REDOX

Affordable, High Performance, Intermediate Temperature Solid Oxide Fuel Cells

Redox Cube

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

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Redox Power Systems, LLC

6/11/2015

FC115

Overview

Timeline and Budget

- **Project Start Date:** 10/01/14
- **Project End Date:** 03/31/16
- **Total Project Budget:** **$1,340,566**
  - *Total Recipient Share:* $342,399
  - *Total Federal Share:* $998,167
  - *Total DOE Funds Spent*:* $208,229

** As of 3/31/15*

EERE Project Partners

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

Fuel Cell Barriers Addressed

- **A. Durability**
  - Redox SOFC has 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 simple 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

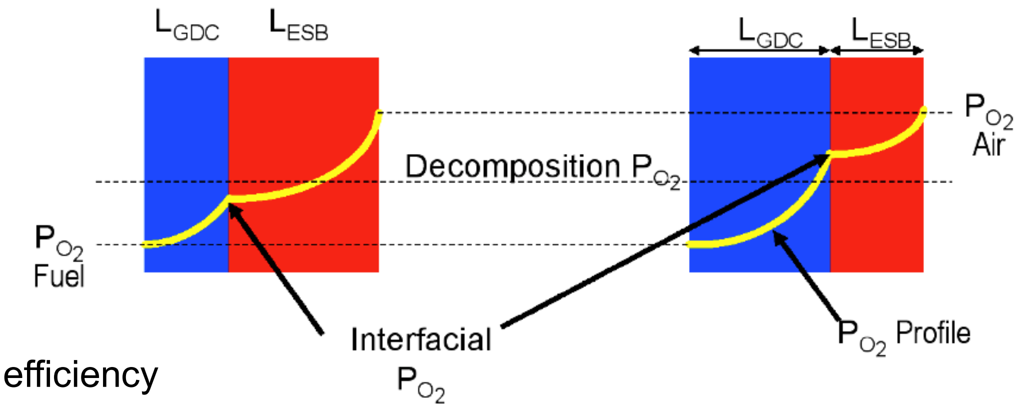
- **High Energy Conversion Efficiency To Reduce Petroleum Consumption**
  - Direct chemical to electrical efficiency of 55% (greater than 2020 FCTO target)
  - Combined heat and power (CHP) applications as high as 90% (2020 FCTO target)
- **Fuel Flexibility For a Diverse Energy Infrastructure**
  - Conventional 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 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 (*10/1/14 project start*) focus on cell & model improvements:**
  - Validation of multi-physics bilayer cell & stack model to experiment (Project Q1 Milestone)
  - Button cell OCP performance of ≥ 0.9V demonstrated (Project Q2 Milestone), transition to larger cells by Q4
  - Button cell resistance data ASR ≤ 0.2 Ω-cm^2 and power density ≥ ~1 W/cm^2 on track to be achieved by Q3 of project.

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

**Reporting Period through M6*

Task/Milestone	Month Due*	% 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	100%
M1.2 – 10x10 ESB/GDC Bilayer Cell OCP of ≥ 0.9 V at ≤ 600°C	M12	50%
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	95%
M2.2 – 10x10 ESB/GDC Bilayer Cell ASR ≤ 0.2 Ω-cm^2 at ≤ 600°C	M15	50%
M2.3 – Achieve degradation rate ≤ 2% per 1,000 h at ≤ 600°C with 10x10 cells	M18	10%
3.0. Optimize ESB/GDC Stacks for IT Operation		
M3.1 – Low ASR Interconnects & Contacts	M9	45%
M3.2 – Validation of ESB/GDC Cell/Stack Modeling Tool	M3	100%
4.0. ESB/GDC Bilayer Stack Demonstration (*most work later on*)		
M4.1 – Develop ESB/GDC Bilayer IT-SOFC Stack Performance Maps	M15	8%
M4.2 – Demonstration of Full (~1 kW_e) Stack Under CHP Conditions & Nat. Gas	M18	5%

Go/No-Go: 1) OCP of ≥ 0.9 V using large format 10x10 cells at ≤ 600°C

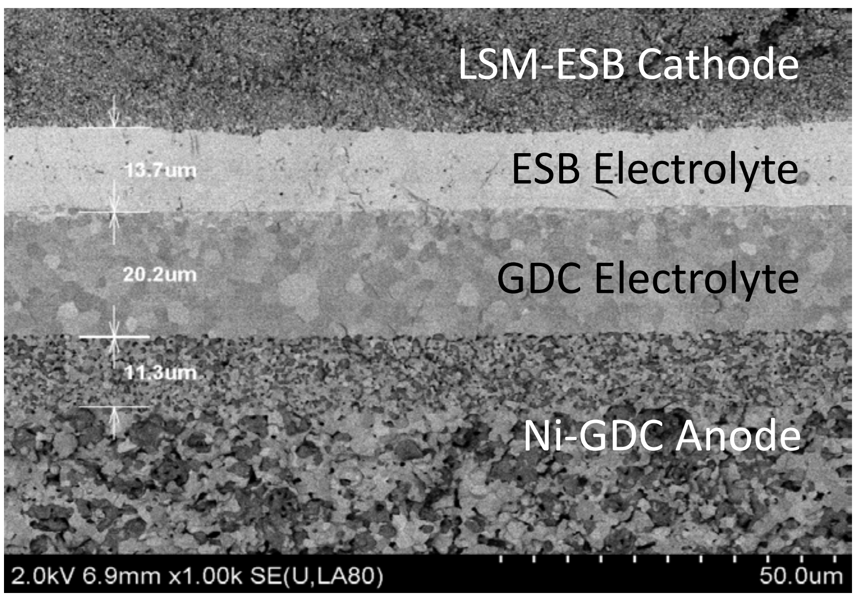
(Month 12*) 2) button cell ASR ≤ 0.2 Ω-cm^2 at ≤ 600°C (target max. power density ≥ ~1 W/cm^2)

**Currently at M6*

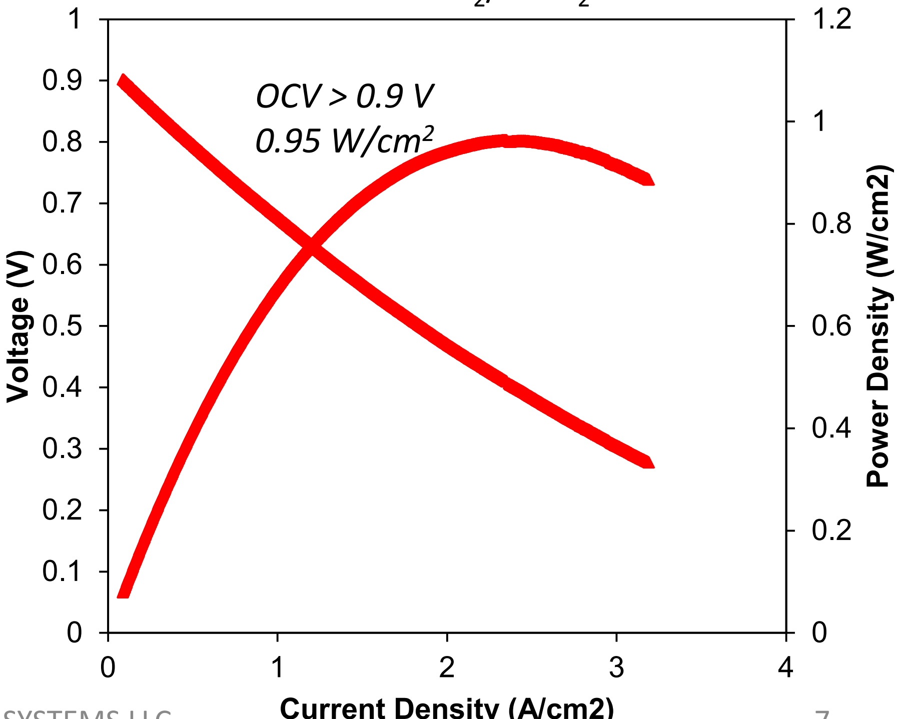
Accomplishments and Progress

- **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
    - **Close to meeting M2.1** — ASR ≤ 0.2 Ω-cm2 & ~1 W/cm^2 at ≤ 600°C (*due 06/30/15*)
  - Cost reduction with commercial production partner Trans-Tech

Micrograph of typical GDC/ESB Bilayer Cell

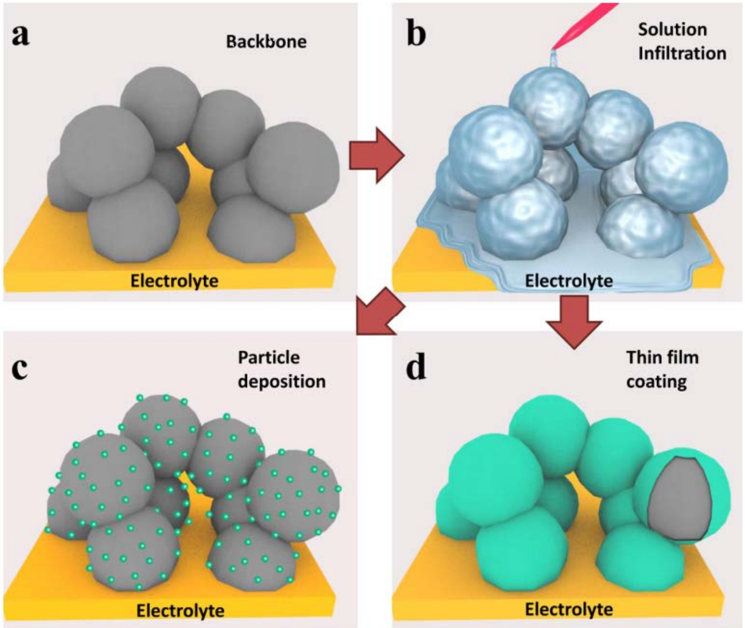


GDC/ESB Bilayer *Button Cell* at 600°C
1 atm with 97% H_2/3% H_2O fuel

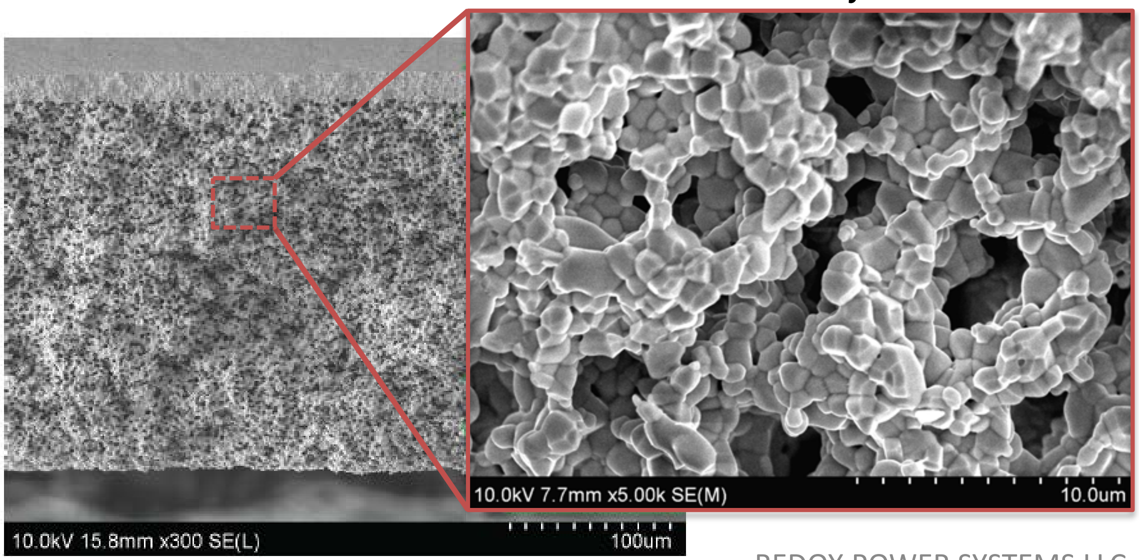


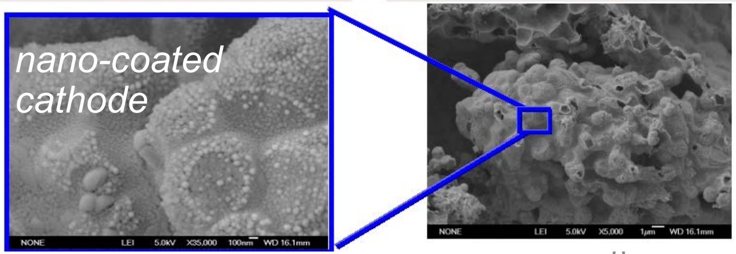
Accomplishments and Progress

- **2.0. Design & Optimization of High Performance Electrodes**
  - Increase as-fabricated anode porosity without compromising mechanical strength
    - Similar strength for new unreduced porous anode & conventional reduced anode (both ~30% porous)
  - 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 show improvement but more work needed



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



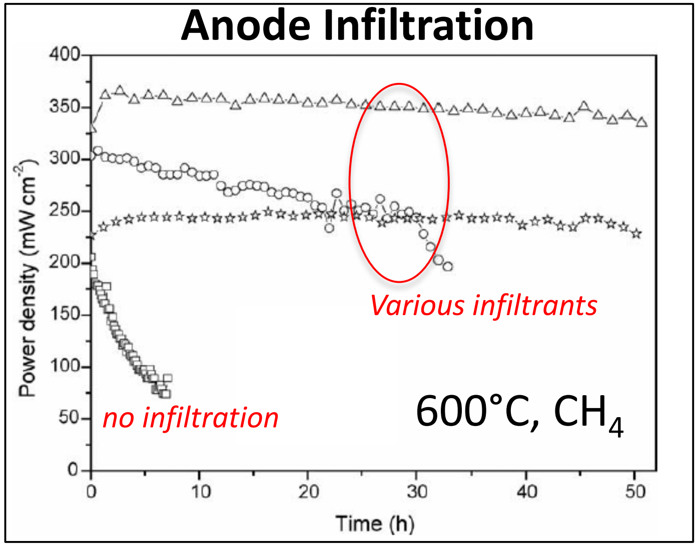


Accomplishments and Progress

- **2.0. Design & Optimization of High Performance Electrodes**
  - Anticipated performance enhancements in Redox 10 cm by 10 cm cells

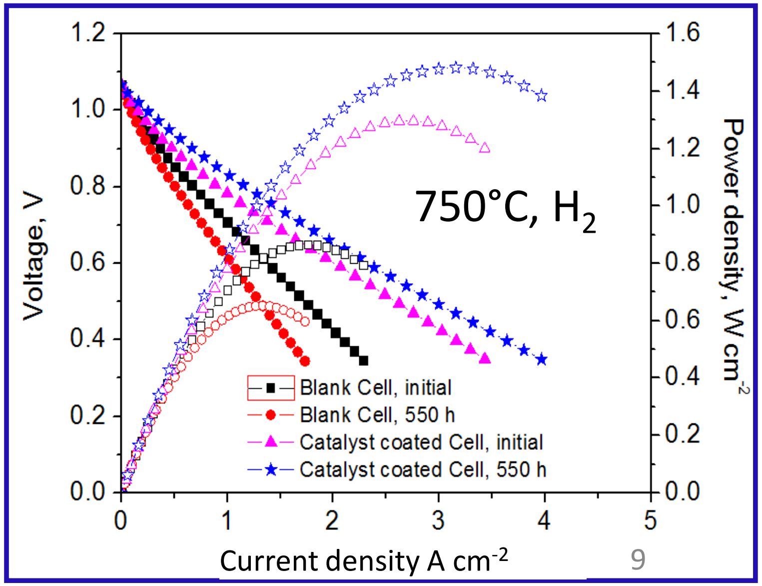
Anode:

- Increased power density in CH_4
- Improved coking tolerance
- Improved stability in sulfur (≥ 40ppm H_2S)



Cathode:

- Infiltrated cell will improve the ORR and improve power density
- Proper catalyst selection can also improve long-term stability



*Prev. work by Redox Sr. Mat. Engr, Dong Ding, Ph.D.

-Journal of Power Sources 237 (2013) 243-259

-Energy Environ. Sci., 2014, 7, 552

Accomplishments and Progress

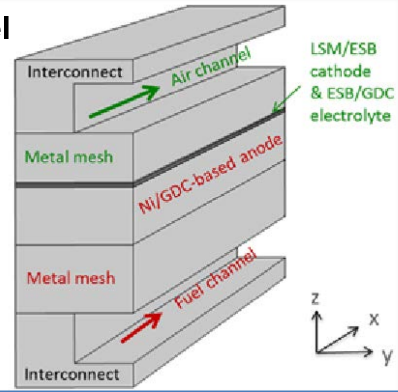
• 3.0 Optimize ESB/GDC Stacks for IT Operation

– Redox Multi-Physics Cell / Stack Modeling
  - Add ESB/GDC bilayer to single-channel model
  - Change BCs to model different stack regions

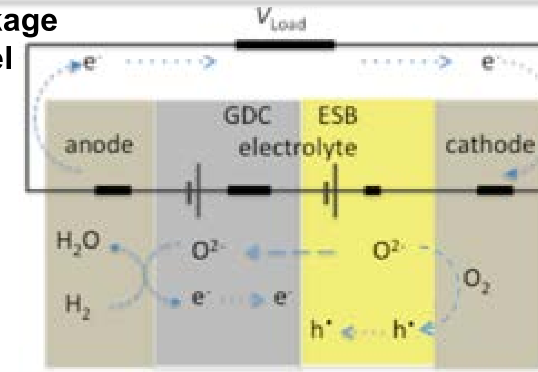
– Embedded voltage probes in cell
  - Further validation of bilayer model
  - Can be used to help debug stability issues (M2.3)

– Interconnect coatings/current collector contacts
  - Currently optimizing microstructure & composition
  - Adhesion of layers being optimized
  - New test setup complete & evaluation starting

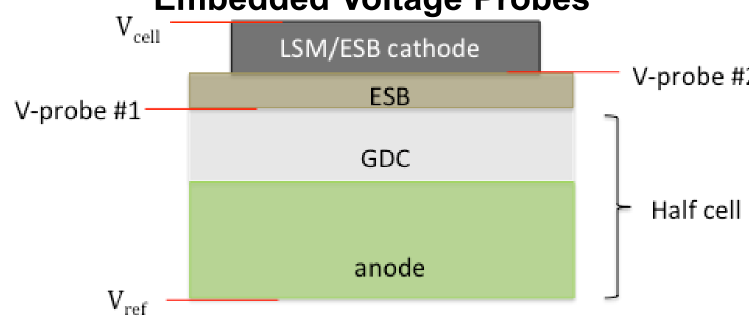
single channel multi-physics model



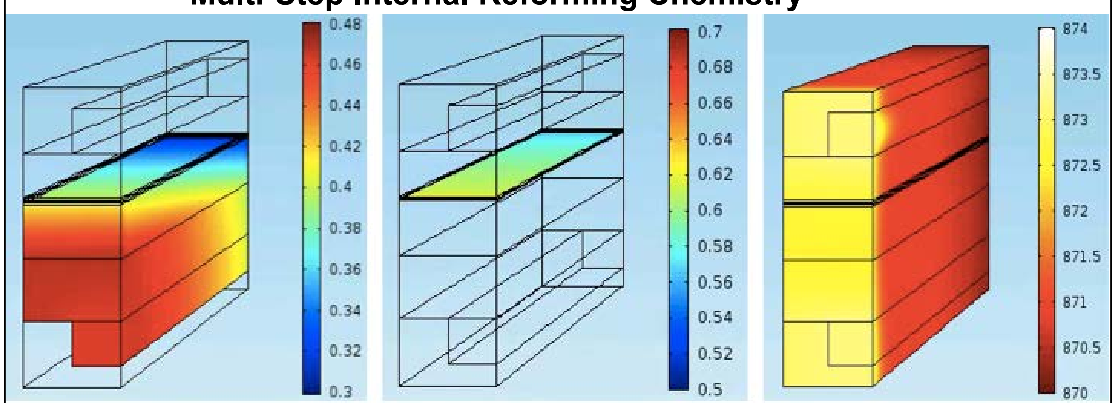
Bilayer / Leakage Current Model



Embedded Voltage Probes



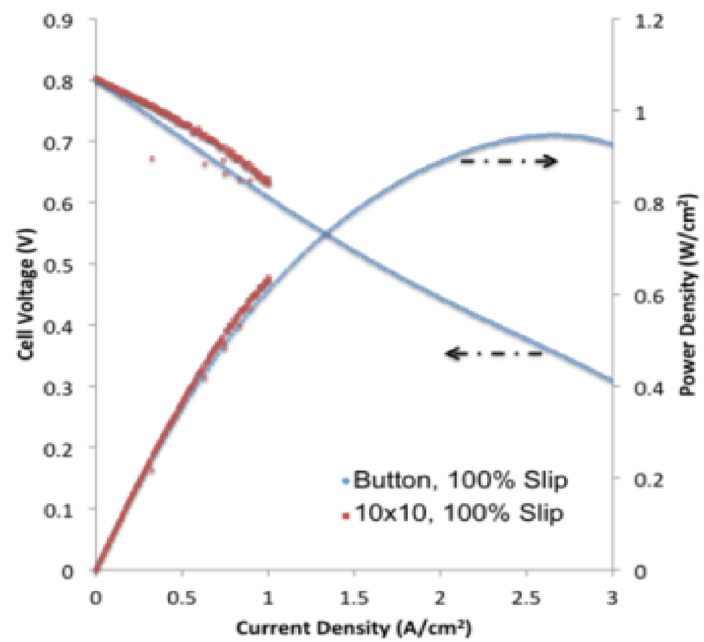
Multi-Step Internal Reforming Chemistry



H_2 Mole Fraction | Local current density (A/cm^2) | Temperature (K)

Accomplishments and Progress

- **4.0 ESB/GDC Bilayer Stack Demonstration**
  - IT-SOFC Stack Performance Maps
    - 10x10 cell performance matches that of button cells (single GDC electrolyte)
    - Should be able to achieve similar high performance for bilayer enhancements
    - Beginning to map out performance of single cell bilayer and short stacks (V-I, power, and exhaust temperature)
  - Demo ~1 kW_e Stack Under CHP conditions
    - Beginning to characterize short-stacks for CHP conditions
    - Additional setups / instrumentation upgrades almost complete
    - Multiple gas analyzers for quantifying fuel utilization



***Most of work in this task planned for later in project**

No.	Name (Task, Subtask, Milestone)	Start Date	End Date	YEAR 1 Q1	YEAR 1 Q2	YEAR 1 Q3	YEAR 1 Q4	YEAR 2 Q5	YEAR 2 Q6
4.0	**ESB/GDC Bilayer Stack Demonstration**	10/1/14	*3/31/16*						
4.1	**Stack Characterization & Testing**	10/1/14	*3/31/16*						
M4.1	***ESB/GDC Bilayer IT-SOFC Performance Maps**		*Q5*						
4.2	**Full (~1kW$_e$) Stack Demo Under CHP Relevant Conditions**	4/1/15	*3/31/16*						
M4.2	***Demonstration of Full (~1kW$_e$) Stack**		*Q6*						

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**
  - Successfully demonstrated ~1 W/cm^2 at ≤ 600°C,
    - push performance further with optimized infiltration
    - achieve very repeatable results as we scale to the 10x10 cell size
  - Translate already achieved performance at button cell level (≥ 0.9 V and ~1 W/cm^2 at ≤ 600°C) to the 10 cm by 10 cm cells

- **2.0 Design & Optimization of High Performance Electrodes**
  - Optimize anode pore formers for increased degree of open porosity without compromising mechanical strength
  - Determine degree of internal reforming that can be achieved at ≤ 600°C without negatively impacting stability
  - Achieve high performance while maintaining stability at ≤ 600°C

Future Work

- **3.0 Optimize ESB/GDC Stacks for IT Operation**
  - Use upgraded model to optimize stack design for bilayer cell
  - Consider different operating conditions that might improve durability and reduce degradation (e.g., reduced thermal gradients)
  - Use cell portion of model in conjunction with ongoing button cell and 10x10 bilayer thickness optimization

- **4.0 ESB/GDC Bilayer Stack Demonstration**
  - Finish mapping stack performance up to the full 1 kW_e size and move into conditions of residential CHP conditions with natural gas
    - Minimize degree of external reforming
    - sulfur is a concern and may necessitate some desulfurization
  - Obtain similar performance at 10x10 single cell and short-stack level in the ~1 kW_e stack size under CHP conditions

Technology Transfer Activities

- Redox has developed an ISO 9001 SOFC cell manufacturing and development chain over the past three years
  - Single layer electrolyte production cells available in partnership with Trans-Tech, Inc.
  - Basic bilayer cells have been produced in manufacturing, finalization pending EERE development (on track by Q5)
- 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)™ cost analysis of fuel cell systems & energy devices
  - Market input from Microsoft, a development partner and potential end-user, as well as other major players
  - Commercialization guidance from experienced MTech staff
- Redox is also in advanced discussions with other manufacturing partners as part of its Cube product

Project Summary

- **Objectives**
  - to 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, culminating in a ~1 kWe operating stack demonstration 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**
  - Leverage 25 years of SOFC R&D to optimize a bilayer electrolyte cell with academic and manufacturing partners to result in a 1 kWe CHP demo.
- **Accomplishments**
  - Validated simulation models and demonstrated high OCP measurements on bilayer materials, building the foundation for scaling to production cells for higher power and reliability.
- **Collaborations**
  - **EERE** project leverages strong group of academic (**UMD**, UCI, CSM), manufacturing & commercialization (**Trans-Tech**, **MTech,** SA), & end-user (Microsoft) partners beyond core EERE team.