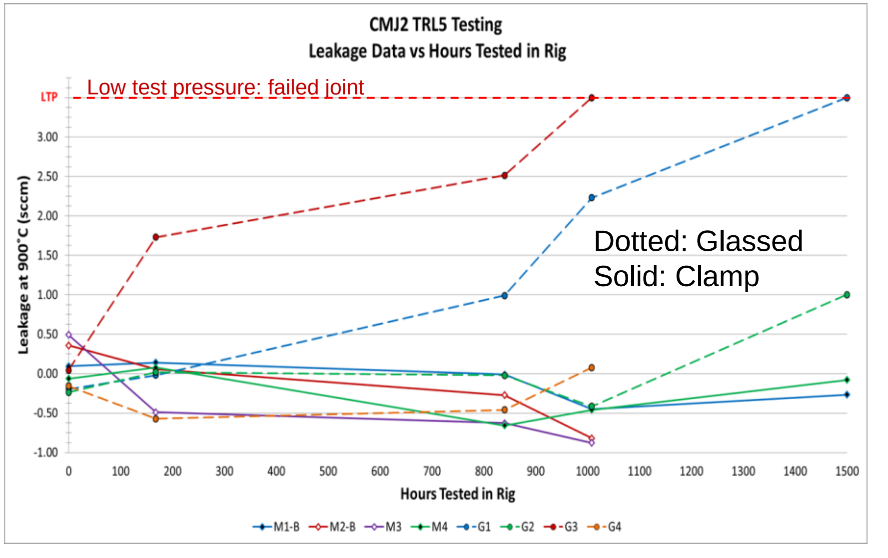
Improved Fuel Cell Stacks (Amit Pandey)

- Reliability activities
- Durability improvement
- Strip cost reduction

Reliability - Ceramic-Metal Joint

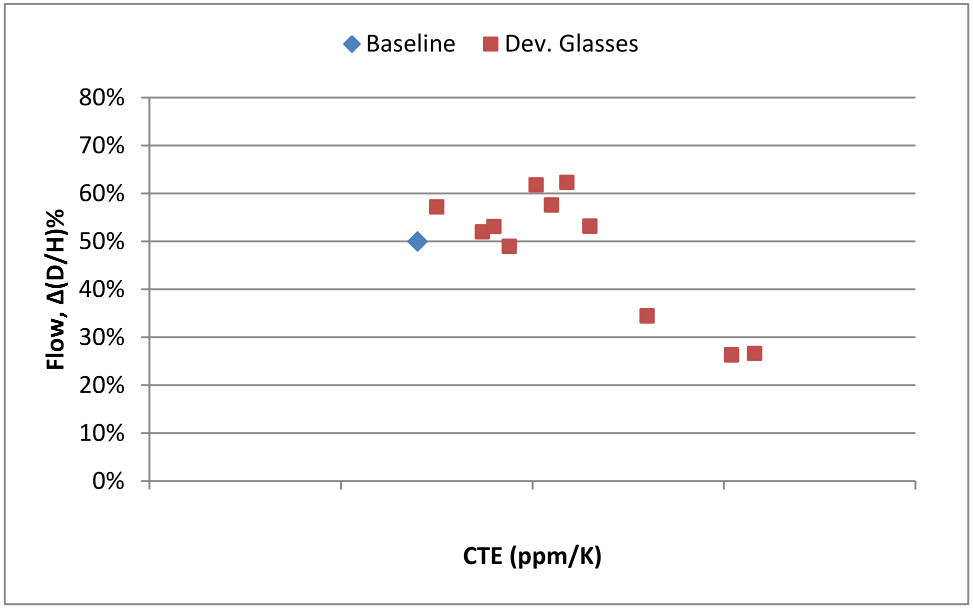
- New mechanical clamp design joint is showing improved leakage stability compared to historical glass sealed joint
- Established a new rig for long-term reliability testing under a fuel-air environment, including cycling
- Performing block fit-ups. Entering block testing in Q1 2017

12 joints, dual atm. fuel+air

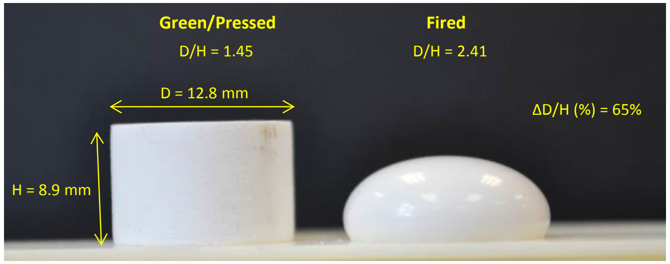


Reliability: New glasses for lower residual stress

- Composition adjustment for CTE and flow improvement
- Improve manufacturing yield rates
- Minimize thermal stresses during transient states

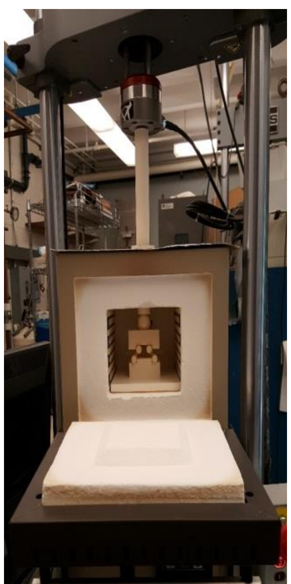


Flow Test

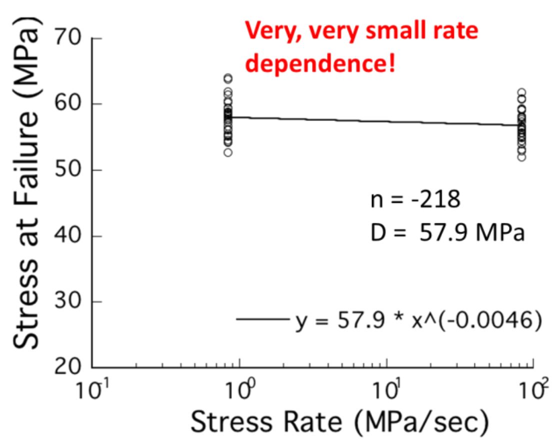


Reliability - MMA Characterization
(University of Washington)

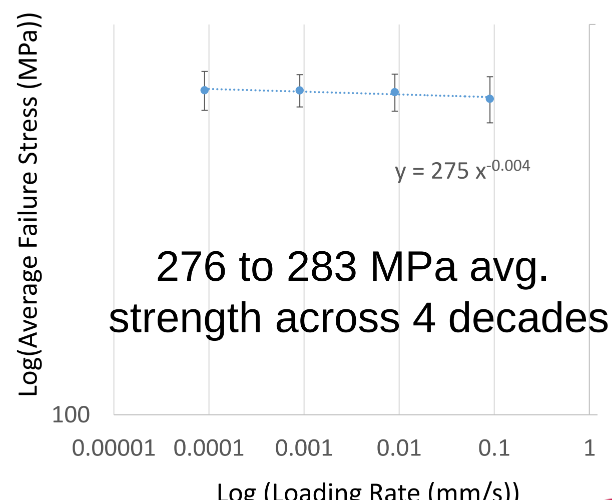
- **Dense MMA: Room temperature MOR = 302 MPa, Weibull m= 20.7**
  - **At 850°C and 3.5% H2O MOR = 290 MPa**
- **Extremely small rate dependence for failure stress indicates high resistance to slow crack growth, strength retention during service**
- **Similar test for porous MMA substrate material underway**



Constant Stress Rate SCG Response of tube 850°C (50%H_20+2.25H_2+47.75N_2)



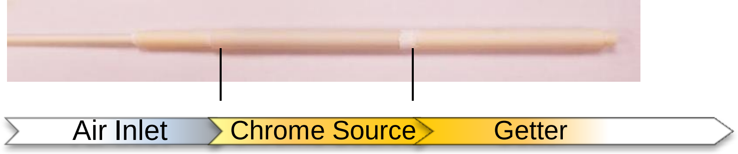
Constant Stress Rate SCG Response Dense part 850C (3.5% H_2O)

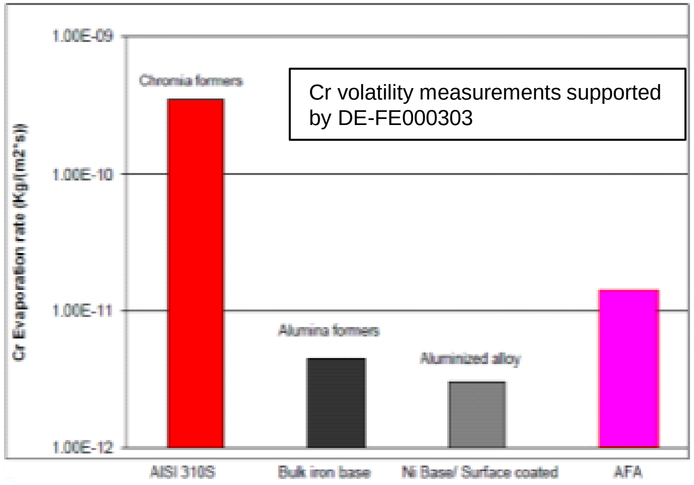


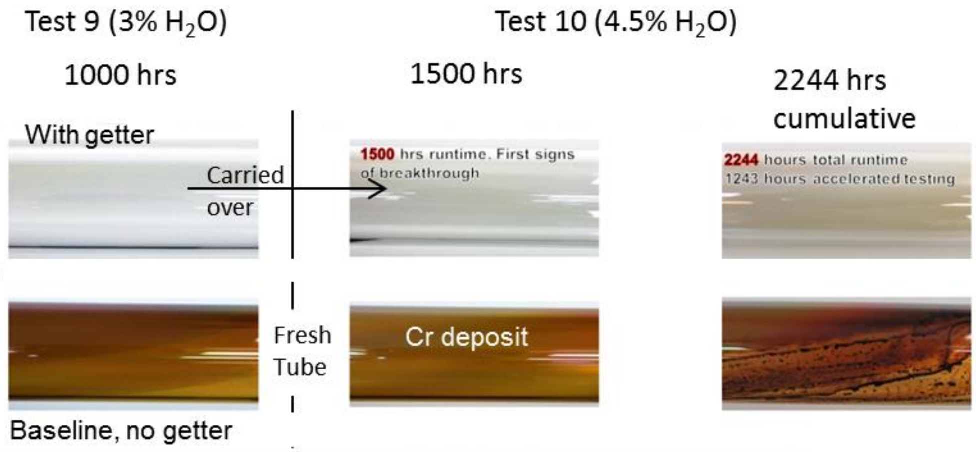
Durability: Validating a Cr-getter

- **Accelerated screening of candidate getter materials**
- **Testing condition**
  - **8 slpm, 12 mm diameter**
  - **14%O2 3%-4.5%H2O, 825C**
- **Cr2O3 pellets as source**
- **Accelerated life test as coated metals have ~1/10th release rate**

Alumina Testing Fixture







Cost: Substrate and print design

- **Longer tubes achieve 82 cells**
  - **Includes shorter primary interconnect pitch (achieves 5% added active area)**
- **Evaluating optimized channel spacing for additional ~5% cell width**

+72%

68x245 mm, 60 cells

68x300 mm, 82 cells
(PIC width reduced)

80x310 mm, 82 cells

Improved Fuel Cell Stack Summary

- **Reliability activities**
  - **New ceramic-metal joint testing at TRL6 conditions (dual atmosphere)**
  - **New glass compositions show better CTE and flow characteristics**
  - **Dense MMA slow crack growth behavior very favorable to long-life**
- **Durability improvement**
  - **Cr-getter material showing efficacy in aggressive lab-scale testing at system face velocity**
  - **Supplied to future block tests**
- **Strip cost reduction**
  - **Larger tubes supplied and printing demonstrating ~65% power increase**
  - **TRL5 triple bundle tests of larger tube, bundles planned**

Advanced Materials and Manufacturing

Objective: Qualify materials and manufacturing processes for integrated block metallic components to significantly reduce cost

- Identify/validate advanced materials with foresight on mass production for mechanical properties, corrosion resistance, chromium release
- Validate advanced manufacturing processes for specific components that meet functional requirements and product cost targets
  - Additive Manufacturing (AM)
  - Hot Isostatic Pressing (HIP)
  - Powder Injection Molding (PIM)
  - Spin Forming
- Demonstrate in a block test that the new materials and components meet functional requirements do not adversely impact stack performance through block testing

Advanced manufacturing net shape powder metal

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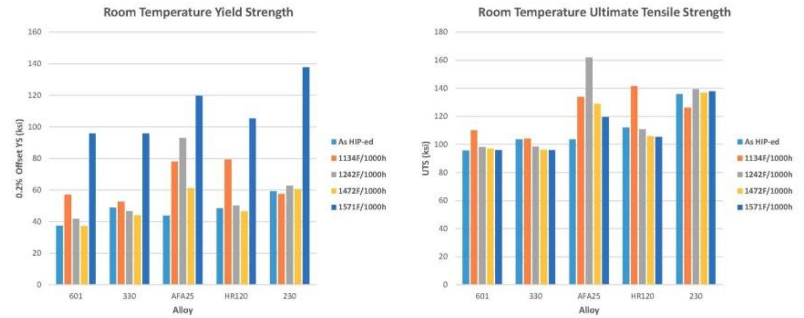
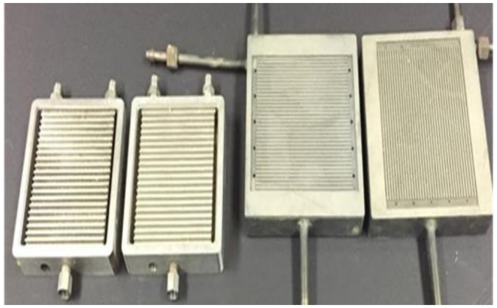
Program Partners

- **Carpenter Technology Corporation**
  - **Down-selected alloys powders: AM**
  - **Hip'd alloys: mechanical and corrosion testing; microstructural analysis**

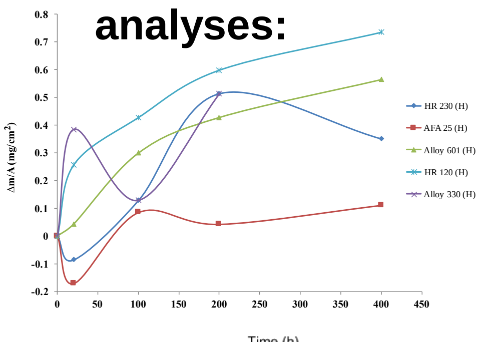
RT Strength – As HIP-ed and After High Temperature Exposures



- **Gas Technology Institute**
  - **Corrosion testing (SOFC conditions)**
    - **Oxidizing, reducing and dual atmospheres**
    - **Thermal cycling**



- **University of Akron**
  - **Corrosion testing: AM materials, Accelerated testing, Microstructural analyses:**



Program Status

- **Task 3.1: Components and Materials**
  - Alloys: 625, H-120, RA330, AFA25, 601, H-230, H-214
  - Ejectors: cathode, anode and auxiliary
  - Metal Fittings: ceramic-to-metal joints
  - Mechanical and corrosion testing

- **Task 3.2 Manufacturing Processes**

• Additive Manufacturing (AM)	• spin forming
• Metal Injection Molding (MIM)	• lost wax casting
• Hot Isostatic Pressing (HIP)	• other processes

  - Cost analysis
  - Manufacturing Trials

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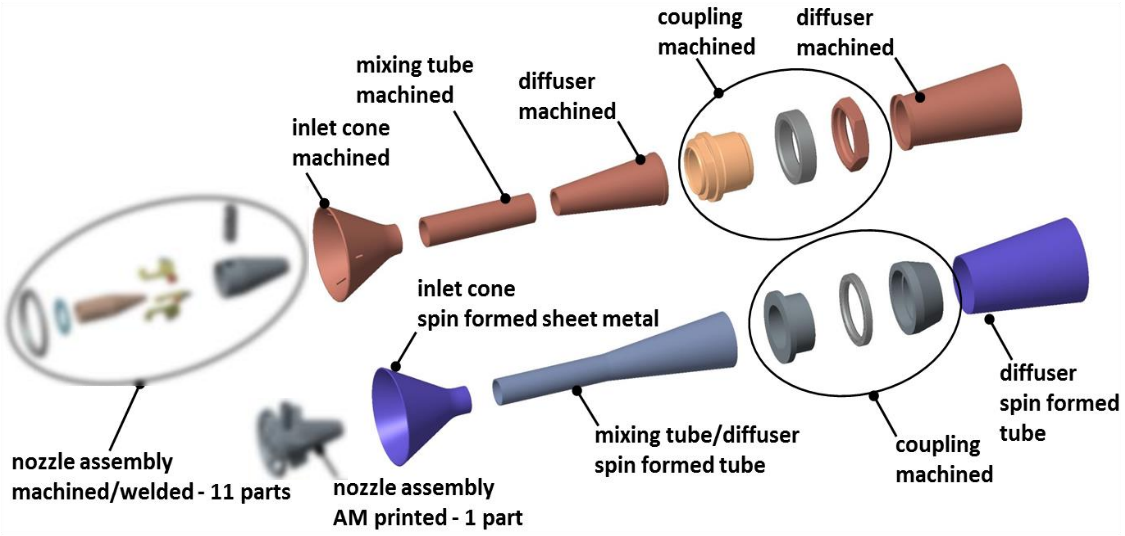
Program Status

- **Task 3.2: Manufacturing Approach: Auxiliary Ejector**



- **Manufacturing cost analysis:**
  - **140-160 MW fuel cell production**
  - **High throughput AM machines**
  - **Estimated 60% cost reduction**

Advanced Materials and Mfg. Summary

- **Alloy down-selection *completed***
- **Mechanical testing of alloys *completed***
- **AM Manufacturing cost analysis: significant cost reductions for complex ejector parts *completed***
- **Corrosion testing underway**
- **Additive manufacturing trials starting**

- **2017 Activities**
  - **Design for additive manufacturing**
  - **Manufacturing/qualification: AM ejectors**
  - **1000 hour fuel cell durability test with AM ejectors**
  - **Explore other advanced manufacturing processes**
    - **spin forming, Metal Injection Molding (MIM)**

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Acknowledgements

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