Low-Temperature Solid Oxide Fuel Cells for Transformational Energy Conversion

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Redox Cube

- 25 kW, natural gas, stationary power system
- > 50% efficiency
- Compact (~1 m^3)
- Lightweight (< 1000 lbs)

Introduction

- **High Specific & Volumetric Power Density to Reduce Costs/Market Barriers**
  - High power densities at lower temperatures reduce costs and enable compact power systems
  - Lower temperatures provide for better thermal cycling, rapid startup & load following (*MYRDD ’12*)
  - Appeal for reduced weight systems in commercial, defense, and consumer applications drives widespread adoption and leverages economies of scale to further reduce cost

Stack Performance Metrics	Proposed ARPA-E Targets
Size (kW)	1
Operating Temperature Range (°C)	300-500
Open Circuit Voltage (V/cell)	1.0-1.1
Current Density at 70% Nernst (A/cm^2)	≥0.2
Electric Efficiency at Rated Power (%)	≥54
Startup Time (minutes)	<10
Transient Response, 10-90% (minutes)	<1

ARPAE Collaborators

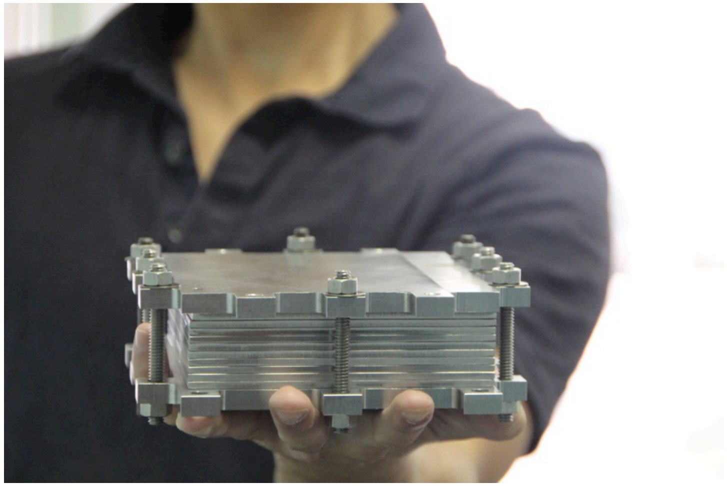
- Microsoft Inc. (*datacenter, server rack embedded power*)
- Nat'l Fuel Cell Research Center, UC-Irvine (*independent test*)
- Strategic Analysis Inc. (*techno-economic analysis*)
- Trans-Tech, Inc. (*production cell manufacturing*)
- University of Maryland (*cell R&D*)

Redox Additional Partnerships

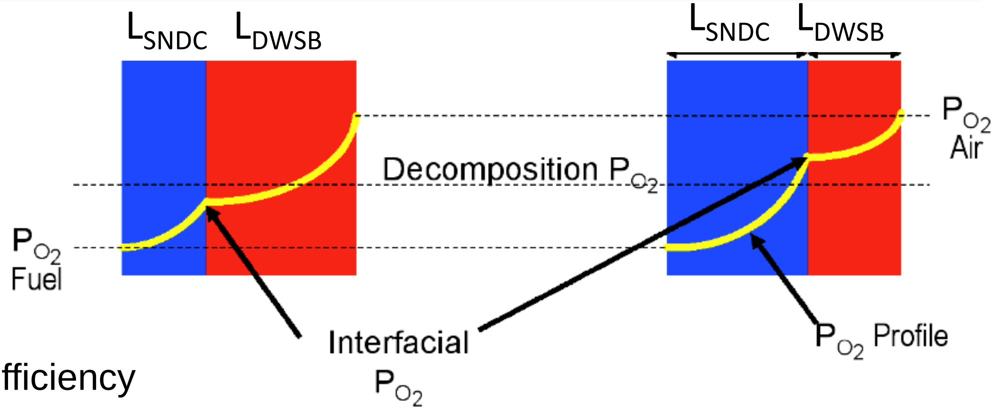
- MTech (*incubator & business growth)*
- Colorado School of Mines (*fuel processing/system expertise*)

Relevance: Project Objectives

- **To improve the performance/durability of Redox technology through the:**
  - development of an optimized bilayer electrolyte with increased open circuit potential (OCP) and thus greater fuel efficiency for natural gas fueled, LT operation of ≤500°C;
  - optimization of compositions and nanostructures for the cathode to increase power density, and the anode to improve carbon- and sulfur-tolerance in hydrocarbon fuels;
  - development of reduction-oxidation stable ceramic anodes for more robust stacks;
  - use of a custom multiphysics model and advanced materials to optimize the performance of bilayer stack designs for LT operation; and
  - development & demonstration of a 1 kW LT-SOFC stack with load following between 300-500°C for datacenter and distributed generation applications.



Approach Summary: LT-SOFC Stack



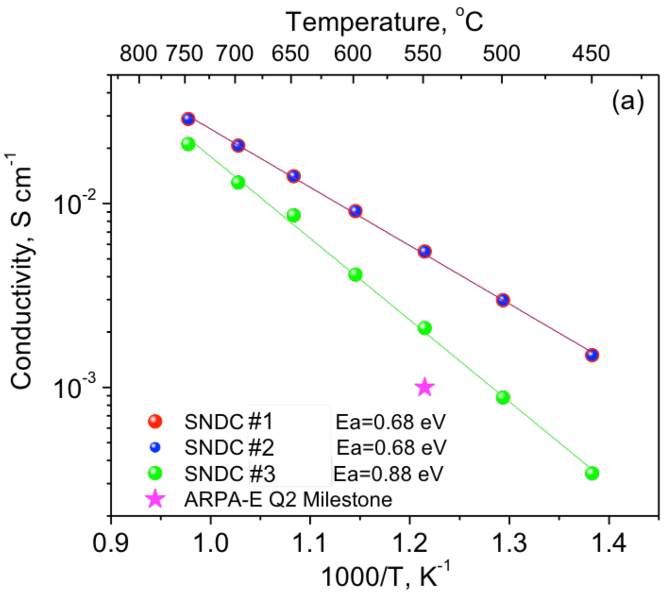
- **Increased Efficiency**
  - Dy/W stabilized Bi_2O_3 (DWSB):
    - 70X conductivity of YSZ @ 500°C
    - unstable at low PO_2 (fuel conditions)
  - Sm/Nd doped CeO_2 (SNDC):
    - > 10X conductivity of YSZ @ at 500°C
    - electronic leakage in fuel conditions, lowers efficiency
  - ***Solution***: A bilayer of SNDC (fuel side) and DWSB, stops ceria electronic leakage & Bi_2O_3 decomposition
  - ***Goal***: Optimize *total bilayer electrolyte thickness* and *relative thickness* of SNDC & DWSB
    - maximize efficiency (increase OCP to 0.9-1.0V) & minimizing ASR for ~0.5 W/cm^2 (@ ~0.8V) at ≤ 500°C

- **Higher Power Density**
  - Improve carbon/sulfur tolerance with catalyst infiltration into as-fabricated porous anodes (10 cm by 10 cm)
  - Optimize LSM-DWSB cathode composition to increase power density (reduce cost)

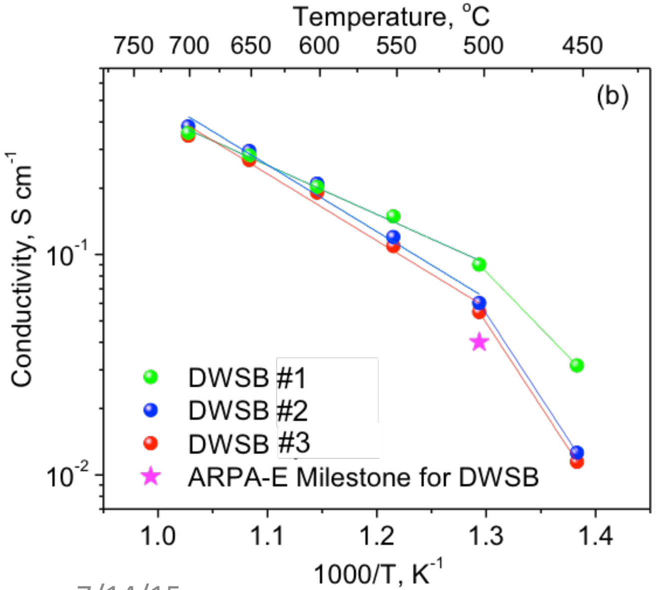
- **Optimized stack designs for LT operation**
  - Integrate SNDC/DWSB bilayer Redox multi-physics model and use to optimize stack design
  - Maximize internal versus external reforming
  - Conductive ceramic anodes for more robust cells and stacks

- **1 kW stack demo for load following**
  - Bilayer cell performance maps for stack, feed results back to model for design optimization
  - 1 kW$_e$ stack demo for load following applications such as datacenters

High Conductivity Electrolytes



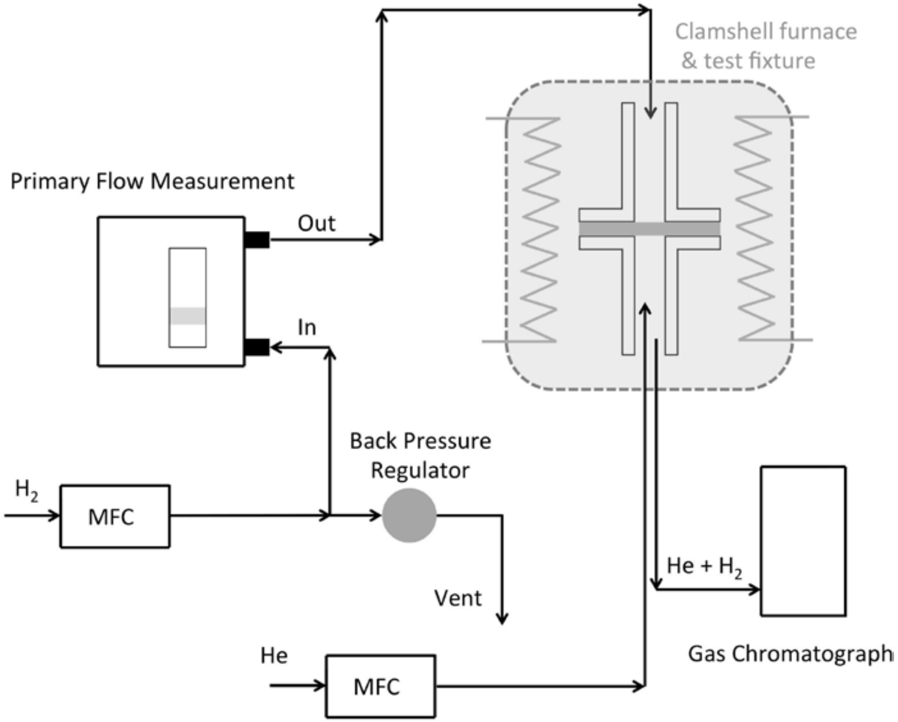
- The conductivity of SNDC is 0.011 S/cm at 550°C
  *one order of magnitude higher than the target
  *confirmed by multiple synthesis routes
- XRD showed single cubic phase and fluorite structure



- The conductivity of DWSB is 0.09 S cm-1 at 500°C
  **_2X the Q2 target_*
- Powders derived from different approaches have a nano-scale to submicron distribution.
- *Future Work:*
  - Evaluate new formulations for reduced cost while maintaining performance at lower temperatures

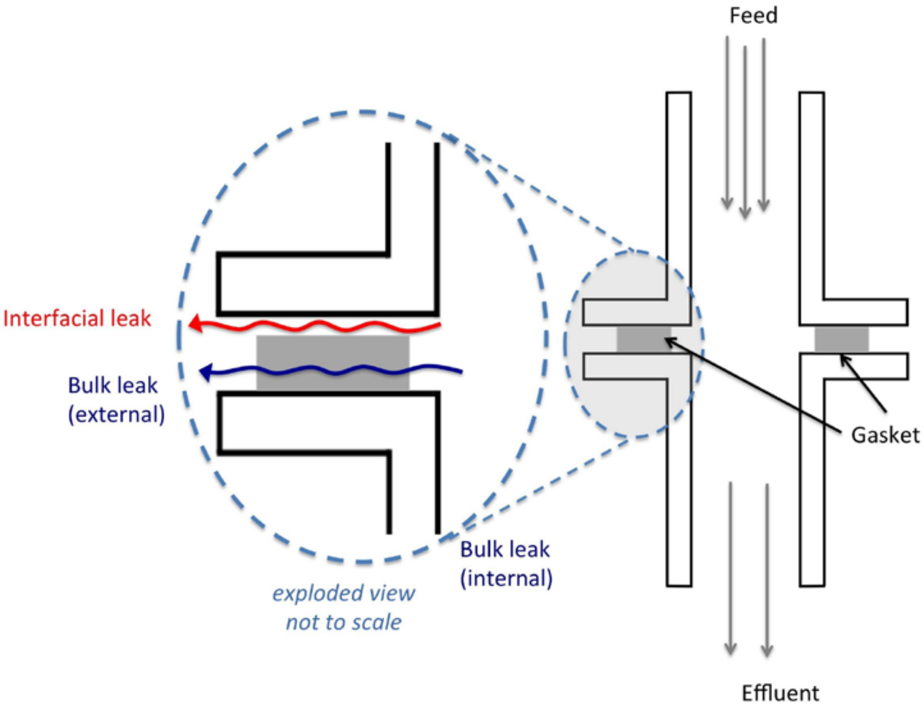
Improved Low Temperature Gaskets

Stagnation Flow Testing Configuration



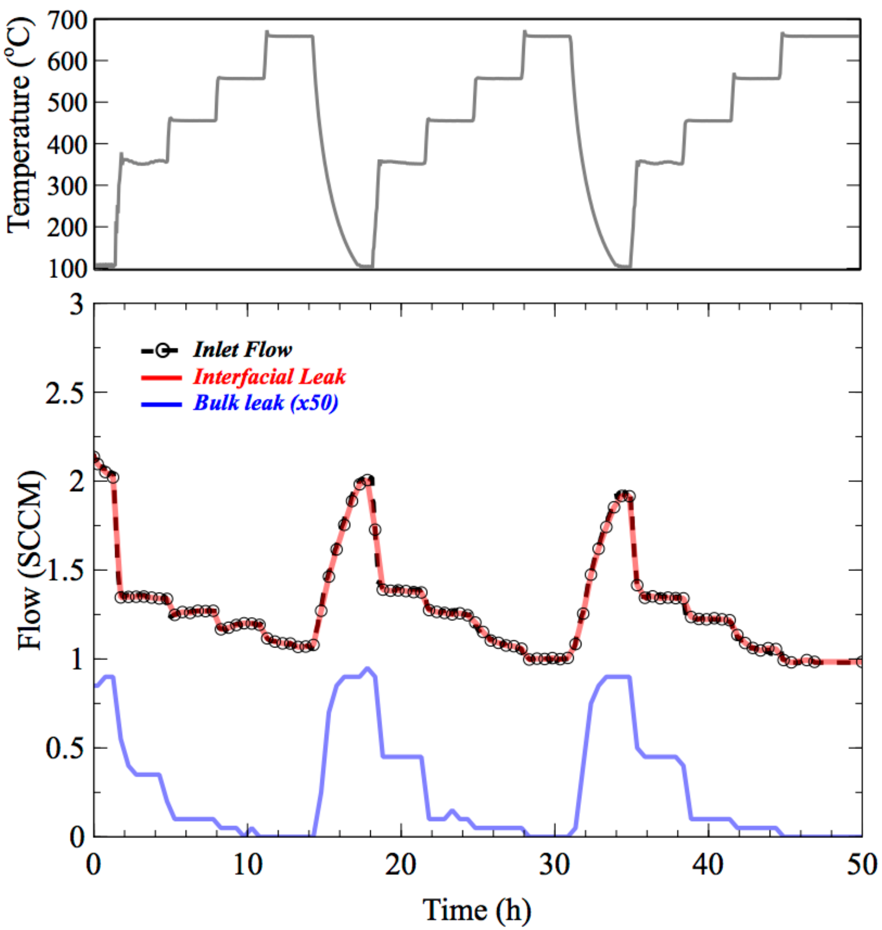
Measures interfacial and bulk leakage with stagnant fuel flow

Flow-Through Testing Configuration



Measures only interfacial leakage with realistic fuel flow

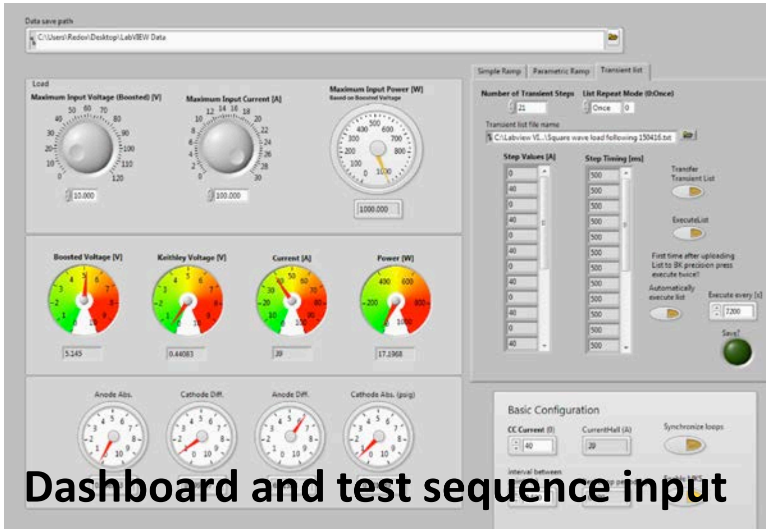
Improved Low Temperature Gaskets



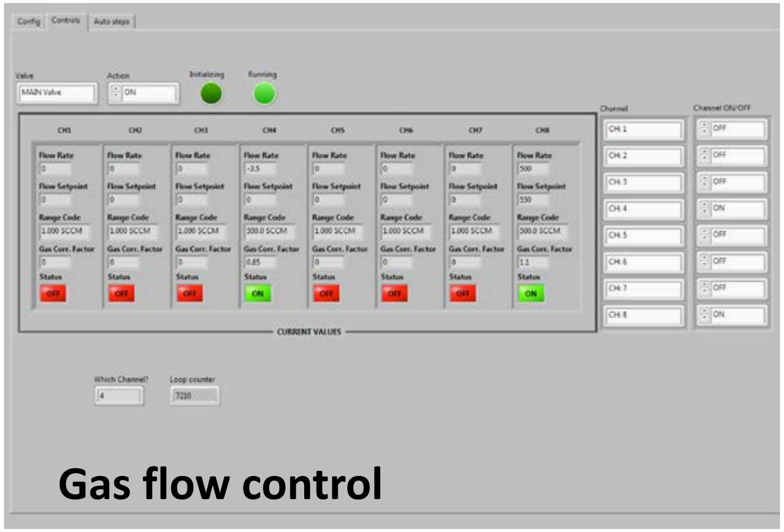
- Compiled data from multiple tests as a function of seal pressure
- Fuel leak rate < 2%

Load Following at Lower Temperatures

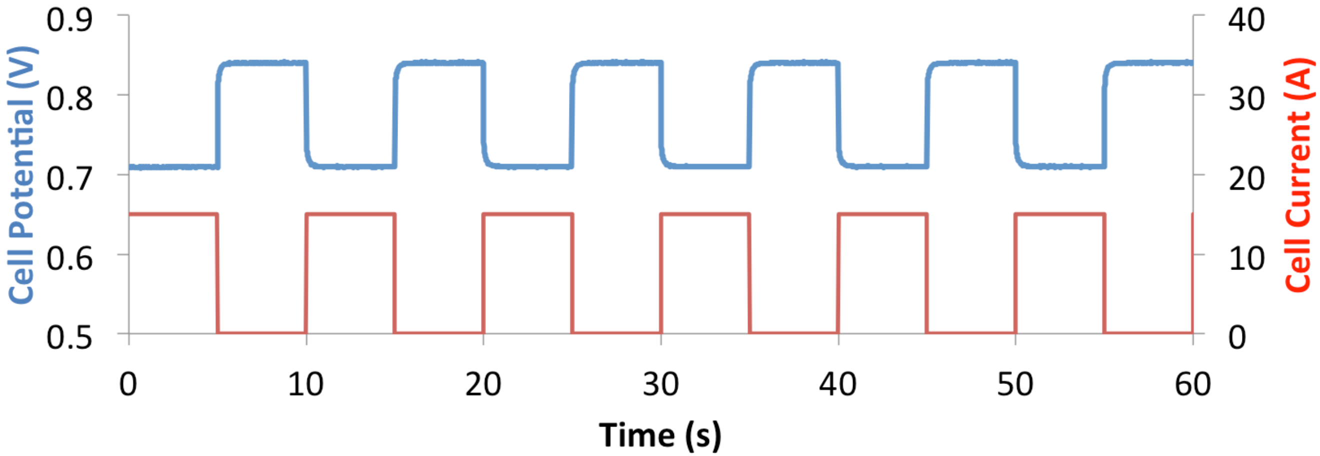
***M5.3.1:** Demo short stack (1-3 cells) using GDC cell from 550-600°C for load following*



Dashboard and test sequence input



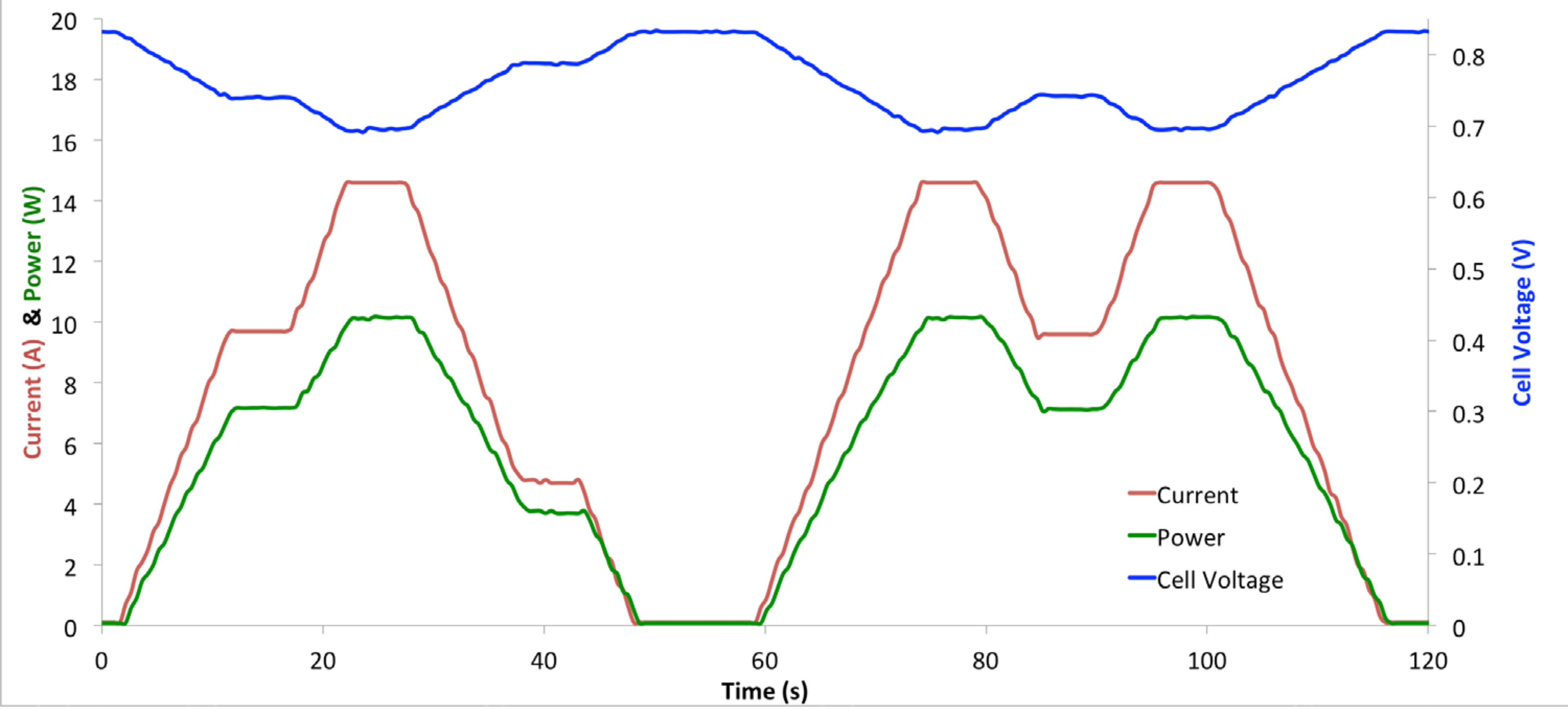
Gas flow control



Rapid pulse performance verification

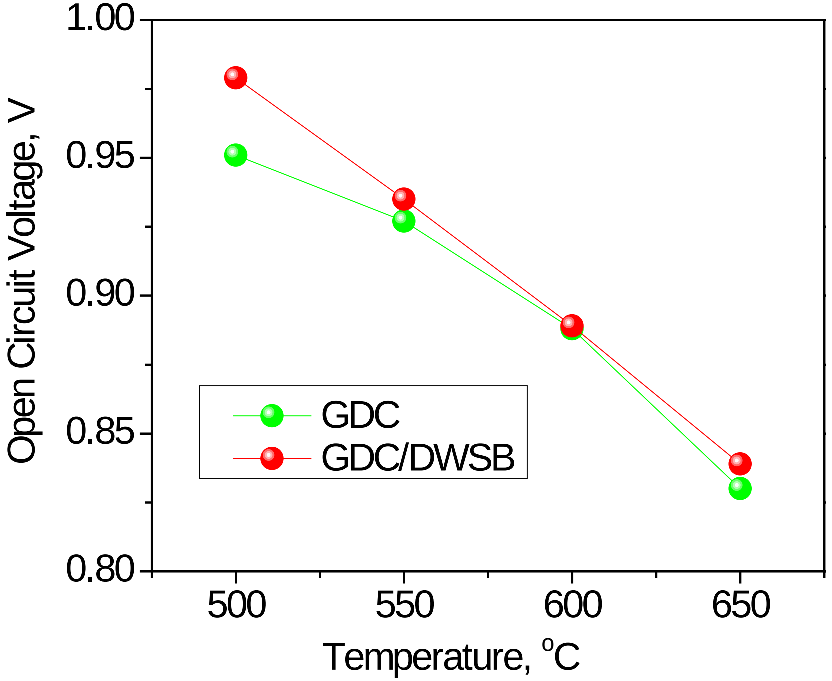
More Complex Load Profiles *(Active Fuel Control)*

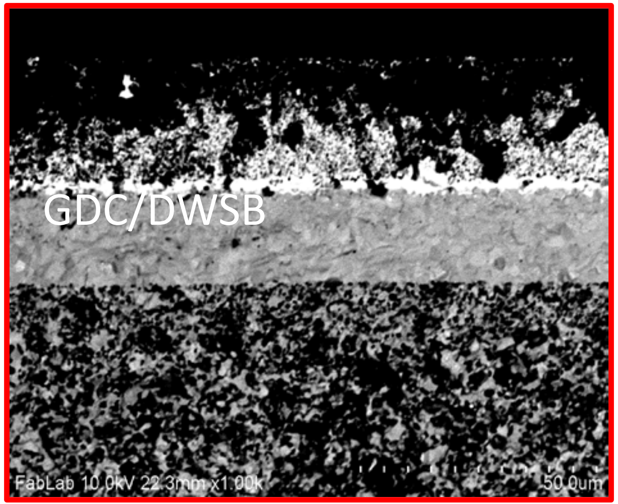
- Fuel flow actively adjusted as cell power changes
  - 10cm by 10cm cell
  - Tested between 575°C and 500°C



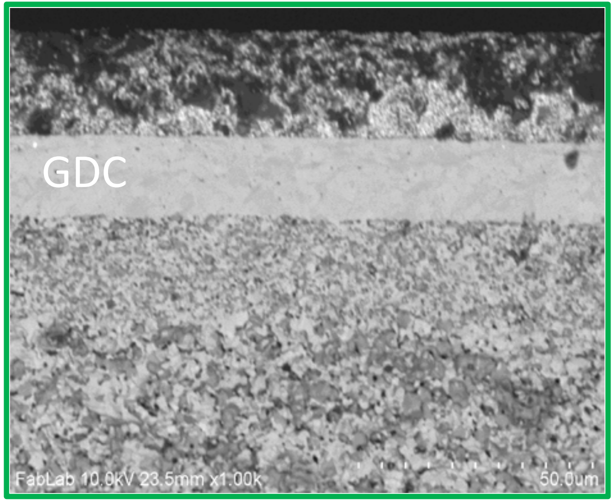
Bilayer Thickness Optimization for Increased OCP

M1.1.2: *Demo button cell with optimized relative/total bilayer thickness for OCP~1V*





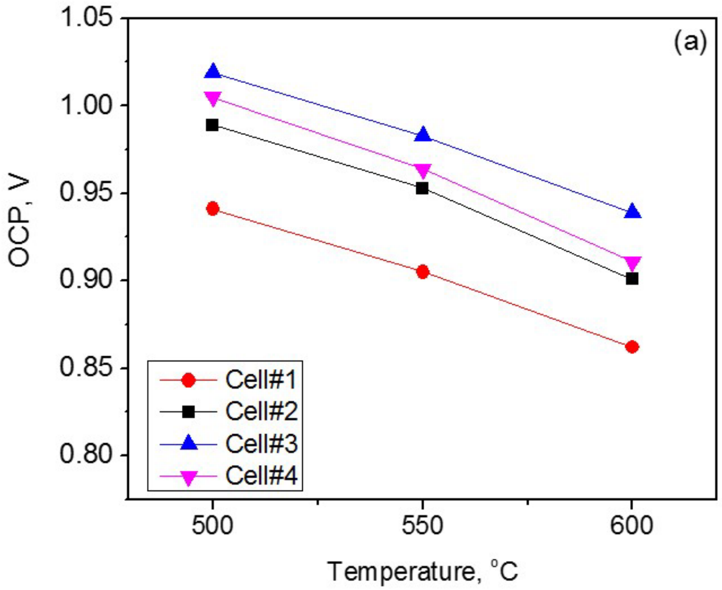
Bilayer Button Cell

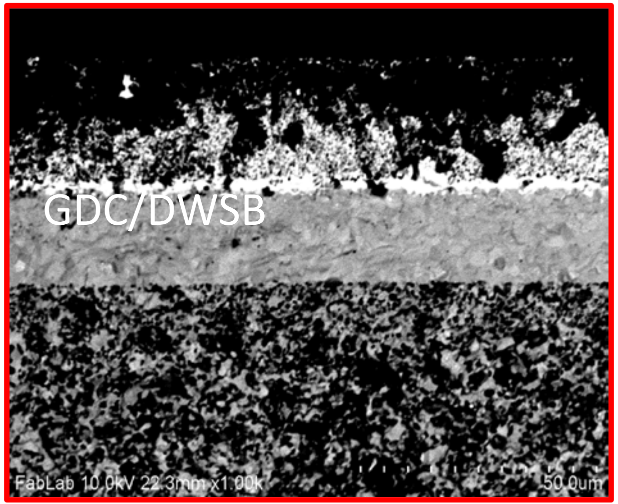


Single Layer Button Cell

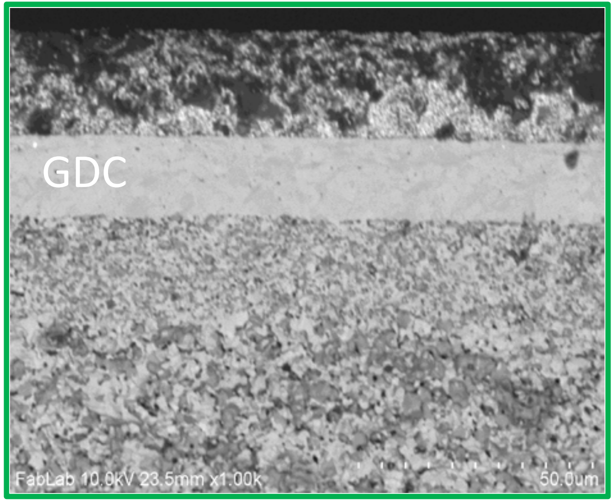
Bilayer Thickness Optimization for Increased OCP

***M1.1.2:** Demo button cell with optimized relative/total bilayer thickness for OCP~1V*





Bilayer Button Cell

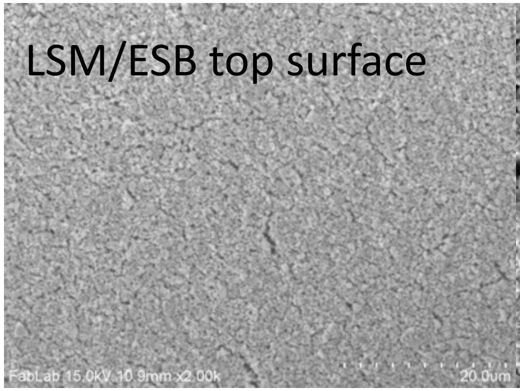


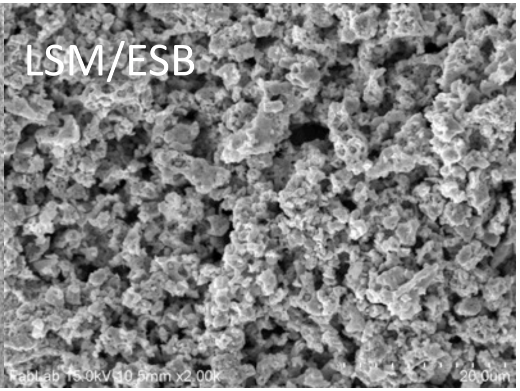
Single Layer Button Cell

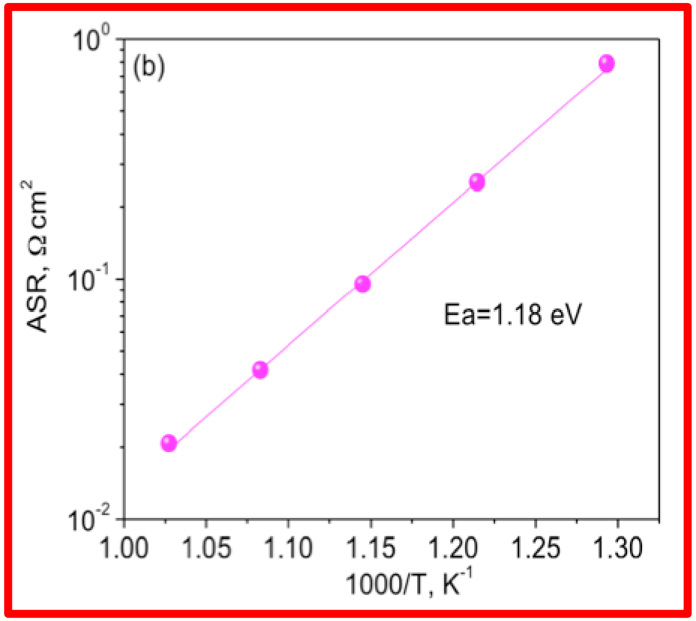
Most recent results:
OCV @ 500°C = 1.02 V

Advanced Low Temperature Cathodes

M2.1.1: *Cathode ASR ≤0.7 Ω-cm^2 at 500°C*


LSM/ESB top surface


LSM/ESB

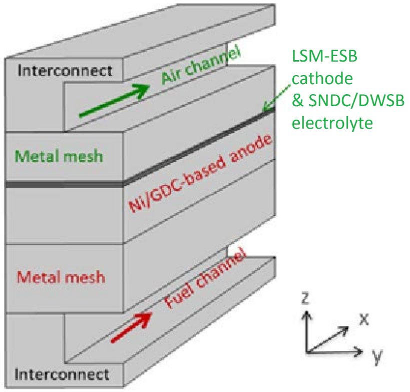


- Currently working to further optimize microstructure
- Examine long-term stability at ≤500°C
- Scale up to commercial production using low cost techniques

Bilayer Cell & Stack Modeling

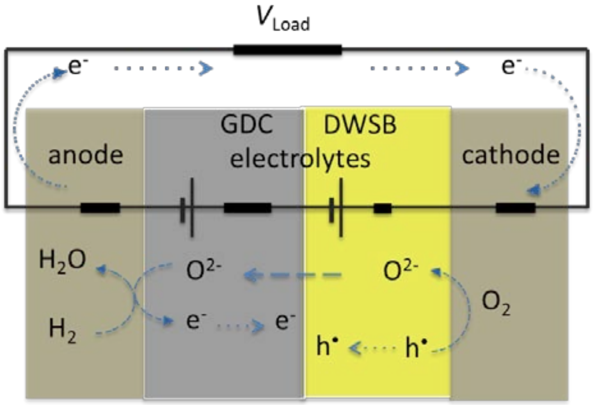
M5.2.1: *Validation of LT-SOFC Model for Cell/Stack*

Single channel multi-physics model

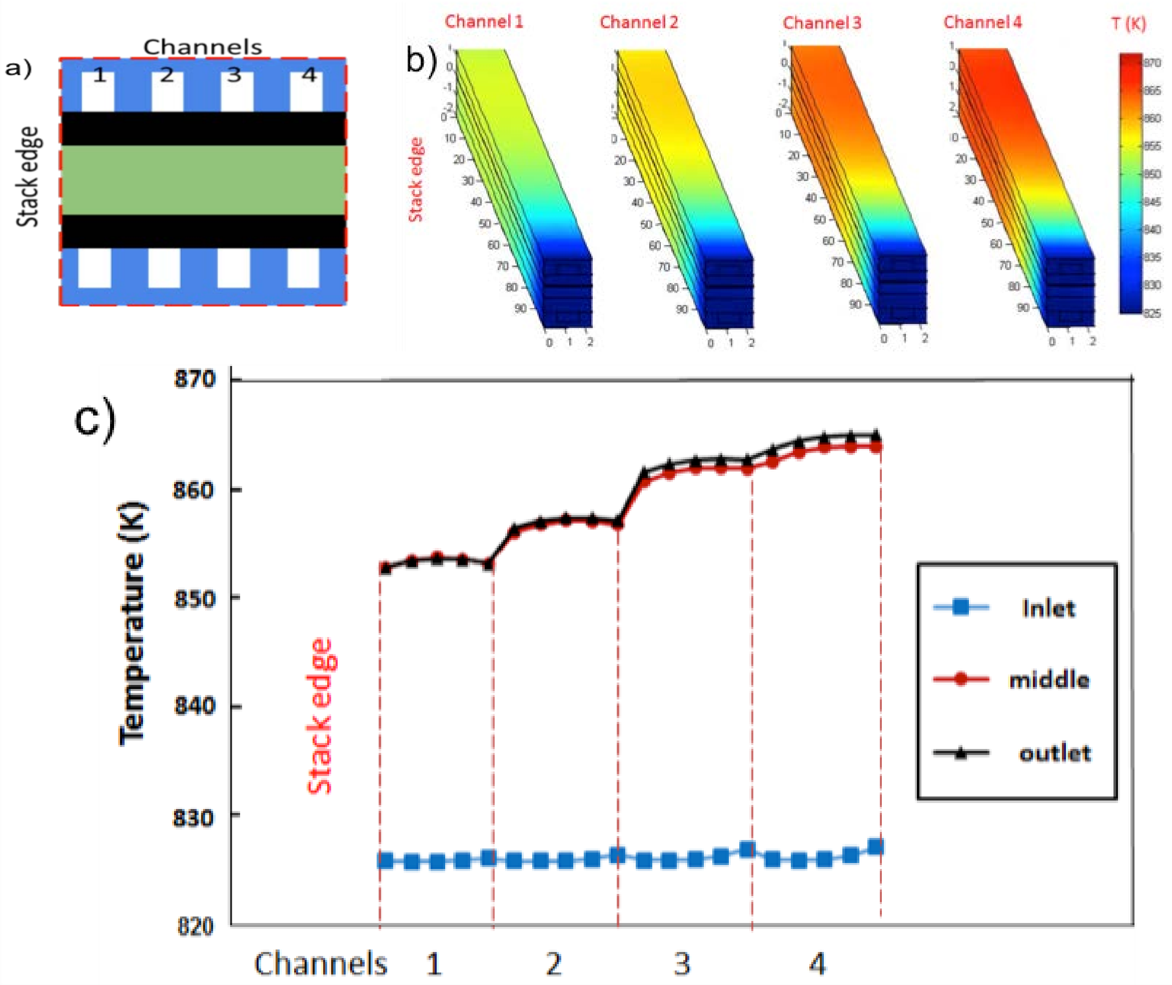


Captures: *Heterogeneous catalysis
*Electrochemistry
*Temp. dependence of materials

Bilayer / leakage current model

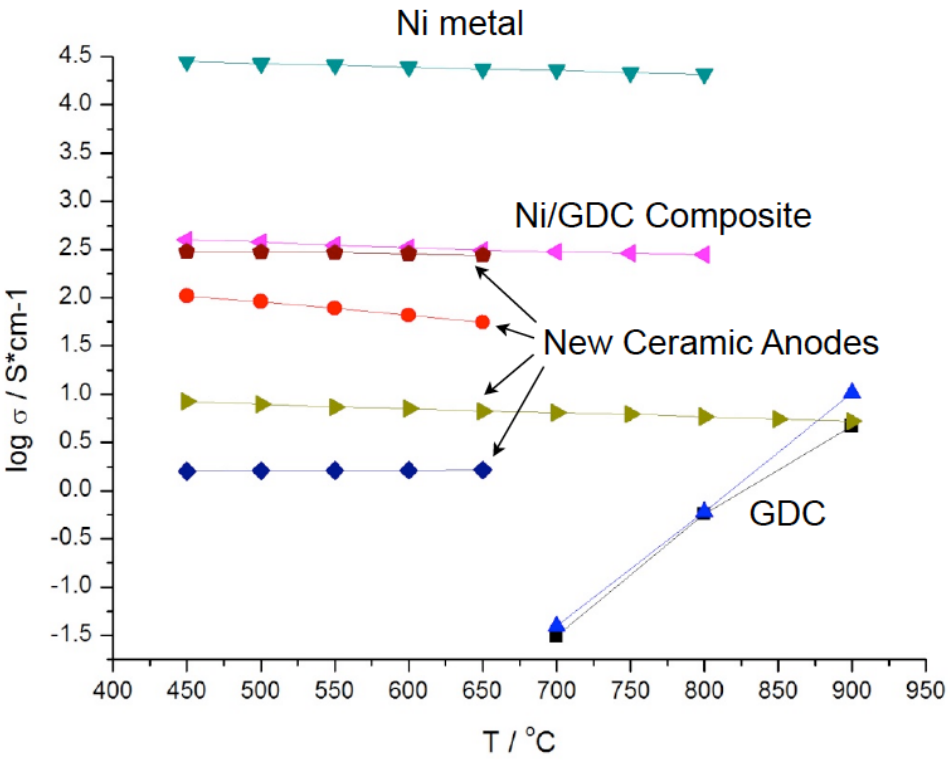


Expanding model to full stack for design optimizations



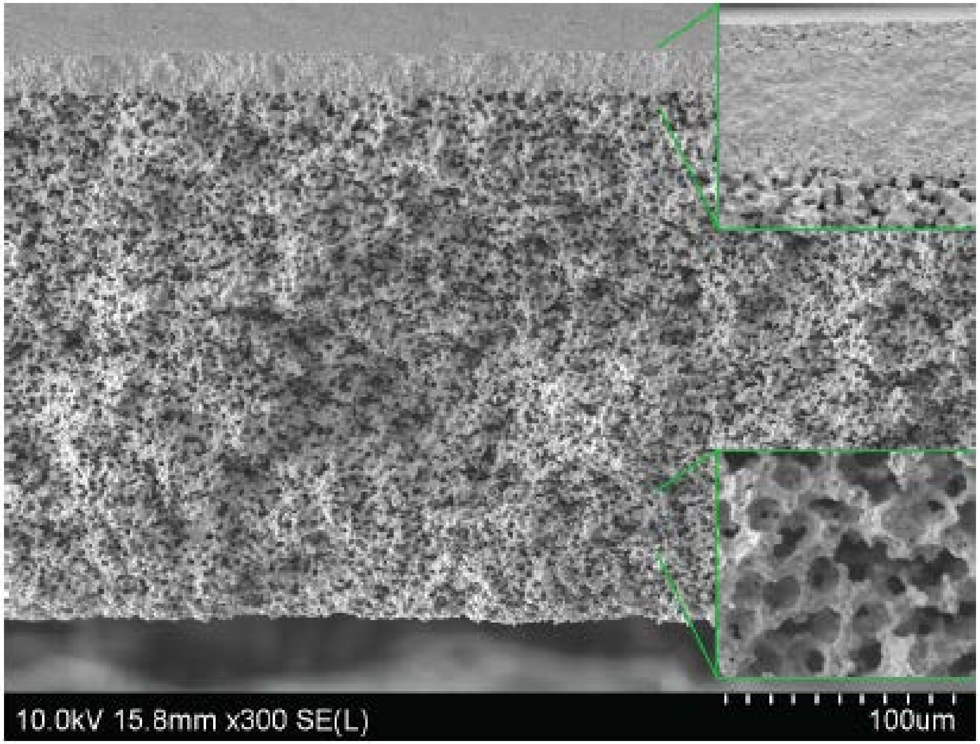
Red-Ox Stable Ceramic Anodes

- New conductive ceramic anode materials compatible with low temperature stack designs
- Comparable conductivity with conventional nickel cermet anode materials
- Conductivity stable when cycling between air and reducing fuel environments

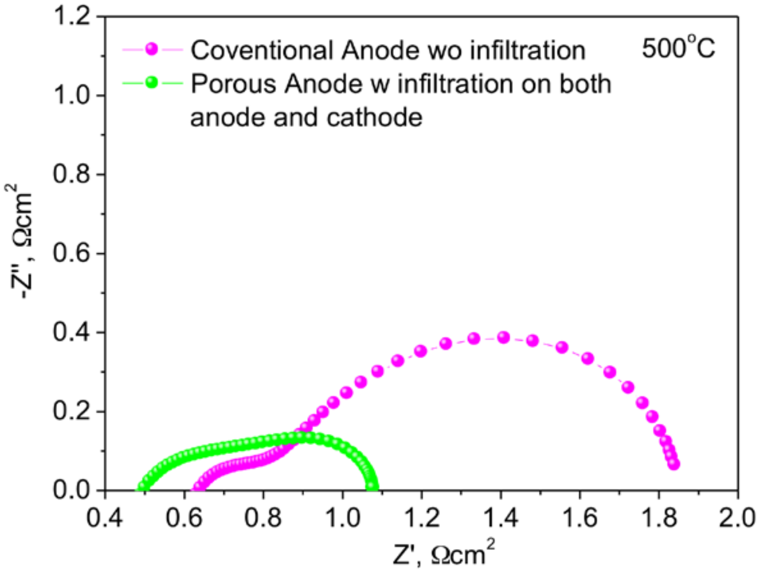


Red-Ox Stable Ceramic Anodes

- Porous anodes allow introduction of catalysts for enhanced low temperature catalytic activity

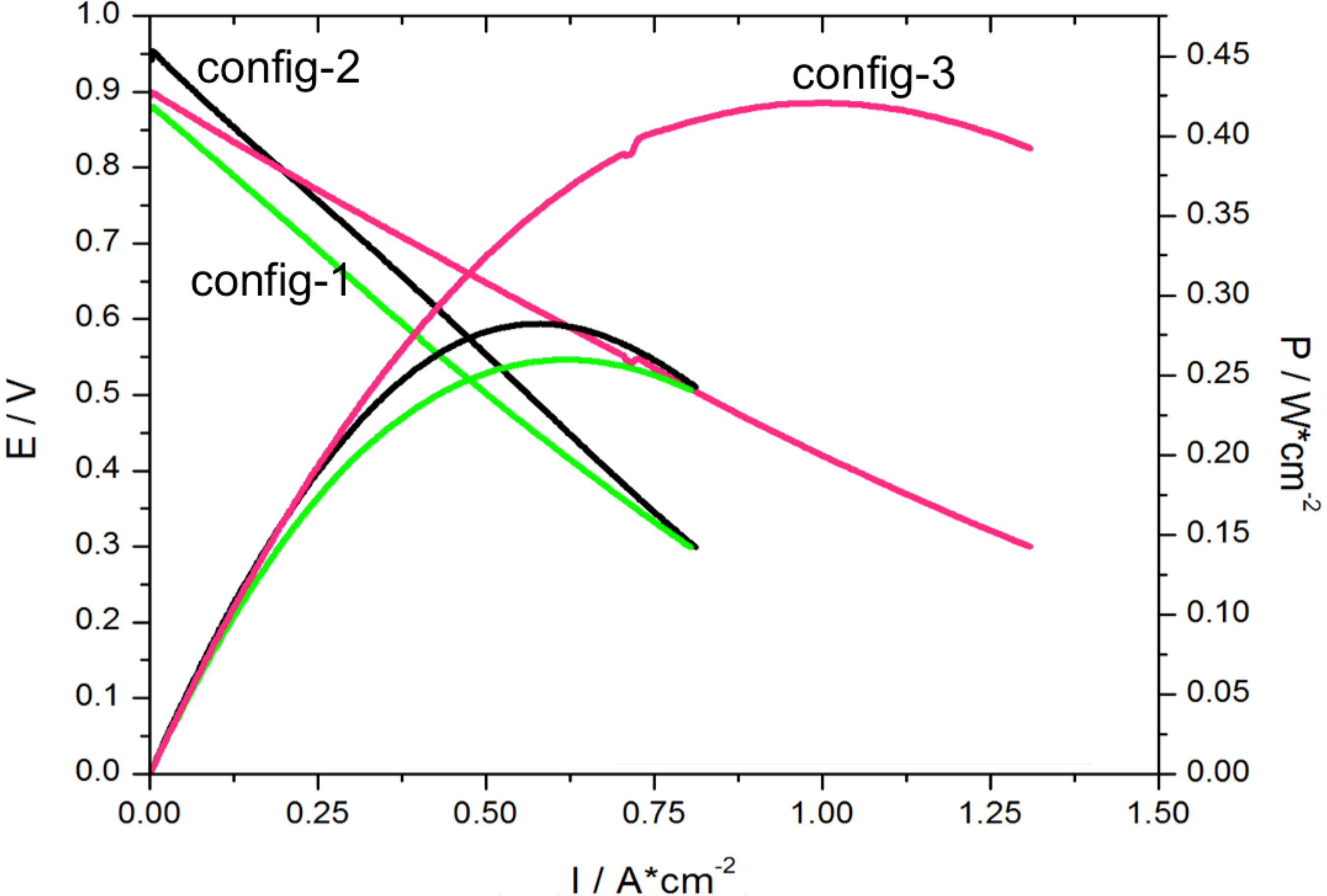


Early results show drastic improvements



Red-Ox Stable Ceramic Anodes

- Preliminary button cell results utilizing red-ox stable anode at 500°C (>0.4 W/cm^2 peak, ~0.28 W/cm2 @ 0.7 V)
- Other configurations (not shown) have achieved >1 V at 500°C, & ~0.55 W/cm^2 at 525°C



Thank You

Questions?