IT-SOFC Stacks for Robust/Reliable Distributed Generation

FE0026189

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Project Status:
Entering Q4 out of 10 quarters

NETL SOFC Project Review Meeting

Pittsburgh, PA

07/21/2016

NETL Project Objectives

- **Purpose:** To further develop high power density, intermediate temperature SOFC stacks for reliable distributed generation.

- The objective of the overall project is to improve performance/durability of IT-SOFC stacks while reducing costs through:
  - the scale-up of current stack module designs from 1 kW to 5 kW
  - the determination of cell and stack degradation mechanisms
  - cell and stack optimization to improve long-term stability
  - a cost analysis to show a 20% manufacturing cost reduction

Project Team

REDOX

Project Partners:

calce®
Center for Advanced Life Cycle Engineering

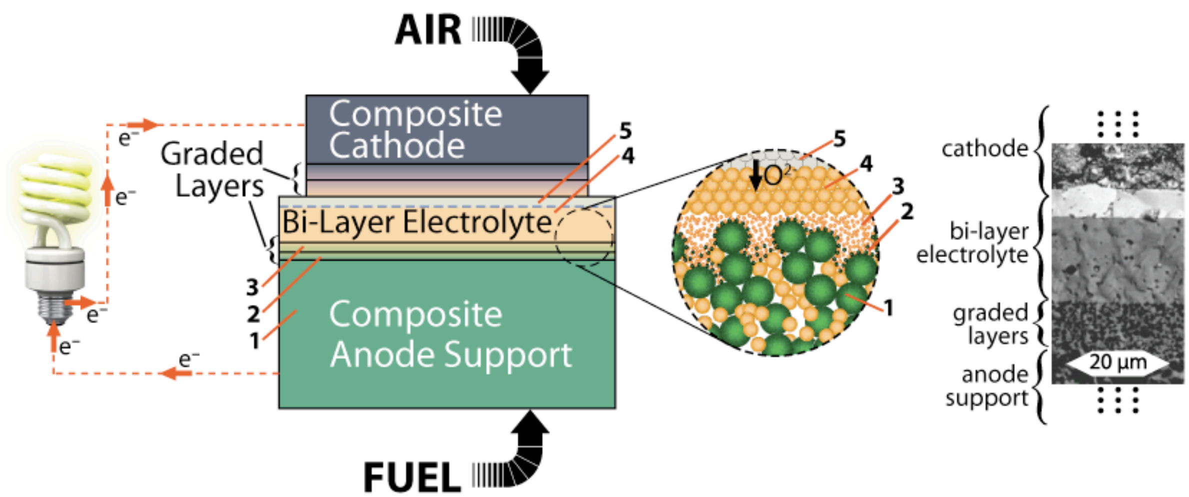
UNIVERSITY OF MARYLAND 1856
ENERGY
RESEARCH CENTER

Additional Redox Partners:

Trans-Tech™
Ceramics and Advanced Materials

Project Approach

- General Approach
  - Bilayer electrolyte
  - Utilize previously developed techniques to understand degradation under operating conditions and using accelerated test protocols (developed with CALCE)
  - Improve structure, manufacturing, and metrology for cells as well as stack assembly procedures for improved reliability
  - Optimize stack designs with enhanced multi-physics model (reduce thermal gradients and mechanical stresses as stack size increased)

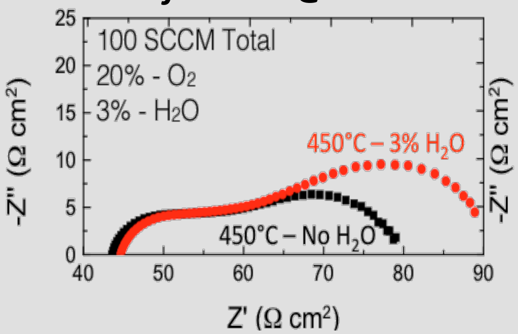


- GDC, leakage current
- Bi_2O_3, high conductivity but unstable in fuel (low PO_2)
- Together form a bilayer with a synergetic performance boost

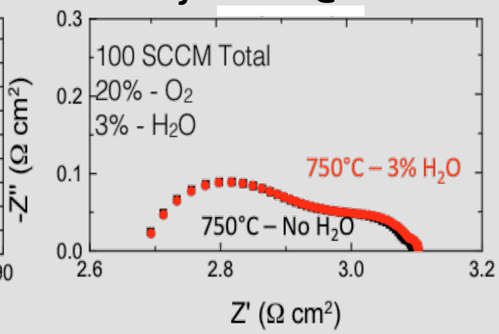
Improve Stability/Reliability of the Cell

- Use techniques demonstrated in past SECA projects to study degradation mechanisms

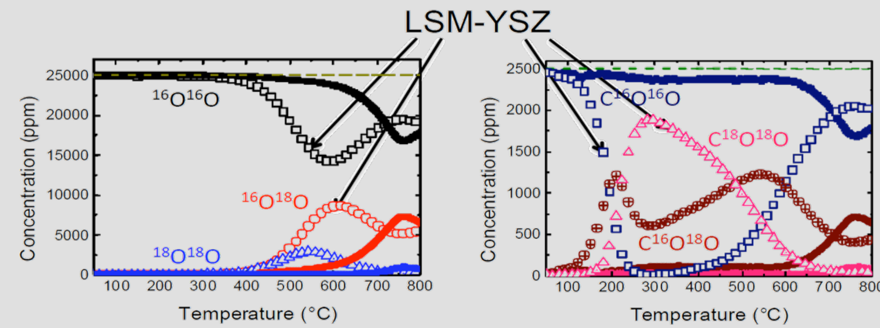
EIS for LSCF @ 450°C



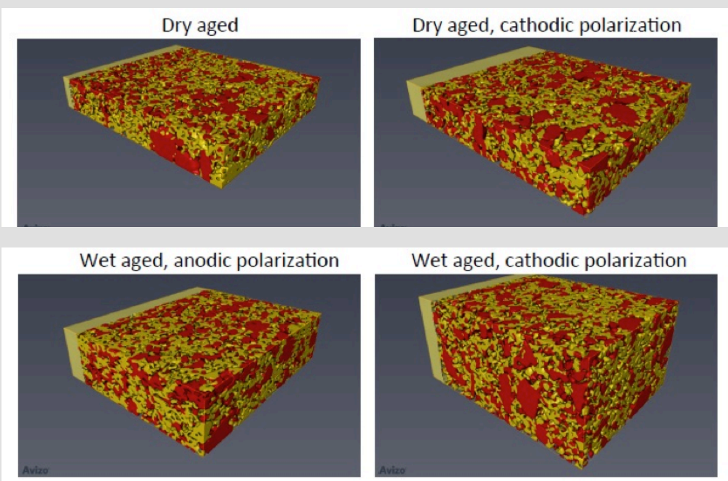
EIS for LSCF @ 750°C

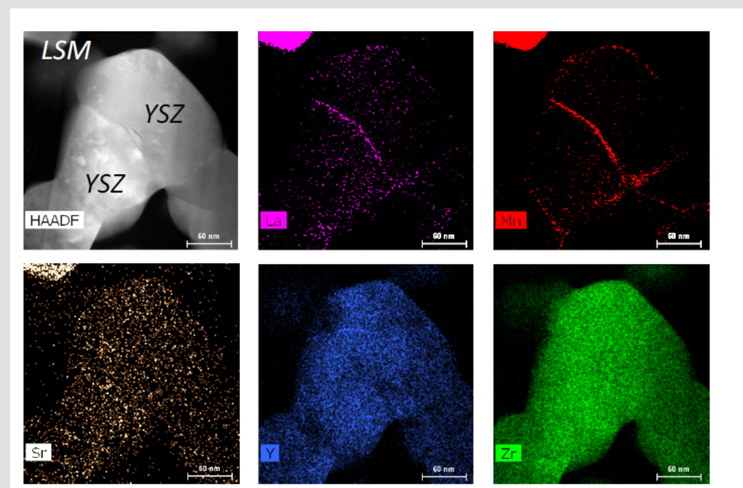


Isotope Exchange for impact of CO_2



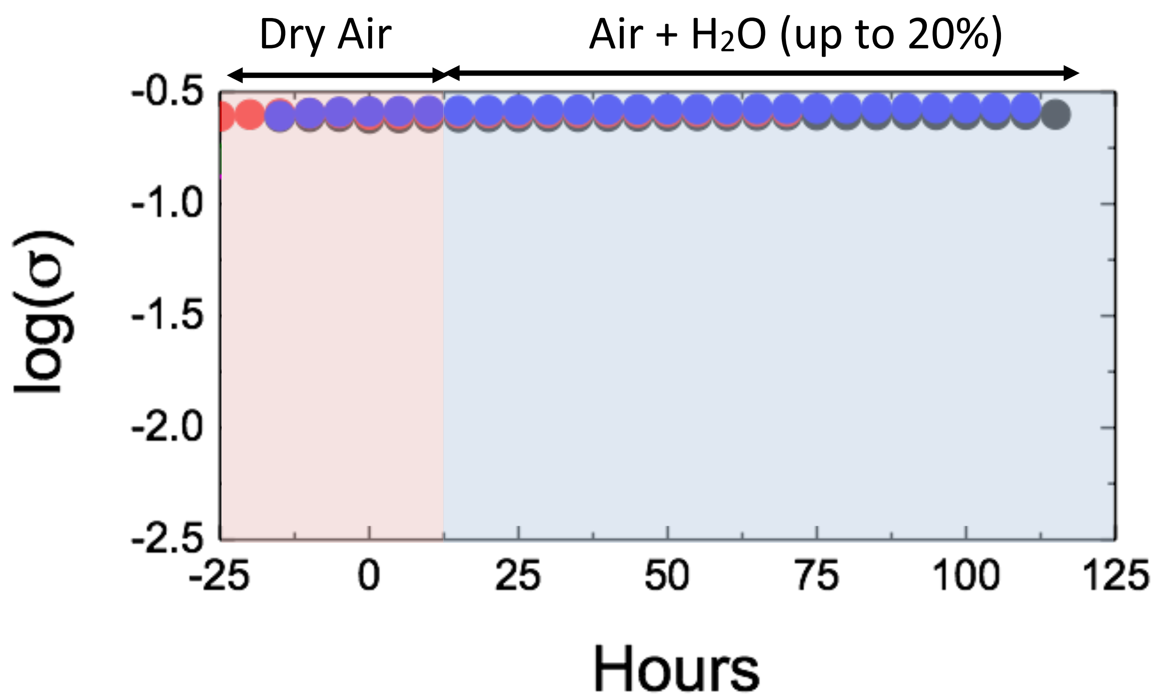
FIB/SEM + TEM/EDS for LSM/YSZ





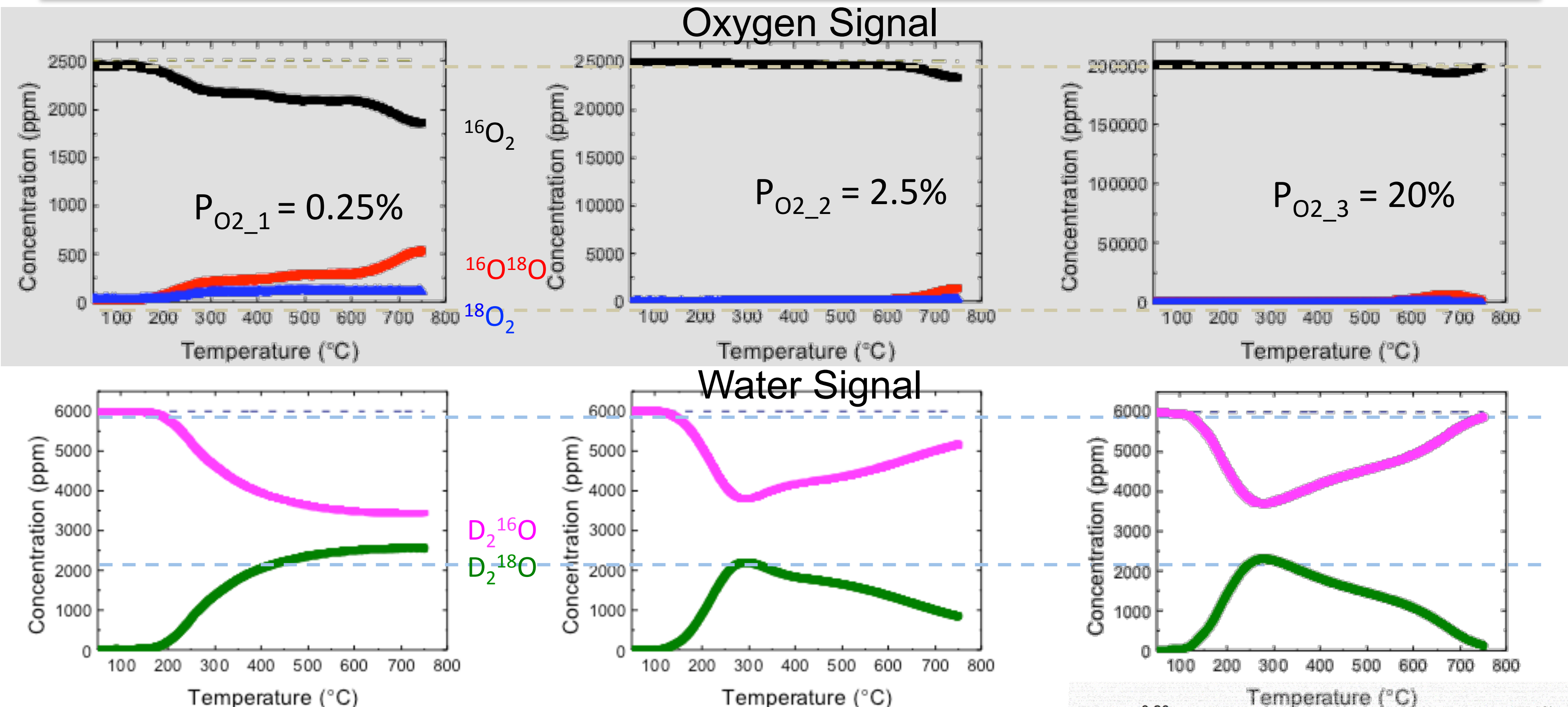
-Impact of H_2O, CO_2, Cr vapor for LSM-ESB cathode
-EIS and oxygen isotope exchange
-FIB/SEM and TEM/EDS

Degradation Mechanism Studies

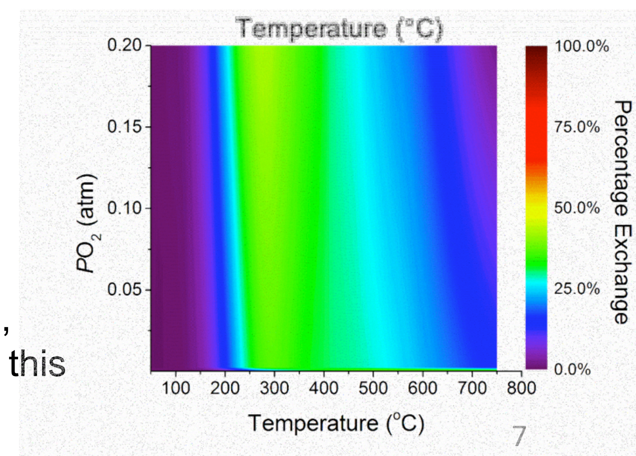


- Evaluated the impact of humidity on $(Er_{0.2}Bi_{0.8})_2O_3$ (ESB) conductivity
  - Conductivity measured on ESB pellets with gold contacts
  - Tested primarily at 650 °C
  - Humidity has no apparent impact on conductivity up to 20% H_2O in air

Isotope Exchange: Impact of Water

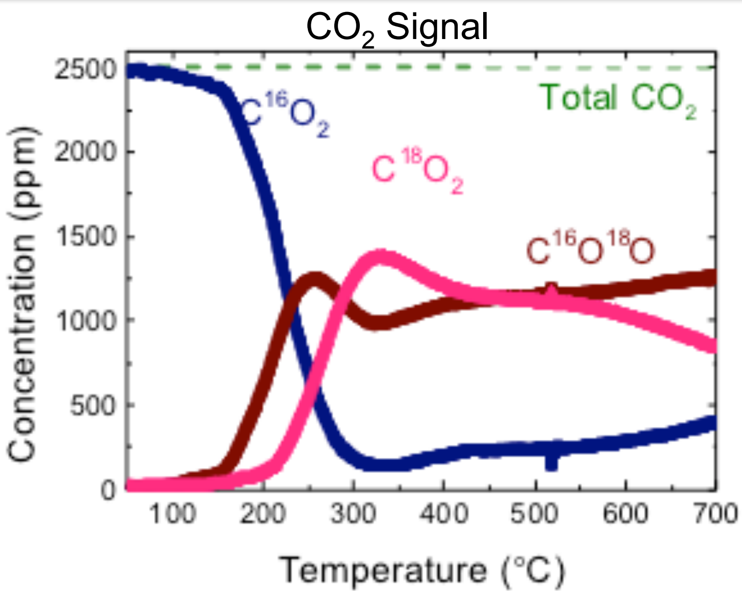


- $(Er_{0.2}Bi_{0.8})_2O_3$ (ESB) powder sample pretreated with ^{18}O
- Water and ^{16}O flowed over sample during test
- Heavy water (m/z=20) was use to avoid H_2O overlap with ^{18}O (m/z=18)
- As PO_2 increases, water signal peaks shift to lower temperatures
- *Initial Conclusions*: water actively participates in surface reactions on ESB, forming different intermediate species on surface, but still unclear whether this impacts degradation



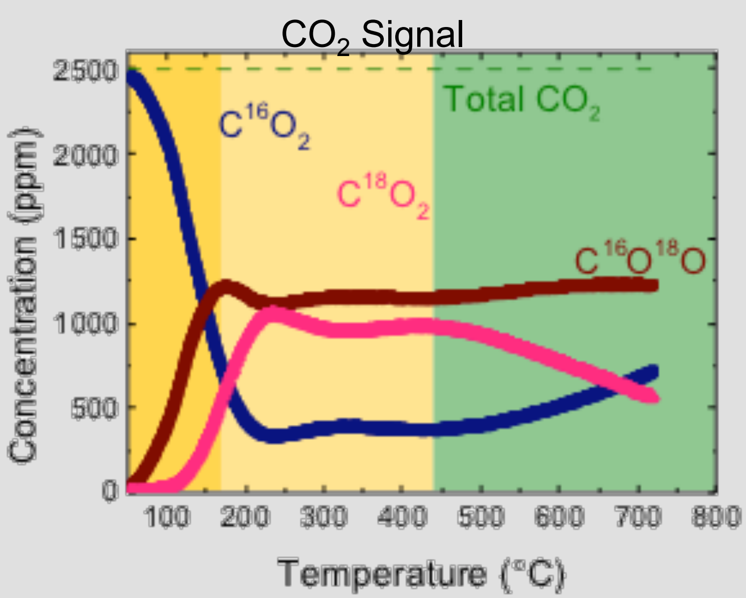
Isotope Exchange: Impact of CO_2

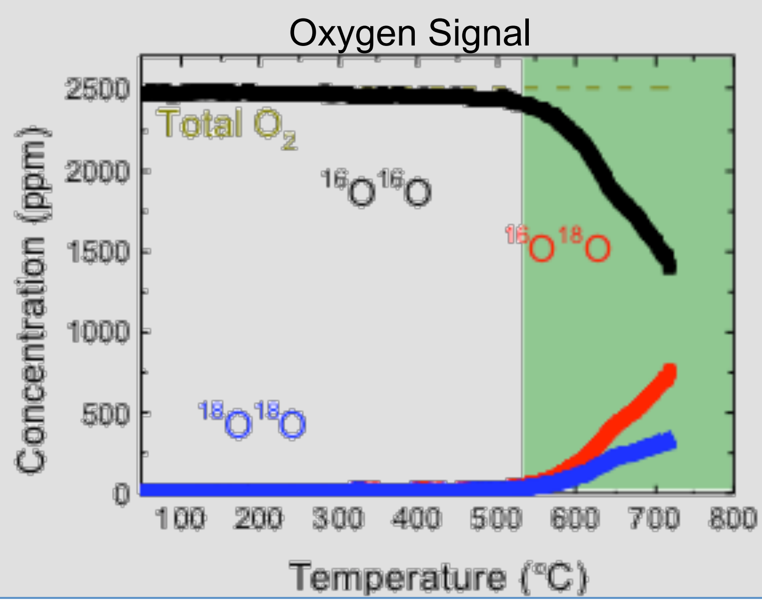
CO_2 only:



- $(Er_{0.2}Bi_{0.8})_2O_3$ (ESB) powder sample pretreated with ^{18}O
- CO_2 or CO_2 and ^{16}O flowed over sample during test
- With addition of ^{16}O, oxygen incorporation from CO_2 shifts to lower temperatures (additional interaction); lattice oxygen participates in CO_2 exchange above 550 °C
- *Initial Conclusions*: CO_2 actively participates in surface reactions on ESB, but it is unclear whether this impacts degradation

CO_2 & $^{16}O_2$ together:

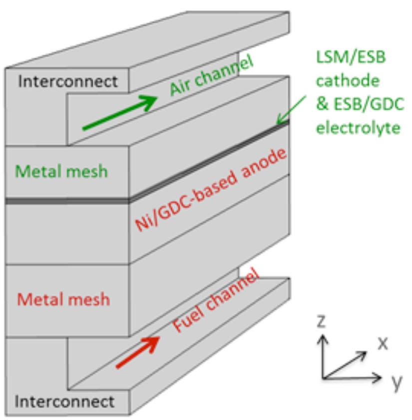




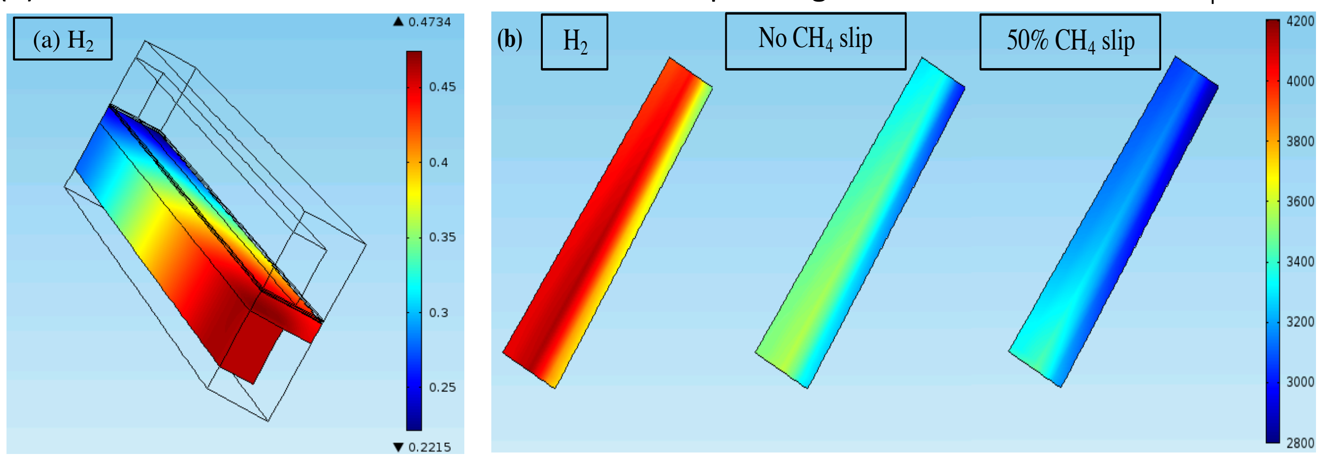
Multi-Physics Tool for Stack Scale-up

- Takes into account the unique thermochemical and physical properties of the Redox materials
- Considers impacts of leakage current (electron current) on the OCV drops from theoretical Nernst potential due to over-potentials associated with the electrolyte and electrodes
- Captures the kinetics of electrochemical and heterogeneous internal reforming reactions in the anode

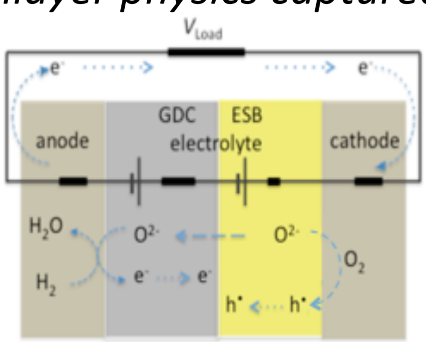
Detailed Single Channel Model



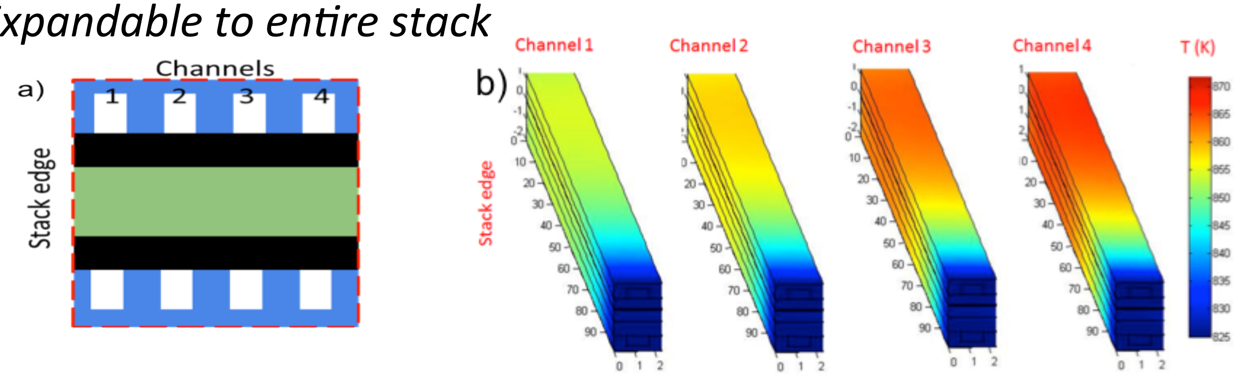
(a) Mole fraction of H_2 for 0.7V at standard fuel utilization for 0% CH_4 slip at 600°C inlet temp.
(b) 2D current distribution for 3 anode fuel feeds operating at 0.7 V and 600°C and a U_f of 80%



Bilayer physics captured



Expandable to entire stack

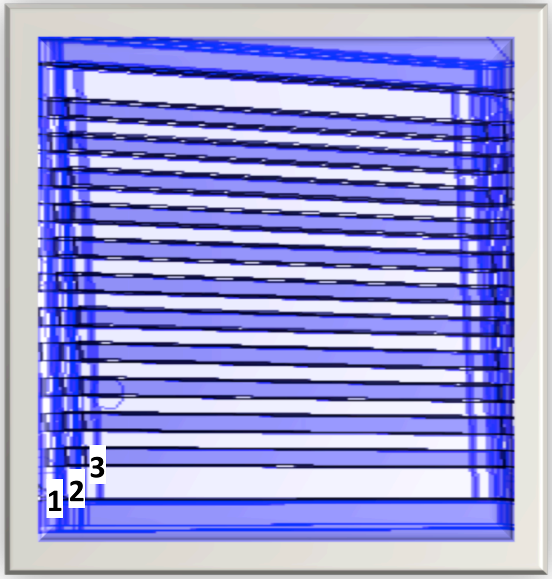


Modeling Effort in NETL Project

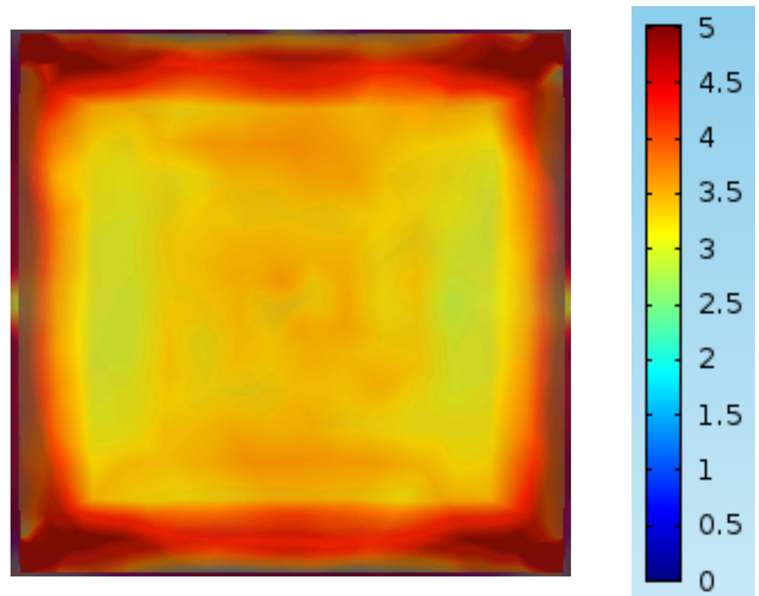
- Add ability to assess mechanical stress due to thermal gradients and phenomena such as creep at elevated temperatures
- Optimize stack design through parametric studies
  - modify cell geometry/composition and interconnect flow field geometry)
    - minimize pressure drops
    - improve flow distribution
    - minimize thermal gradients

Stack Thermo-Mechanical Model: Initial Results

3-cell stack geometry in Multiphysics modeling for thermo-mechanical study

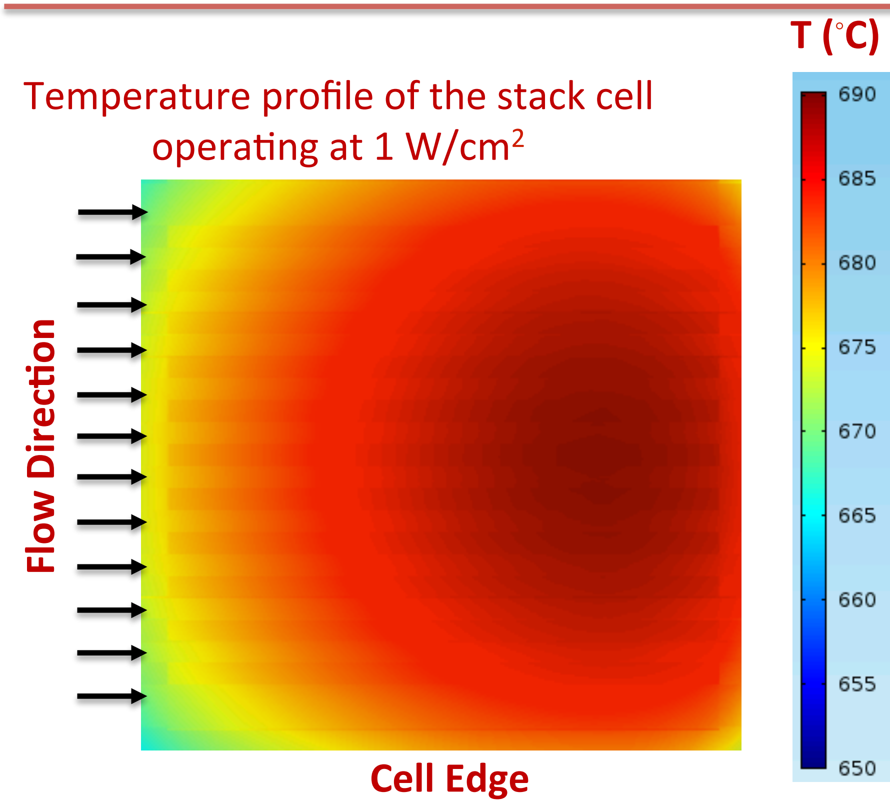


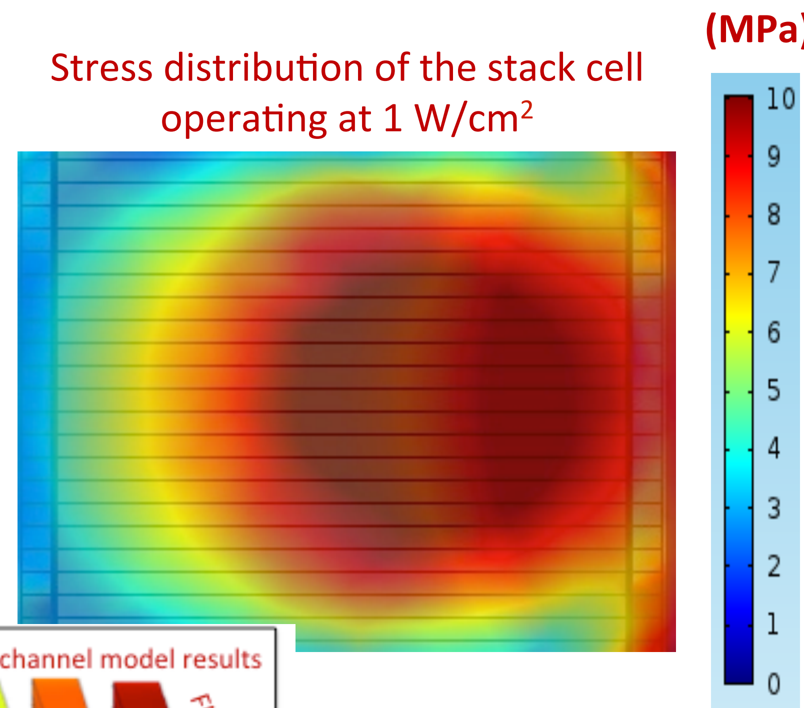
Von Mises stress of the stack cell at room temperature

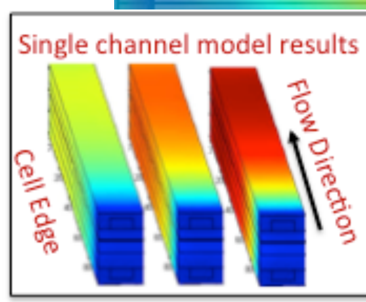


- 3-cell stack under constant load at room temperature after assembly
- Assumes perfectly flat cell
- For current stack design, stresses (~5 MPa) on the cell mainly concentrate at cell edges and corners

Stack Thermo-Mechanical Model: Initial Results



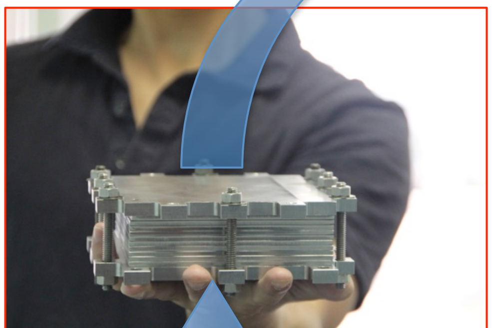




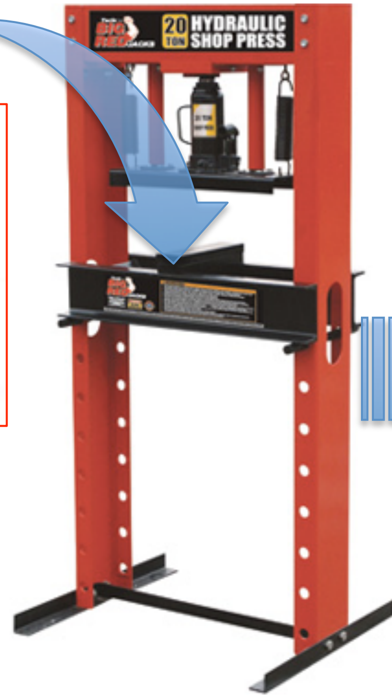
H_2 as fuel

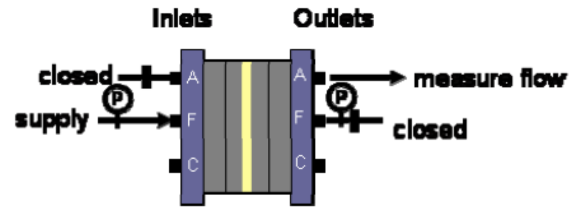
- Integrated thermo-mechanical study based on temperature profile of stack is similar to iterative-solved single channel modeling results
- Stresses increase (up to 10 MPa) as temperatures rise in the center of the stack and concentrate mostly in the center and at end edge
- Next step is to incorporate more realistic cell geometries into model (e.g., edge curl)

Stack Assembly Improvements

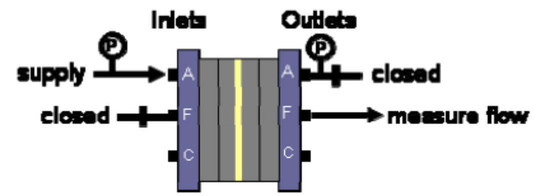


Stack





Fuel to oxidant measurement



Oxidant to fuel measurement *

Redox Production Cells

Stack Assembly Press Instrumentation Upgrade

-increase size & degree of automation
-acoustic emissions
-dynamic tracking of applied load & compression

Leak Check QC

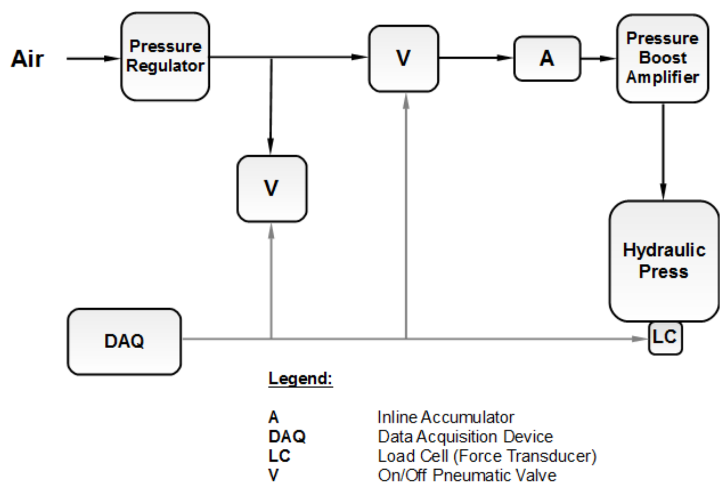
-improved procedures
-correlation to elevated temperature testing & manufacturing QC information

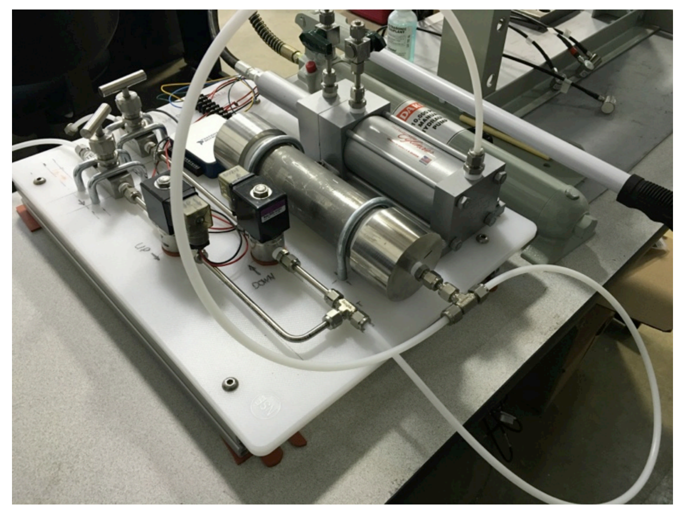
feedback for production optimization

*Ref. US Fuel Cell Council, Document No. 04-070

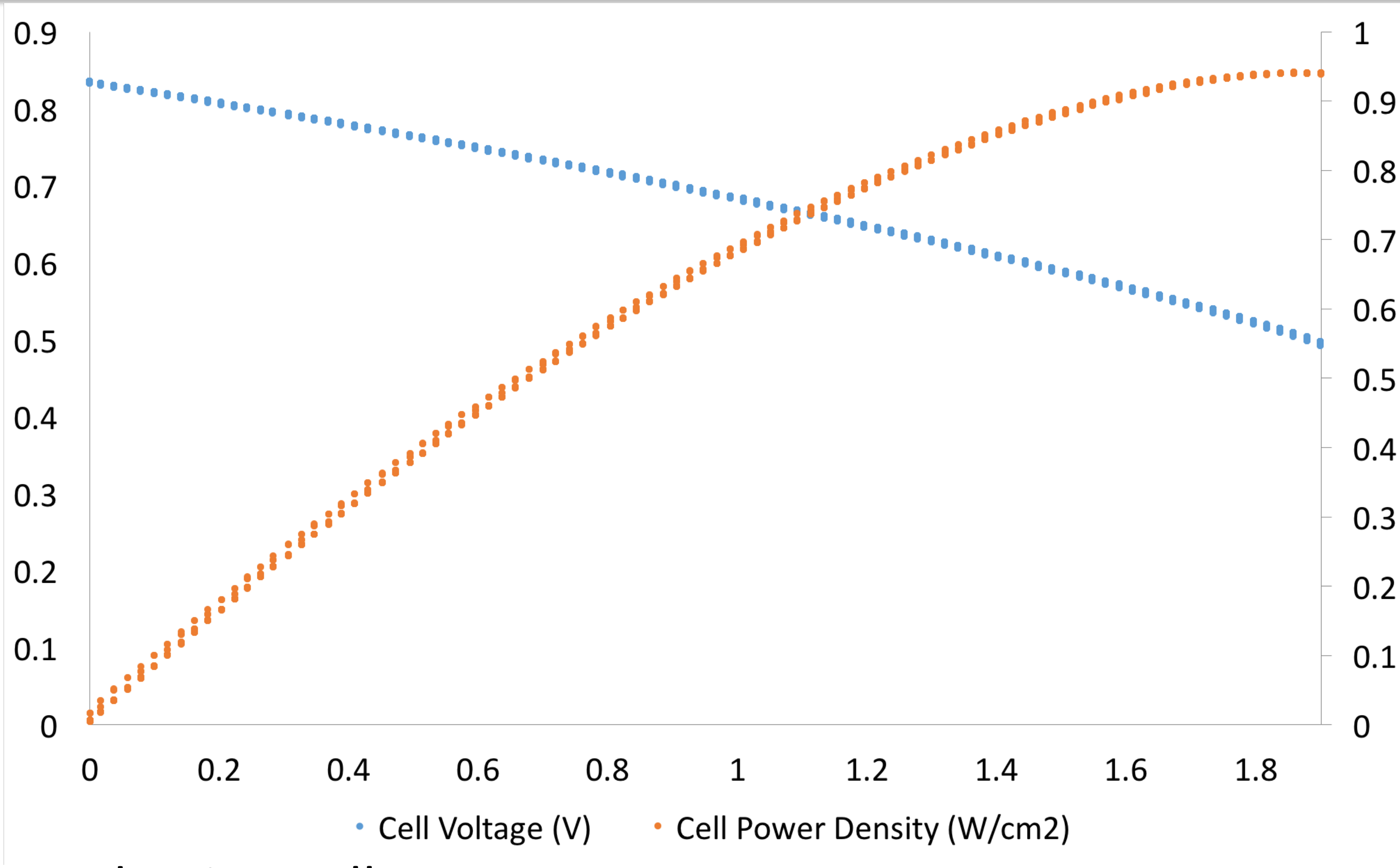
Stack Assembly Automation for Improved Reliability

- To improve reliability and stack to stack repeatability, we upgraded our stack assembly equipment
- Pneumatic-hydraulic setup for ramp rate and setpoint control
- Metrology improvements
  - Displacement, load distribution, and acoustic emisssions
- In-situ pressure decay measurements





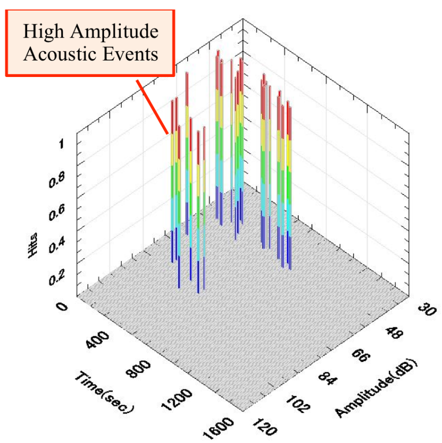
Initial Results Using Upgraded Assembly Setup



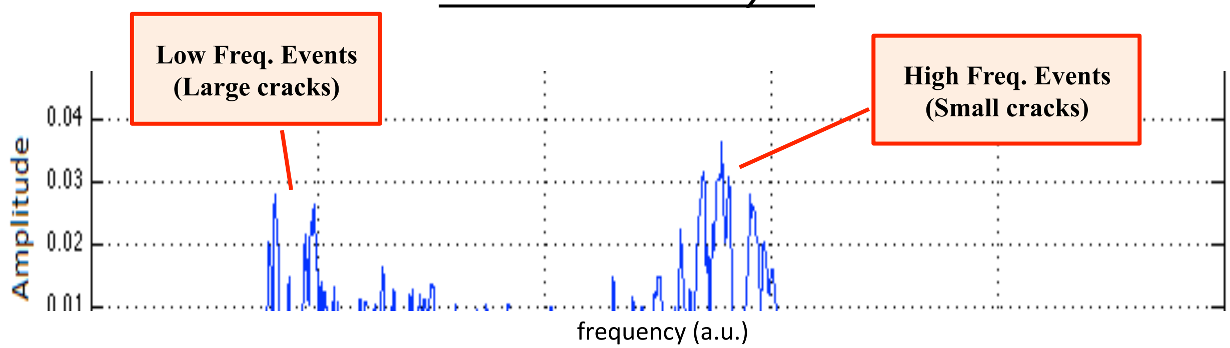
- Production cell
- 650 °C (exhaust temp) in H_2
- Stack assembled with new setup is currently being tested

Stack Assembly Metrology: Acoustic Emissions

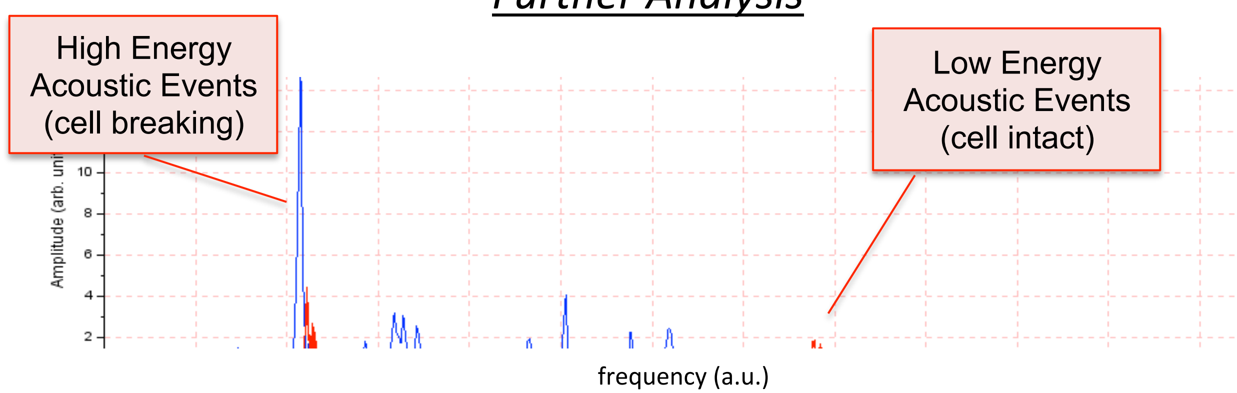
- AE utilizes microphones placed around stack during assembly
  - Listen for “events” (e.g., slipping or cracking)
  - Analyze raw data and identify fingerprints for different events
  - Helps improve quality control and development efforts



Initial Pass Analysis



Further Analysis

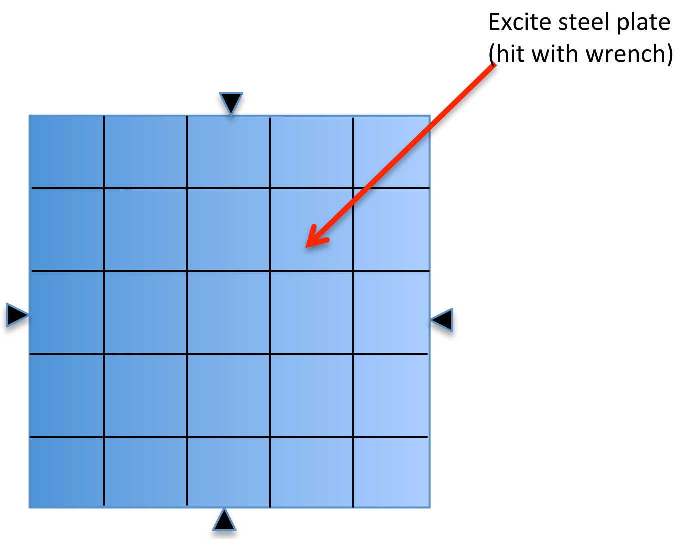


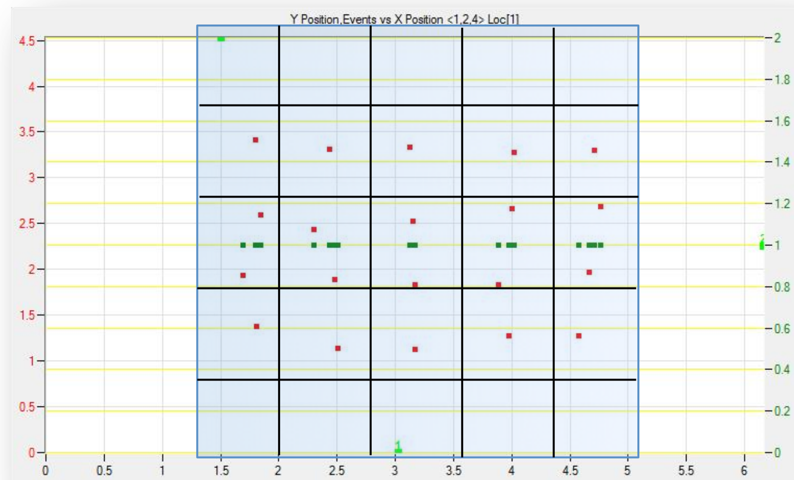
Cell Metrology and Process Improvements

- Manufacturing process improvements → flatter cells
  - edge curl and camber can create stress concentrators
  - cell cracks during assembly and/or stack operation (degradation / failure)
  - 3X reduction in average flatness (i.e., cell is flatter)
  - >1.5X reduction in std deviation (i.e., more cells in batch are "flat")
- Experiment to compare strength during assembly and after reduction
  - Compress single cell with gasket, metal plates, current collectors
  - Control and monitor load with automated setup
  - Detect cracking event with AE technique (determine at what load event occurs)
  - Use as-produced cells (NiO cermet) and reduced cells (Ni-cermet)
- Old (un-optimized) Cells
  - Reduced cell: cracked along edges at about 1.5 times the standard assembly load
  - As-processed cell (QC reject due to high edge curl): cracked below assembly load
- New Flatter Cells
  - Reduced cell: did not crack even up to ~4 times the assembly load
- Work is on-going, but promising for higher yield of stackable cells and increased mechanical reliability

Acoustic Emissions: Event Localization

- Explored the use of AE data for localization of certain "events"





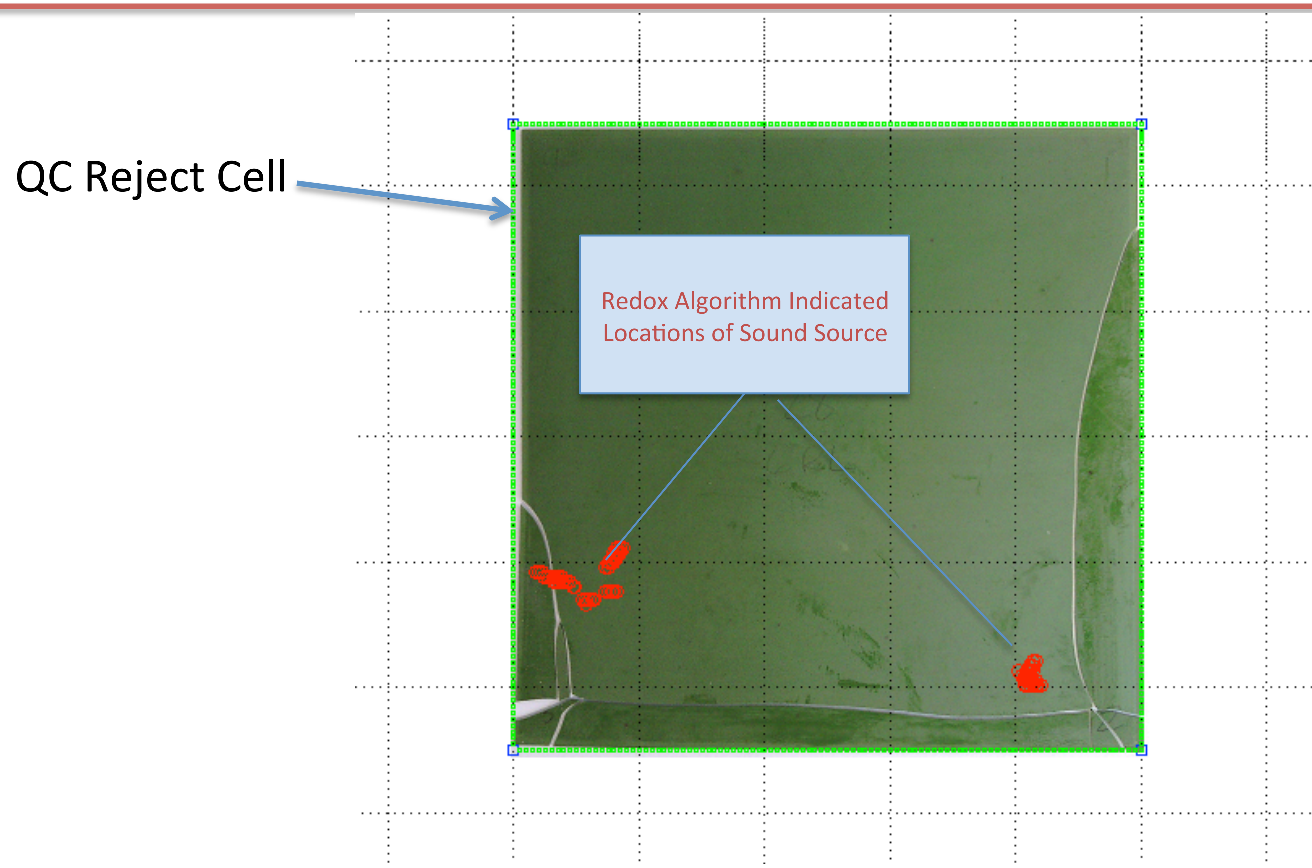
Red dots are what is important (ignore green dots)

-red dots represent algorithm prediction of source of sound

-accuracy of ~±10 mm

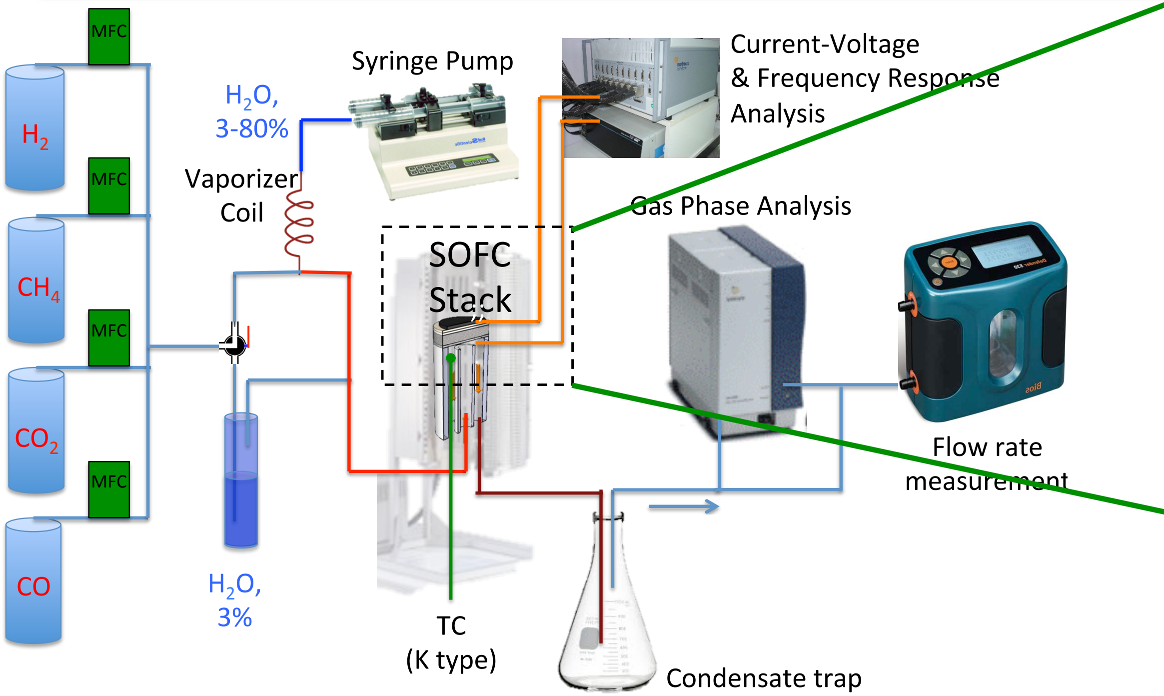
-method works with metal, but will it work with ceramic & metal?

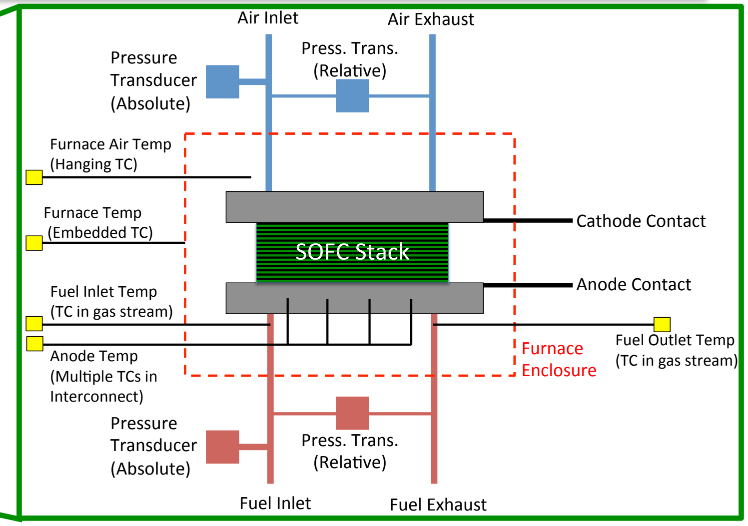
Acoustic Emissions: Event Localization



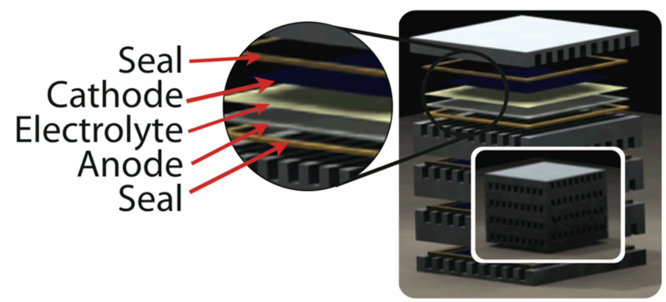
- Initial results for localization on SOFC during assembly is encouraging
- Additional optimization possible with algorithm improvements and additional microphones
- Technique will be used to pinpoint source of mechanical failure to help us in design and assembly optimization
- We are also utilizing AE during high temperature testing for general “event” detection

Reduce Stack Degradation





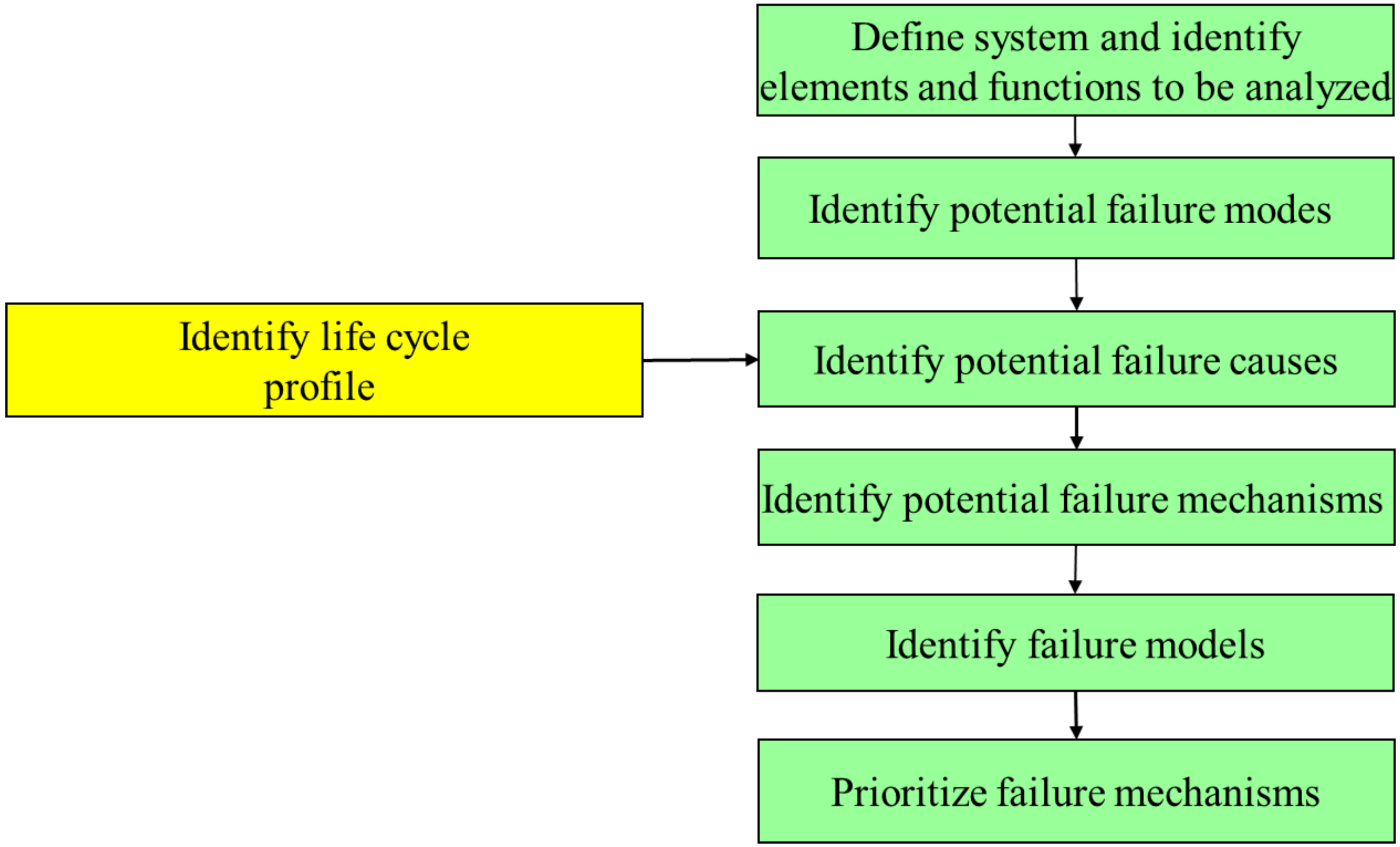
Extensively instrumented to capture dynamic behavior



Stack Lifecycle Analysis Modeled and Evaluated Using:

- Strength, creep, and acoustic emission spectroscopy data of stack materials & components
- Multiphysics modeling of components
- Long-term measurements under normal operational conditions
  - Power output, voltage changes, component conductivity
- Accelerated stack testing under extreme temperature and load
- Modeling of material and operational costs over lifetime of stack

Developing Accelerated Test Protocols



Failure Mode, Mechanism and Analysis (FMMEA) Methodology

Developing Accelerated Test Protocols

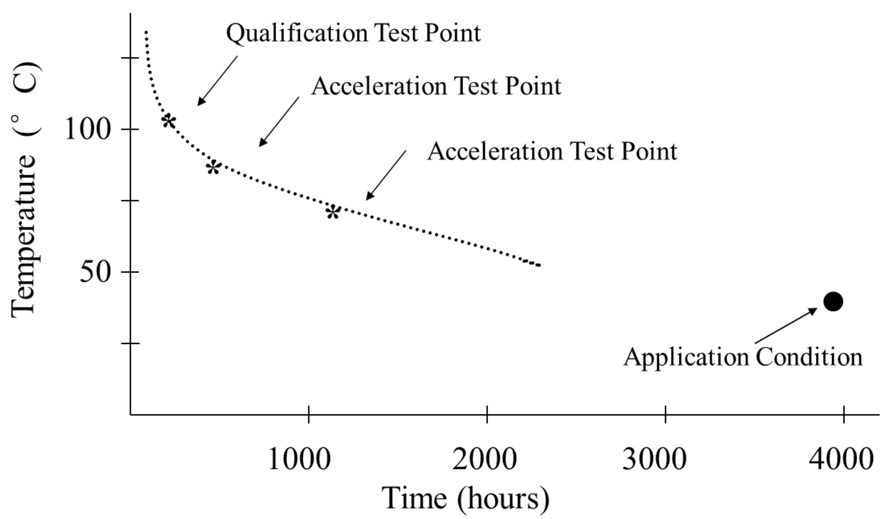
Component	Potential mode(s)	Potential failure mechanism(s) Type	Mechanism type	Observed effect	Potential failure causes	Likelihood of occurrence	Severity of occurrence	Ease of detection
Cathode	Precipitation by ionic hydration	Chemical reaction	Wearout	Increase in polarization resistance	Humidified air	Low	Low	Moderate
	Cr-poisoning	Chemical reaction	Wearout	Increase in polarization resistance	Metallic interconnect or and gas tube	High	Moderate	Low
	Interfacial delamination	Mechanical stress	Overstress	Increase in area specific resistance	Reduction of the contact area	Low	Low	Low
Seal material	High leak rates	Mechanical stress, Thermally driven sealant	Wearout	Structural or functional failure, Shortage of fuel and anode reoxidation	Mismatch in thermal expansion	Low	High	Low
Contact material	Corrosion, Reactions with stack	Chemical reaction	Wearout	Performance degradation	Reduction in contact area	Low	High	Moderate

- Identified possible failure mechanisms, potential causes, and likelihood of occurrence
- Accelerated tests can be performed at elevated temperature, humidity, voltage, pressure, vibration, etc., or in a combined manner
- The test stresses should be chosen so that they accelerate only the failure mechanisms under consideration
- For failure mechanisms and stresses there are commonly accepted acceleration transforms that one can start from as the first approximation

Developing Accelerated Test Protocols

Fuel Cell Component	Standard	Failure Mechanism	Accelerated Test Variables	Monitored Parameters
Cathode	JEDEC 22-A110E Accelerated Temperature and Humidity Test	Microstructural changes, Surface poisoning	Temperature, RH	V, I, ASR
	IEC 62282-2 Overpressure Test	Phase stability, Coarsening	Pressure	V, I, ASR
	IEC 62282-3-100 Overload Test	Structural changes, Chemical changes	Cell current loading (A/cm^2)	V, I, ASR
Anode	JEDEC 22-A105C Power and Temperature Cycling	Coarsening, Mechanical stress	Cell loading and Temperature cycling (frequency and amplitude)	V, I, ASR
Electrolyte	IEC 62282-2 Gas Leakage Test	Chemical reactions, Chemically induced mechanical stress	Cell loading Pressure Temperature	V, I, ASR Exhaust composition

- JEDEC Microelectronic Standards Considered for Matching with Failure Mechanisms
- Also considered standard tests from the IEC 62282-2 Fuel Cell Modules 2012



- Next steps
  - Focus on the cathode initially
  - Apply degradation models
  - Determine range of parameter values for each test

Summary of NETL Efforts

- Initial investigations into degradation mechanisms
  - Bi_2O_3 based electrolyte (ESB) and cathodes (LSM-ESB)
  - No apparent impact of humidity
  - But there is some interaction of H_2O and CO_2 with oxygen exchange
- Stack assembly equipment upgrades & Stack Design
  - Automation of load application rate and setpoint
  - Load distribution measured
  - Acoustic emissions for event detection and localization
  - Multiphysics model with new mechanical capabilities will be used to design more robust stack
- Cell process improvements
  - Flatter cells result in more robust cell
- Accelerated test protocols
  - Use of FMMEA methodology
  - Identified existing protocols and applied to possible failure mechanisms for cathode, electrolyte, and anode
  - Next steps involve using degradation mechanisms identified by UMERC to finalize parameter value ranges for accelerated testing

Acknowledgments

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  - Seth Lawson

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  - Energy Research Center (fundamental R&D) – Prof. Wachsman
  - CALCE (accelerated / lifecycle test plans) – Prof. Pecht/Diganta Das