REDOX

Redox Cube

- 25 kW, natural gas, stationary power system
- > 50% efficiency
- Compact (~1 m^3)
- Lightweight (< 1,000 lbs)

Affordable, High Performance, Intermediate Temperature Solid Oxide Fuel Cells

PI: Bryan Blackburn, Ph.D.

Redox Power Systems, LLC

6/9/2016

FC115

Overview

Timeline and Budget

- **Project Start Date:** 10/01/14
- **Project End Date:** 09/30/16
- **Total Project Budget:** **$1,340,566**
  - *Total Recipient Share:* $342,399
  - *Total Federal Share:* $998,167
  - *Total DOE Funds Spent*:* $810,688

** As of 3/31/16*

EERE Project Partners

- ***Project Lead*: Redox Power Systems**
  – cell/stack dev. & test
- Univ. of Maryland – *fundamental cell R&D*
- Trans-Tech Inc. – *cell manufacturing*
- *MTech – commercialization*

Fuel Cell Barriers Addressed

- **A. Durability**
  - Redox SOFCs have lower operating temperatures than competing SOFCs
  - Internal reforming with catalysts for enhanced sulfur and coking tolerance
- **B. Cost**
  - No PGM materials
  - Lower operating temperature allows use of stainless steel, COTS compressive gaskets
  - Fewer cells due to *higher power density*
  - Lower system cost
- **C. Performance**
  - 10 cm by 10 cm anode supported cell demonstrated > 1 W/cm^2 at 650°C (natural gas)
  - Lab scale demonstrations with peak power density of 2 W/cm^2 at 650°C
  - Maintain performance at ~600°C through various cell enhancements, and improve stability
  - High quality heat available for combined heat and power (2020 FCTO target for 90% CHP efficiency)

Relevance:
Redox Value Proposition for Intermediate Temperature (IT) SOFCs

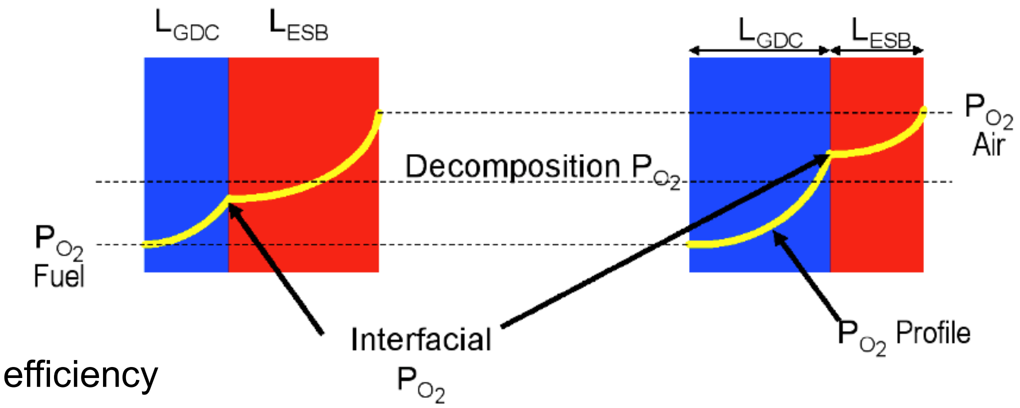
- **High Energy Conversion Efficiency To Reduce Petroleum Consumption**
  - Direct chemical to electrical efficiency of 55% (greater than 2020 FCTO target)
  - Combined heat and power (CHP) application efficiency as high as 90% (2020 FCTO target)
- **Fuel Flexibility For a Diverse Energy Infrastructure**
  - Conventional fuels (natural gas, gasoline, diesel, etc.)
  - Biofuels (biogas, ethanol, biodiesel) — compatible with high CO_2 levels in fuel
  - Hydrogen and syngas
- **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 for better thermal cycling & rapid startup (*advantages in MYRDD '12*)
  - Appeal for reduced weight and size systems in commercial, defense, and consumer applications drives widespread adoption and leverages economies of scale to further reduce cost
- **Reduced Pollution and Greenhouse Gas Emissions.**
  - Higher efficiency results in ~1/2 the CO_2/kWh released compared to typical internal combustion (IC) engines
  - Negligible particulate, CO, hydrocarbon, or NO_x pollution.

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, IT operation of ~600°C;
  - optimization of compositions and microstructures for the cathode to increase power density, and the anode to improve carbon- and sulfur-tolerance in hydrocarbon fuels for IT operation;
  - use of a custom multiphysics model and advanced materials to optimize the performance of bilayer stack designs for IT operation; and
  - creation of bilayer cell performance maps and demonstration of a ~1 kW_e stack for IT operation under CHP conditions with natural gas and minimal external reforming.

- **Reporting period (*4/1/2015-4/1/2016*) focus on scale-up and test:**
  - Performance of porous anode bilayer button cell at 600°C was 25% higher than milestone
  - Open circuit voltage of 10 cm by 10 cm bilayer cell exceeded milestone
  - Scaled-up porous anode supported cell to 5 cm by 5 cm successfully; testing in process
  - No-cost extension due to processing issues in scaling up size of porous anode

Approach Summary: IT-SOFC Stack



- **Increased Efficiency**
  - Er stabilized Bi_2O_3 (ESB):
    - * 60X conductivity of YSZ @ 600°C
    - * unstable at low PO_2 (fuel conditions)
  - Gd doped CeO_2 (GDC):
    - * > 5X conductivity of YSZ @ at 600°C
    - * electronic leakage in fuel conditions, lowers efficiency
  - *Solution*: a bilayer of GDC (fuel side) and ESB, stops ceria electronic leakage & Bi_2O_3 decomposition
  - *Goal*: Optimize *total bilayer electrolyte thickness* and *relative thickness* of GDC & ESB
    - * maximize efficiency (increase OCP to 0.9-1.0V) & minimizing ASR for MPD ~1 W/cm^2 at ≤ 600°C
- **Higher Power Density**
  - Improve carbon/sulfur tolerance with catalyst infiltration into as-fabricated porous anodes (10 cm by 10 cm)
  - Optimize LSM-ESB cathode composition to increase power density (reduce cost)
- **Optimized stack designs for IT operation**
  - Integrate GDC/ESB bilayer Redox multi-physics model and use to optimize stack design
  - Conductive ceramic coatings for interconnect operation at ~600°C
- **1 kW stack demo under CHP conditions**
  - bilayer cell performance maps for stack, feed results back to model for design optimization
  - 1 kW_e stack demo under residential CHP scenario using natural gas and minimal external reforming

Approach/Milestones

** No-Cost Extension Granted*
*** Reporting Period through M18*

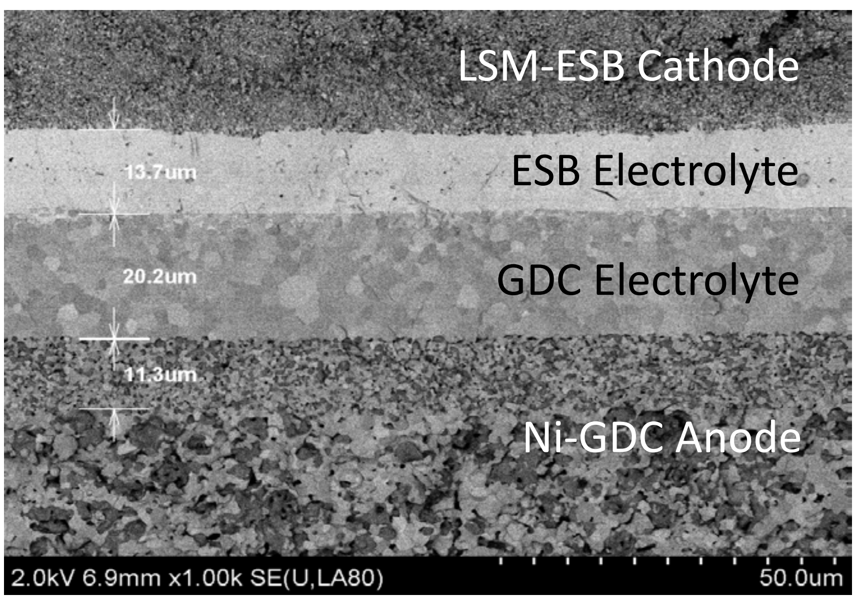
Task/Milestone	Original Due Date	New Due Date*	% Complete **
1.0. Bilayer Electrolyte Development for Improved IT Efficiency			
M1.1: Button ESB/GDC Bilayer Cell OCP of ≥ 0.9 V at ≤ 600°C	M6	n/a	100%
M1.2: 10x10 ESB/GDC Bilayer Cell OCP of ≥ 0.9 V at ≤ 600°C	M12	n/a	100%
2.0. Design & Optimization of High Performance Electrodes			
M2.1: Button ESB/GDC Bilayer Cell ASR ≤ 0.2 Ω-cm^2 & ~1 W/cm^2 at ≤ 600°C	M9	n/a	100%
M2.2: 10x10 ESB/GDC Bilayer Cell ASR ≤ 0.2 Ω-cm^2 at ≤ 600°C	M15	M22	75%
M2.3: Achieve degradation rate ≤ 2% per 1,000 h at ≤ 600°C with 10x10 cells	M18	M24	20%
3.0. Optimize ESB/GDC Stacks for IT Operation			
M3.1: Low ASR Interconnects & Contacts	M9	n/a	100%
M3.2: Validation of ESB/GDC Cell/Stack Modeling Tool	M3	n/a	100%
4.0. ESB/GDC Bilayer Stack Demonstration (*pushed back*)			
M4.1: Develop ESB/GDC Bilayer IT-SOFC Stack Performance Maps	M15	M23	30%
M4.2: Demonstrate Full (~1 kW_e) Stack Under CHP Conditions & Nat. Gas	M18	M24	15%

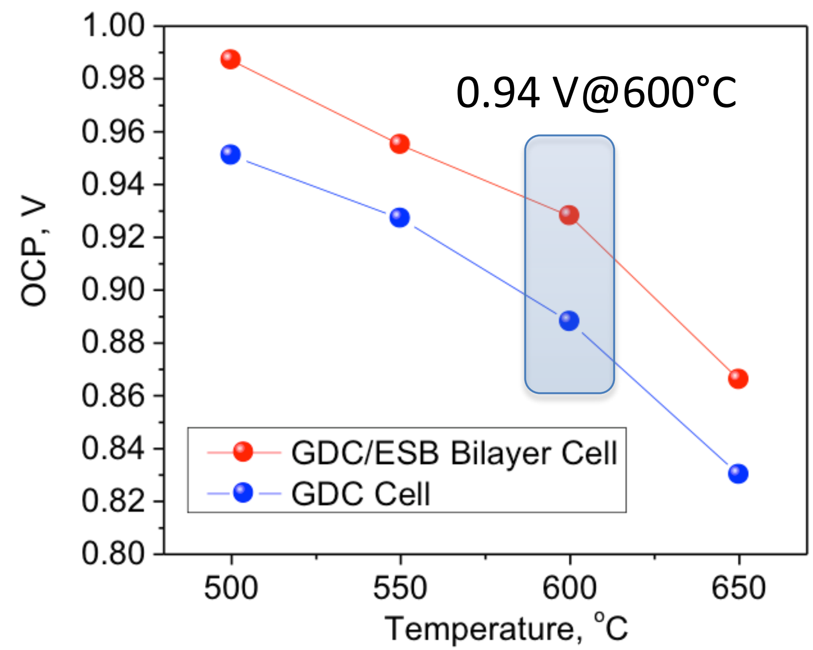
Go/No-Go: 1) OCP of ≥ 0.9 V using large format 10x10 cells at ≤ 600°C **✓ 0.905 Volts at 585°C with 10 cm by 10 cm cell**
(End of Q4) 2) button cell ASR ≤ 0.2 Ω-cm^2 at ≤ 600°C (target max. power density ≥ ~1 W/cm^2) **✓ 1.27 W/cm^2 achieved**

Accomplishments and Progress

- **1.0. Bilayer Electrolyte Development for Improved IT Efficiency**
  - Good progress for GDC/ESB bilayer electrolyte thickness optimization
    - Use of scalable synthesis and fabrication processes
    - **Achieved M1.1:** Button ESB/GDC Bilayer Cell OCP of ≥ 0.9 V at ≤ 600°C
  - ESB synthesis in manufacturing now < 1 day (3 months previously)

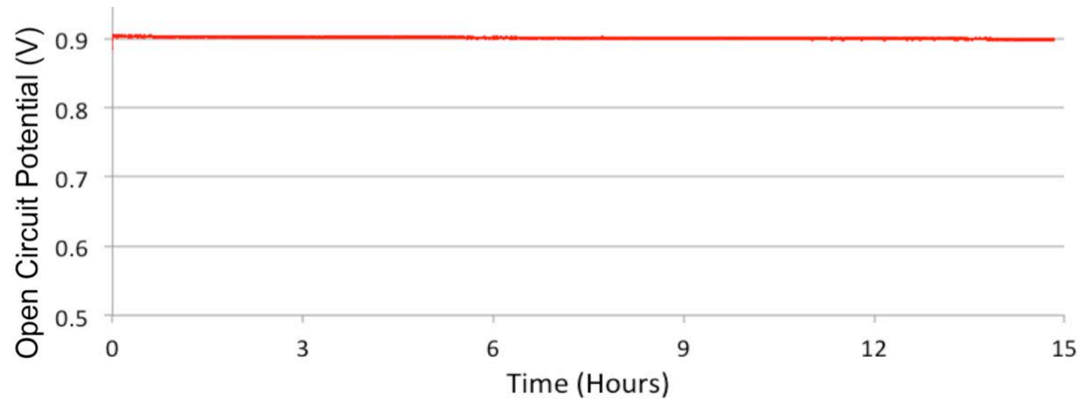
Micrograph of typical GDC/ESB Bilayer Cell at **Button Size**



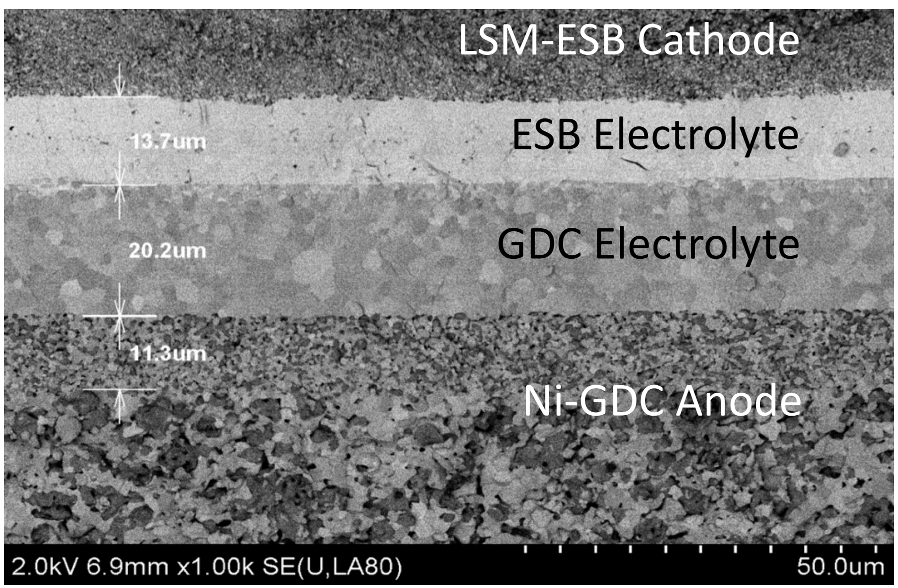


Accomplishments and Progress

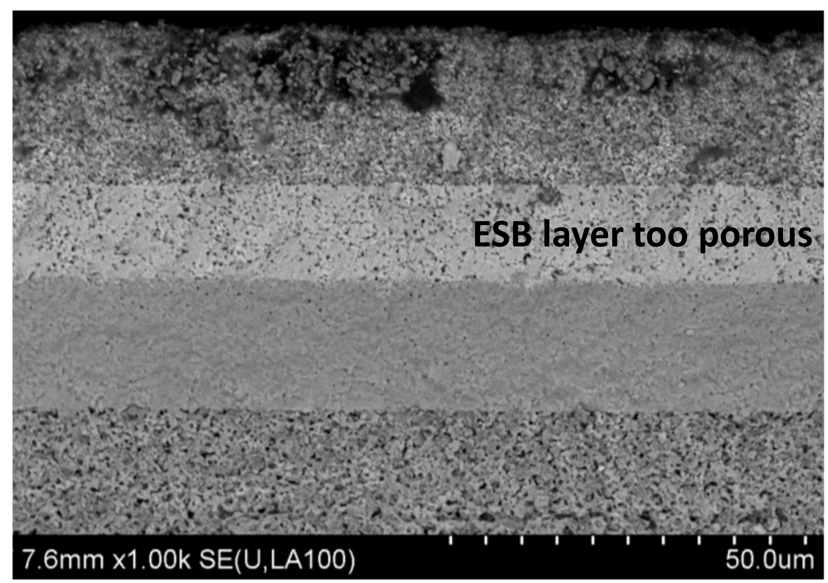
- **1.0. Bilayer Electrolyte Development for Improved IT Efficiency**
  - **Achieved M1.2:** 10 cm by 10 cm ESB/GDC Bilayer Cell OCP of ≥ 0.9 V at ≤ 600°C
  - OCV = 0.905 V at 585°C



Micrograph of typical GDC/ESB Bilayer Cell at **Button Size**



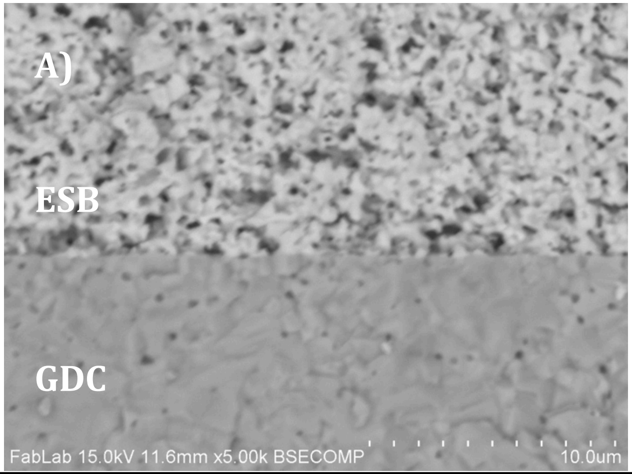
Micrograph of typical GDC/ESB Bilayer Cell at **10x10 Size**



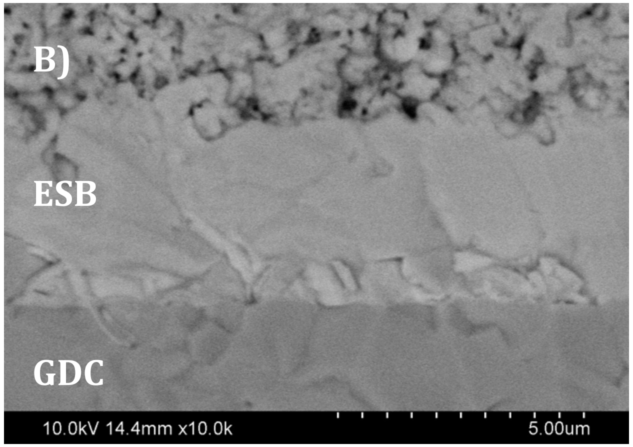
Accomplishments and Progress

- **1.0. Bilayer Electrolyte Development for Improved IT Efficiency**
  - More improvements possible with ESB microstructural optimization
    - Firing temperature optimization and temperature mapping of fabrication furnace
    - Furnace with more uniform temperature distribution

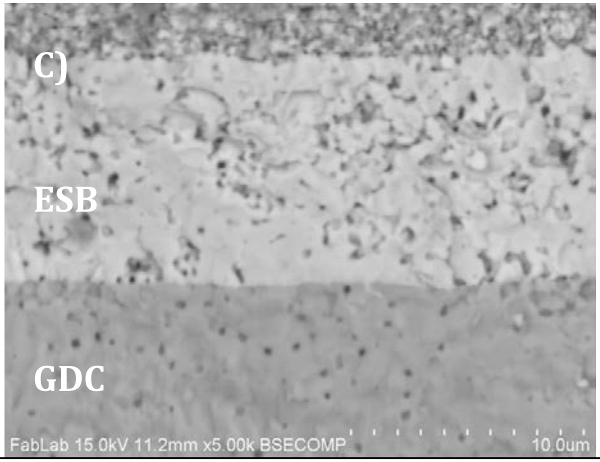
10x10 Cell, ESB Fired at T1 (less than T2)



Button Cell, ESB Fired at T2



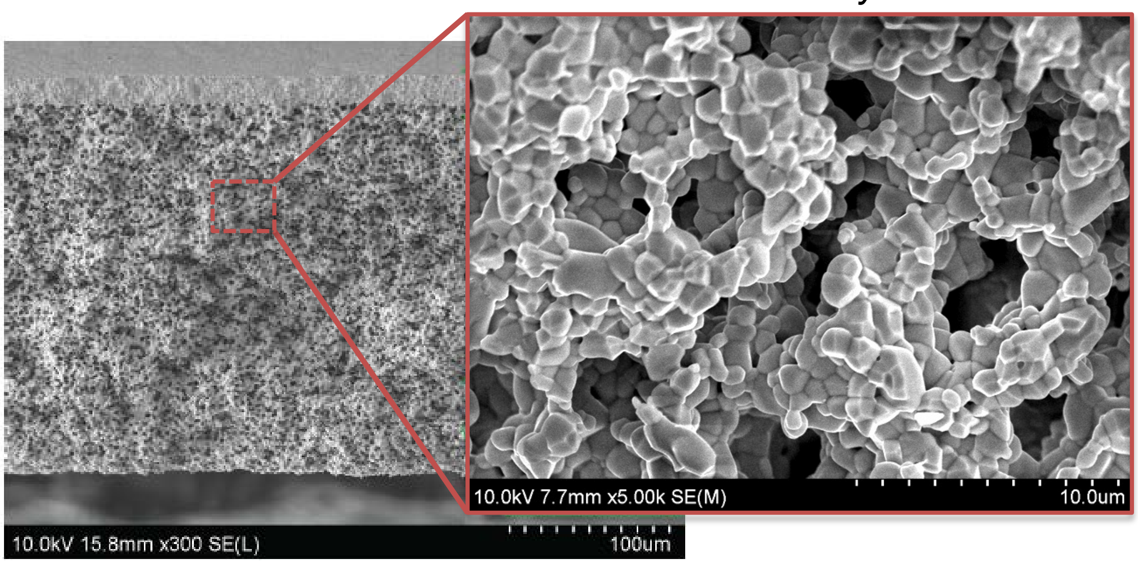
10x10 Cell, ESB Fired at T2

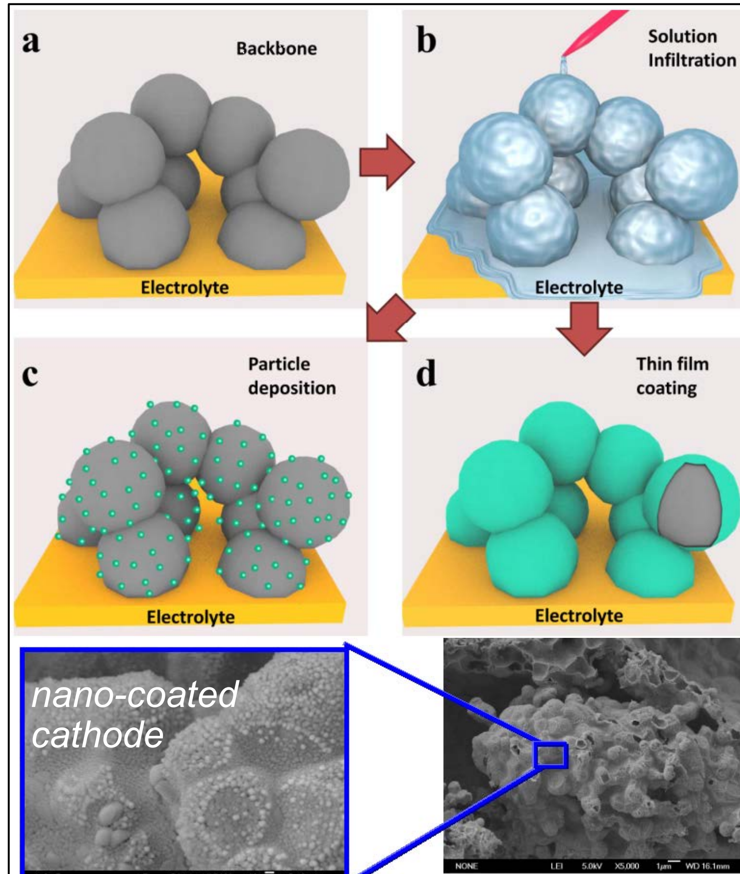


Accomplishments and Progress

- **2.0. Design & Optimization of High Performance Electrodes**
  - Increase as-fabricated anode porosity without compromising mechanical strength
  - Infiltrate nanoparticle catalysts into porous anode
    - Initial results show improved catalytic/electro-catalytic performance
    - Need to verify coking/sulfur tolerance enhancements
  - Infiltrate nanoparticle catalysts into cathode
    - Porous cathode skeleton created
    - Initial results at button level show 10-25% improved performance, need to scale process to 10x10 cell

This work: *New Porous Anode Scaffold for 10 cm by 10 cm cell*

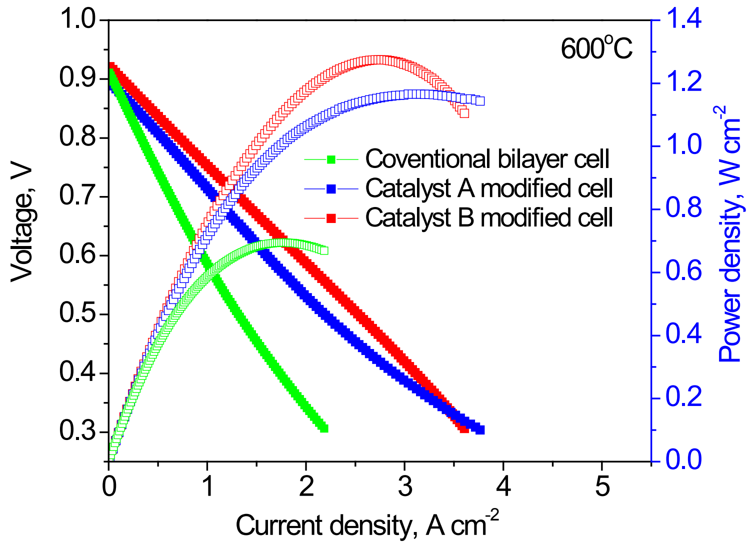


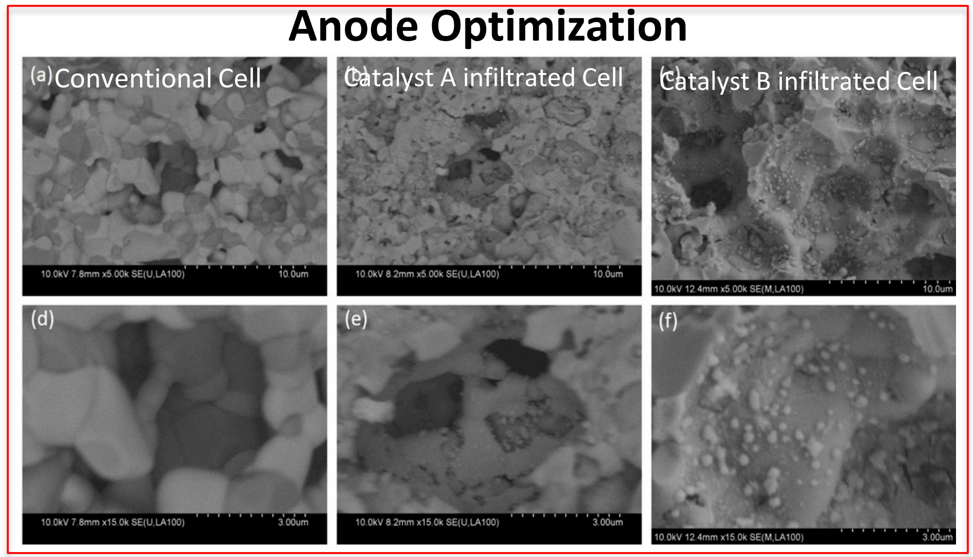


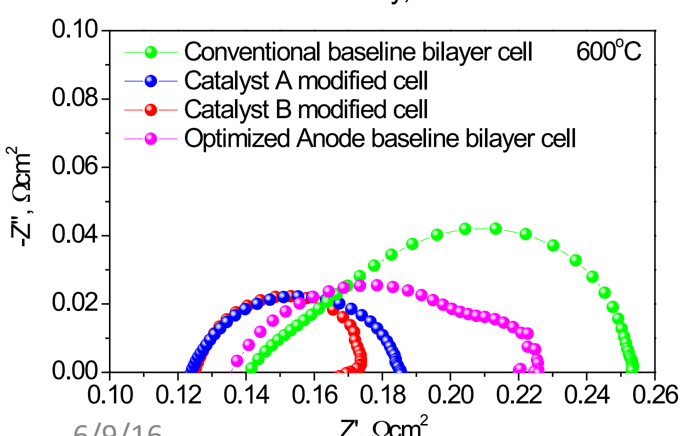
D. Ding et. al. Energy Environ. Sci., 7, pp. 552–575 (2014)

Accomplishments and Progress

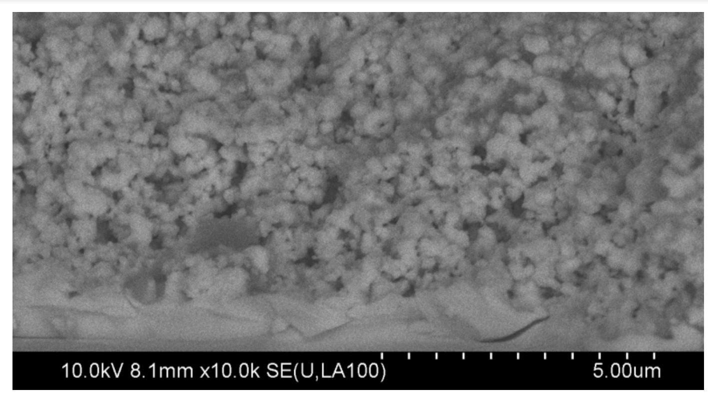
- **2.0. Design & Optimization of High Performance Electrodes**
  - **Achieved M2.1:** Button ESB/GDC Bilayer Cell ASR ≤ 0.2 Ω-cm^2, ~1 W/cm^2 with hydrogen as fuel at ≤ 600°C
  - Exceeded targets by ~30% at 1.27 W/cm^2 with ASR=0.171 Ω-cm^2 (OCV=0.94V)







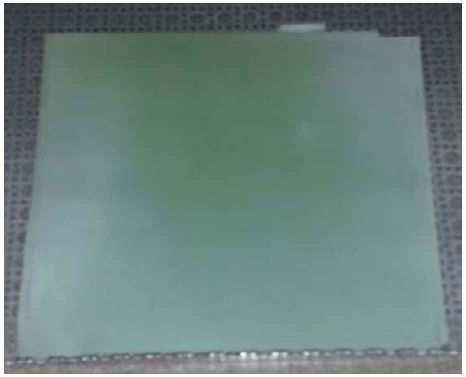
Infiltrated cathode



Accomplishments and Progress

- **2.0. Design & Optimization of High Performance Electrodes**
  - ***Progress* toward M2.2:** 10x10 ESB/GDC Bilayer Cell ASR ≤ 0.2 Ω-cm^2 at ≤ 600°C

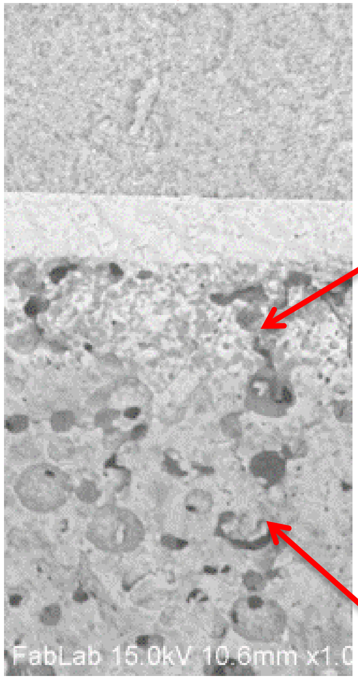
Scaled up porous anode production tapes fired flat without cracks



But had issues with cracking for complete half cell (10x10)

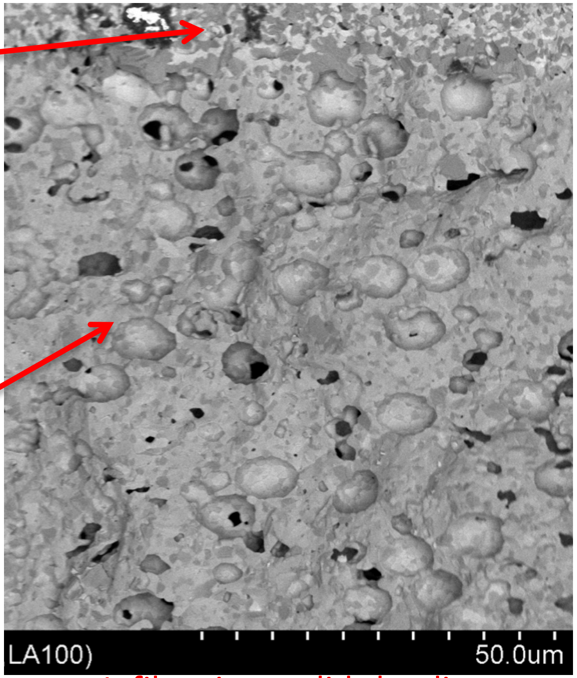
*But crack free for 5x5 (internal + production)

<u>Internal</u>
Porous ASL / Porous AFL



<u>Infiltration: solids loading matched button cell</u>

Initial <u>Production</u> Porous ASL / *Non-Porous* AFL



<u>Infiltration: solids loading ~50% that of button cell</u>

<u>ONGOING PRODUCTION OPTIMIZATION EFFORTS</u>

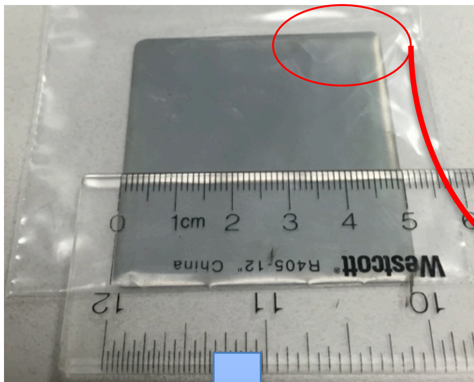
1) Wider pore former PSD should bridge gap between production and internal cells
2) Add scaled-up porous Ni-GDC AFL

Accomplishments and Progress

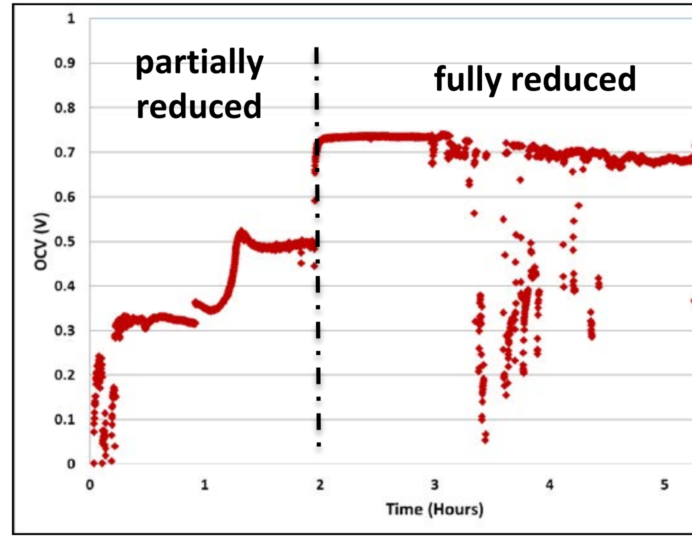
• 2.0. Design & Optimization of High Performance Electrodes

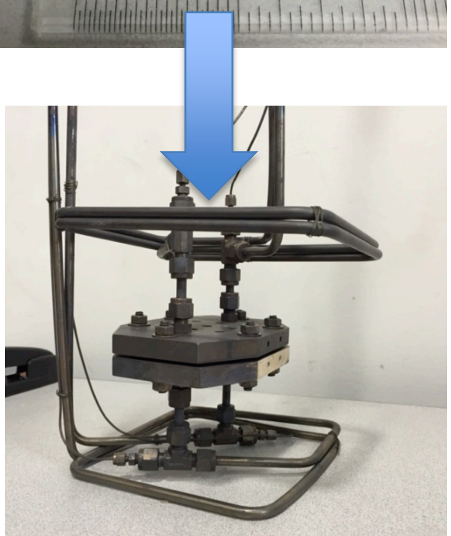
– *Progress* toward M2.2:

"Internal" 5x5 Porous Anode Cell (*no bilayer*)



- Pressure decay curve indicates low external & crossover leakage after assembly
- OCV at 650°C lower than expected
- Confirmed by GC, 2x cross-over leak after reduction compared to before reduction
- Resulted in low performance



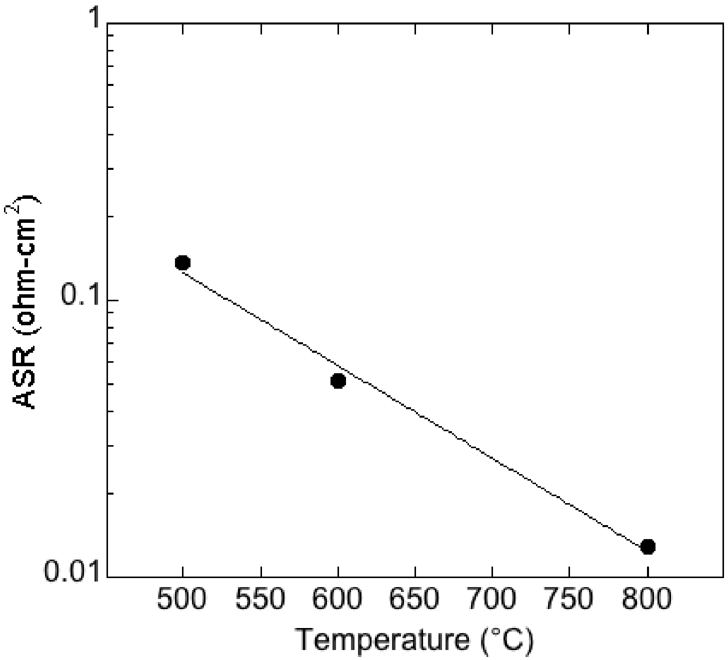


Cell After Test:

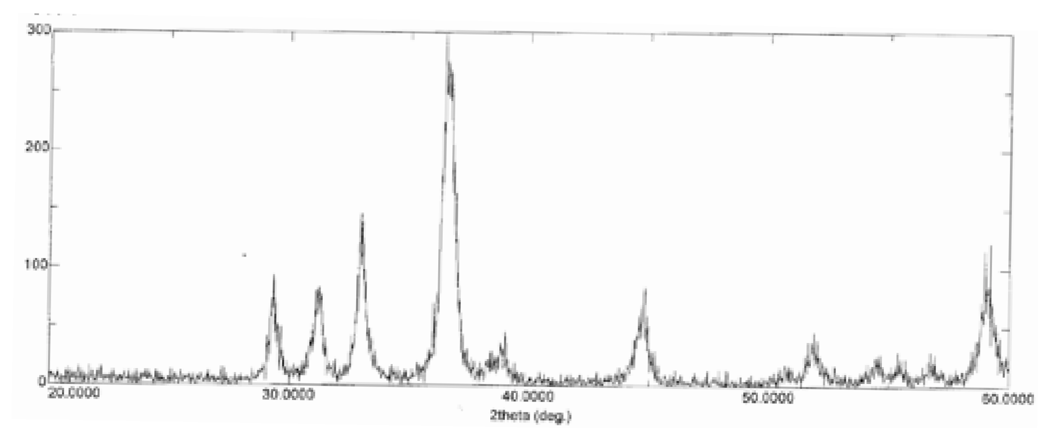
- Cracks on edge potentially due to multiple factors
  - Did not use best practices assembly techniques
  - Large degree of edge curl (2x more than typically acceptable) – stress concentrator
  - Relatively weak cell due to porous anode and use of Ni-GDC
- Solutions moving forward
  - Thicker anode support (for "internal" Ni-GDC ASL)
  - Stronger production cells using Ni-YSZ ASL
  - Post fabrication removal of edge curl

Accomplishments and Progress

- **3.0. Optimize ESB/GDC Stacks for IT Operation**
  - **Achieved M3.1:** Button ESB/GDC Bilayer Cell ASR ≤ 0.2 Ω-cm², ~1 W/cm² with hydrogen as fuel at ≤ 600°C
  - Optimization of manganese cobalt oxide (MCO) spinel coating process results in low ASR
    - 52 milliohm-cm² @ 600°C and 13 milliohm-cm² @ 800°C
  - Redox MCO ASR values for single MCO coating comparable to literature
    - 13-17 milliohm-cm² @ 800°C using LSCM paste contact (PNNL Report 15303, 2005)
    - 12-20 milliohm-cm² @ 800°C using LSM paste contact (Seabaugh et al. 13th Annual SECA Workshop, 2012)



XRD of Trans-Tech MCO Powder



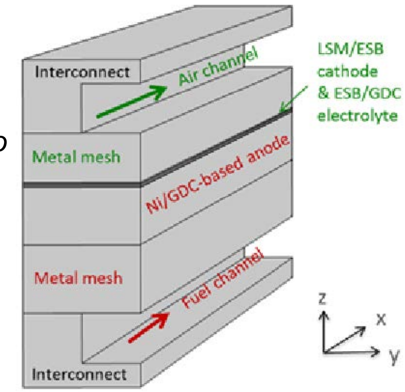
Accomplishments and Progress

• 3.0 Optimize ESB/GDC Stacks for IT Operation

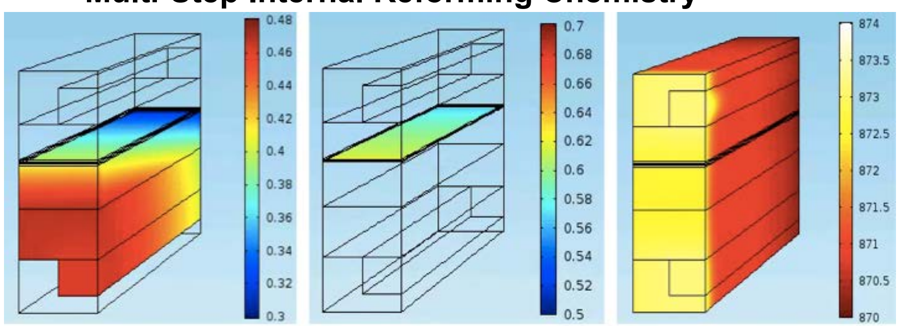
– Redox Multi-Physics Cell / Stack Modeling

- Early in project, added ESB/GDC bilayer to single-channel model
- Optimize stack flow field and operating conditions

single channel multi-physics model
(now expanded to stack in separate project)

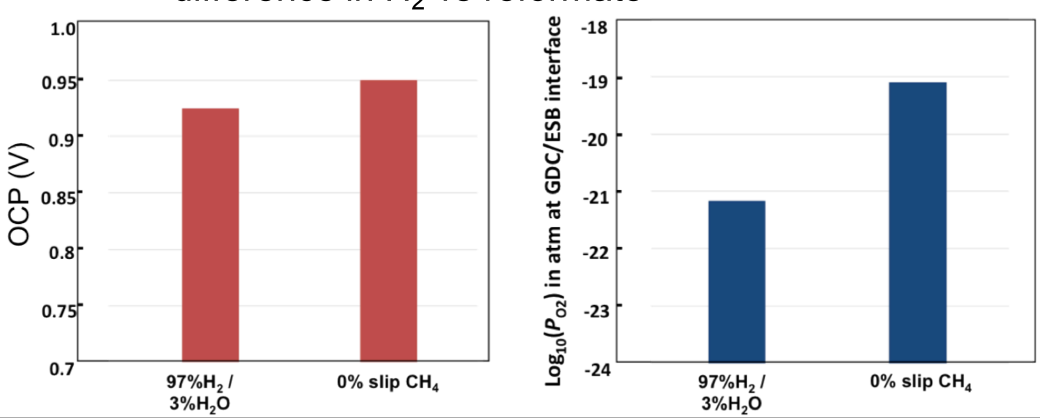


Multi-Step Internal Reforming Chemistry



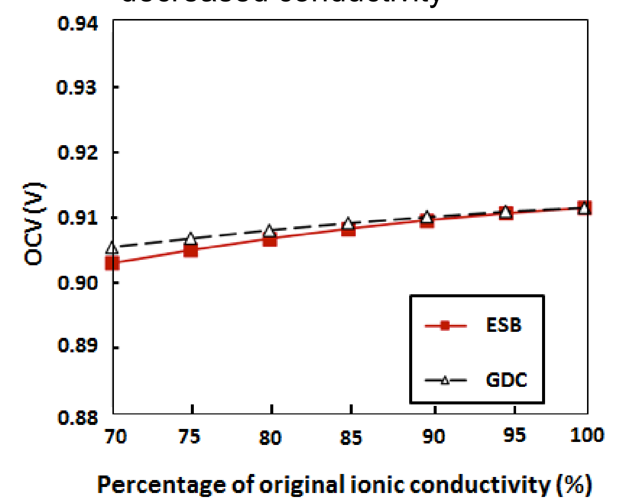
H_2 Mole Fraction | Local current density (A/cm²) | Temperature (K)

Model used to understand performance difference in H_2 vs reformate



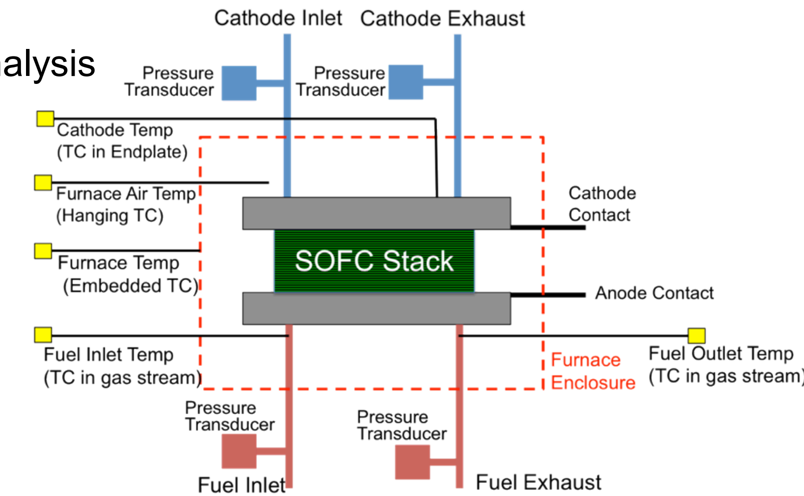
*Model used to understand impact of porosity in ESB layer

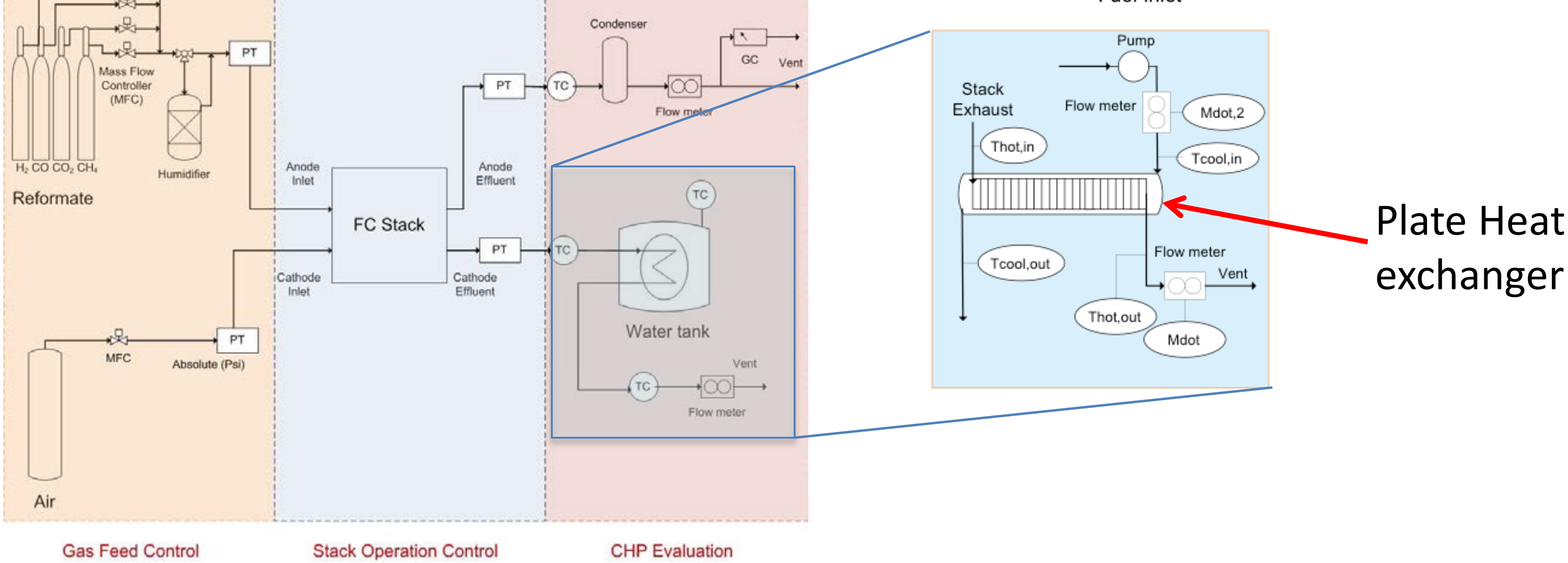
-Increased porosity can reduce OCV due to ineffective TBP and decreased conductivity



Accomplishments and Progress

- **4.0 ESB/GDC Bilayer Stack Demonstration**
  - IT-SOFC Stack Performance Maps
    - Fully instrumented setups with PTs, TCs, Flow Rate, gas analysis
    - Tests on baseline measurements (non-bilayer, non-porous anode) have begun.
    - H_2, reformate, 0%, 25%, and 75% of max current density
  - Demo ~1 kW_e Stack Under CHP conditions
    - Plans for running tests finalized
    - Heat exchanger and other components being assembled





Collaborations

EERE Project Collaborators

- University of Maryland (*cell R&D*)
- Trans-Tech, Inc. (*ceramic powder development*)
- MTech (*incubator & business growth*)

Redox Additional Partnerships

- Microsoft Inc. (*datacenter, server rack embedded power*)
- Strategic Analysis Inc. (*techno-economic analysis*)
- Nat'l Fuel Cell Research Center, UC-Irvine (*independent test*)
- Colorado School of Mines (*fuel processing/system expertise*)
- Trans-Tech, Inc. (*production cell manufacturing*)

Future Work

- **1.0 Bilayer Electrolyte Development for Improved IT Efficiency**
  - Optimize ESB microstructure in 10x10 cell to get closer to 0.94 V open circuit voltage as achieved with button cell (currently 10x10, 0.905 V)

- **2.0 Design & Optimization of High Performance Electrodes**
  - Test current 5x5 porous anode cells ("internal" and production)
    - Optimize infiltration process for larger size cells and validate performance
    - Make short stacks of 5x5 porous anode cells
  - Optimize 10x10 production, porous anode cells (Ni-YSZ ASL) for required strength, porosity, and camber
  - Test 10x10 production, porous anode cells, short stacks, and full stacks
  - Finish running long-term test on baseline (no bilayer, non-porous anode) followed by 1) bilayer with non-porous anode, and 2) bilayer with porous anode

Future Work

- **3.0 Optimize ESB/GDC Stacks for IT Operation**
  - Utilize low ASR interconnects/coatings for improved performance in stack
  - Utilize improved designs for stack (e.g., optimized flow fields)
  - Utilize model to understand stack results (see below)

- **4.0 ESB/GDC Bilayer Stack Demonstration**
  - Stack Performance Maps
    - Complete performance maps for baseline stacks (no bilayer, no porous anode)
    - Move on to performance maps for porous anode stacks (5x5, 10x10)
  - CHP Demonstration
    - Independent test of CHP setup hardware
    - Run stack demo for CHP application

Technology Transfer Activities

- Redox has developed an ISO 9001 SOFC cell manufacturing and development chain over the past four years
  - Single layer electrolyte production cells available in partnership with Trans-Tech, Inc.
  - Use scaled-up production, porous anode cells in EERE, followed by development of specific QC procedures for the particular cell variant
  - Take final, optimized bilayer specifications and processes into manufacturing environment and finalize QC procedures
- Redox techno-economic analysis & T2M work leverages efforts from other Programs and partners
  - Strategic Analysis Inc. (SA) — partner on Redox ARPA-E REBELS project — has extensive experience with design for manufacturing and assembly (DFMA)TM cost analysis of fuel cell systems & energy devices
    - Cell model updated, with stack model updates on-going
  - Market input from datacenter, large retail chains, utility and other partners represent both development/demonstration partners and end-users
  - Commercialization guidance from experienced MTech staff

Project Summary

- **Objectives**
  - Improve the performance/durability of Redox technology ~600°C through development of an optimized bilayer electrolyte based SOFC cell
  - Guided by a custom multiphysics model, demonstrate a ~1 kWe operating stack under combined heat and power (CHP) conditions.
- **Relevance**
  - High energy conversion efficiencies reduce petroleum consumption, pollution, and greenhouse gas emissions
  - Fuel flexibility supports a diverse energy infrastructure; and
  - High power density reduces costs & market barriers to increase adoption and manufacturing economies of scale
- **Approach**
  - Optimize a bilayer electrolyte cell to result in a target of a 1 kWe CHP demo.
- **Accomplishments**
  - Achieved OCV of 0.94 V and power density of 1.27 W/cm^2 (0.171 Ω-cm^2) at button cell level
  - Achieved OCV of 0.905 V at the 10 cm by 10 cm bilayer level with stable results
  - Successfully fabricated 5x5 porous anode cells with testing in progress
- **Collaborations**
  - **EERE** project leverages strong group of academic (**UMD**, UCI, CSM), manufacturing & commercialization (**Trans-Tech**, **MTech,** SA), & end-user partners beyond core EERE team.