REDOX

Affordable, High Performance, Intermediate Temperature Solid Oxide Fuel Cells

<u>Redox Cube</u>

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

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Redox Power Systems, LLC

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FC115

Overview

Timeline and Budget

- **Project Start Date:** 10/01/2014
- **Project End Date:** 03/31/2016

  No Cost Extension Ending: 03/31/2017
- **Total Project Budget:** **$1,340,566**
  - *Total Recipient Share:* $342,399
  - *Total Federal Share:* $998,167

  - *Total Recipient Share Spent:* $346,162
  - *Total Federal Funds Spent:* $998,167

EERE Project Partners

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

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 previously demonstrated > 1 W/cm^2 at 650°C (natural gas)
  - 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.

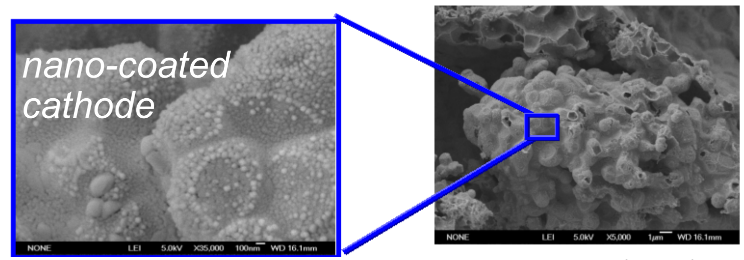
Relevance: Project Objectives

- **To improve the performance/durability of Redox technology through the:**
  - development of an optimized cell 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 stack designs for IT operation; and
  - creation of cell performance maps and demonstration of a stack for IT operation under CHP conditions with natural gas and minimal external reforming.

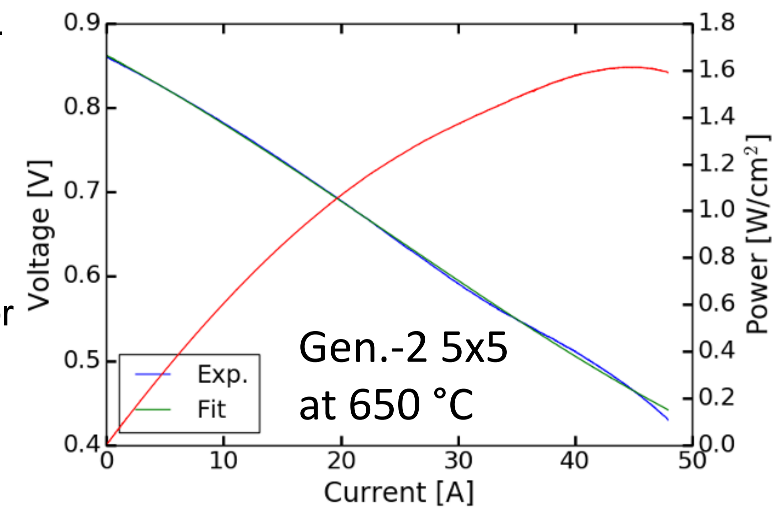
- **Reporting period (*4/1/2016-3/31/2017*) focus on scale-up and test:**
  - Achieved ASR ≤ 0.2 Ω-cm^2 at 600 °C with 10 cm by 10 cm (10x10) porous anode (Gen.-2) cells
  - Achieved 12 and 3 cell 5 cm by 5 cm (5x5) Gen.-2 stack tests with performance comparable to 10 cm by 10 cm and 5 cm by 5 cm single cell tests, demonstrating scalability
  - Achieved 1.6 W/cm^2 & 1.0 W/cm^2 with 5x5 Gen.-2 cells at 650 °C & 600 °C, respectively
  - Successfully integrated a CHP test apparatus with a 20-cell (Gen.-1 cell) stack, demonstrating greater than 10% improvement in fuel utilization recovery from cathode exhaust after high temperature regeneration. Follow-on work to utilize Gen.-2 cells.

Approach Summary: IT-SOFC Stack

- **Optimized stack designs for IT operation**
  - Develop catalyst infiltratable, porous anode (Gen.-2 SOFC) for low ASR and high power density
  - Scale-up button and 5 cm x 5 cm SOFC and infiltration approach to 10 cm x 10 cm cells
- **Increased efficiency**
  - Increase open circuit voltage with improved cathodes → infiltration
- **Higher Power Density**
  - Improve carbon/sulfur tolerance with catalyst infiltration into as-fabricated porous anodes (10 cm by 10 cm)
  - Optimize cathode infiltration to increase power density (reduce cost)
- **Stack demo under CHP conditions**
  - cell performance maps for stack, feed results back to model for design optimization
  - Stack demo under residential CHP scenario using natural gas and minimal external reforming



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



Approach/Milestones

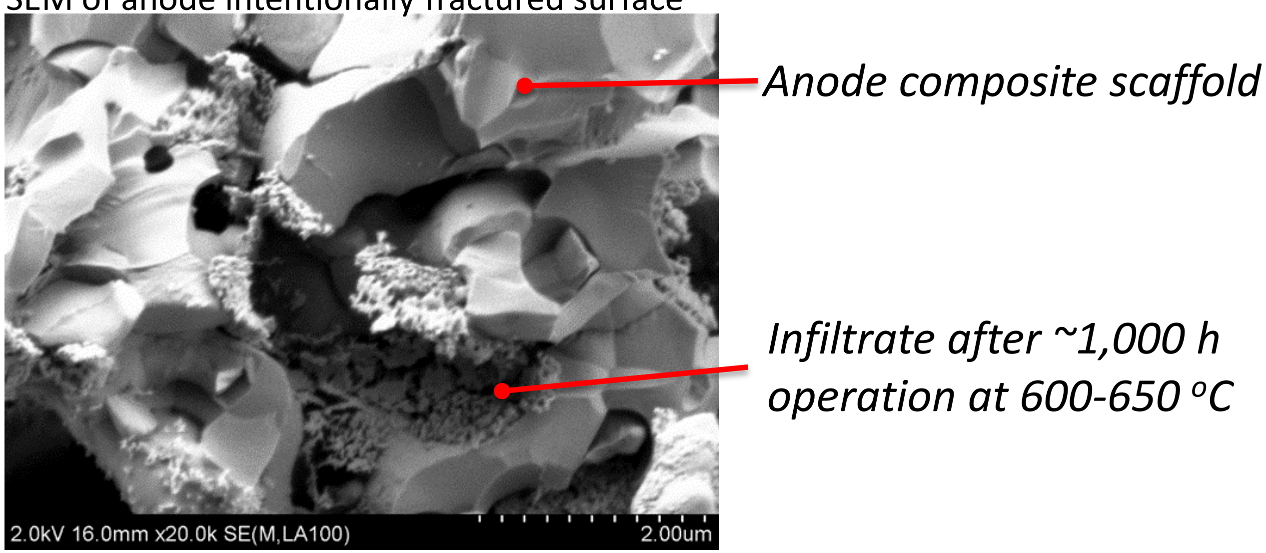
** No-Cost Extension Granted*

Task/Milestone	Original Due Date	New Due Date*	% Completed
1.0. Gen.-2 Porous Anode Cell Development for Improved IT Efficiency			
M1.1: Button Cell OCP of ≥ 0.9 V at ≤ 600°C	M6	n/a	100%
M1.2: 10x10 Cell OCP of ≥ 0.9 V at ≤ 600°C	M12	n/a	100%
2.0. Design & Optimization of High Performance Electrodes			
M2.1: Button Cell ASR ≤ 0.2 Ω-cm^2 & ~1 W/cm^2 at ≤ 600°C	M9	n/a	100%
M2.2: 10x10 Cell ASR ≤ 0.2 Ω-cm^2 at ≤ 600°C	M15	M30	100%
M2.3: Achieve degradation rate ≤ 2% per 1,000 h at ≤ 600°C with 10x10 cells	M18	M30	100%
3.0. Optimize Gen.-2 Stacks for IT Operation			
M3.1: Low ASR Interconnects & Contacts	M9	n/a	100%
M3.2: Validation of updated Cell/Stack Modeling Tool	M3	n/a	100%
4.0. Stack Demonstration			
M4.1: Develop IT-SOFC Stack Performance Maps	M15	M30	100%
M4.2: Demonstrate Stack Under CHP Conditions	M18	M30	100%

Accomplishments and Progress

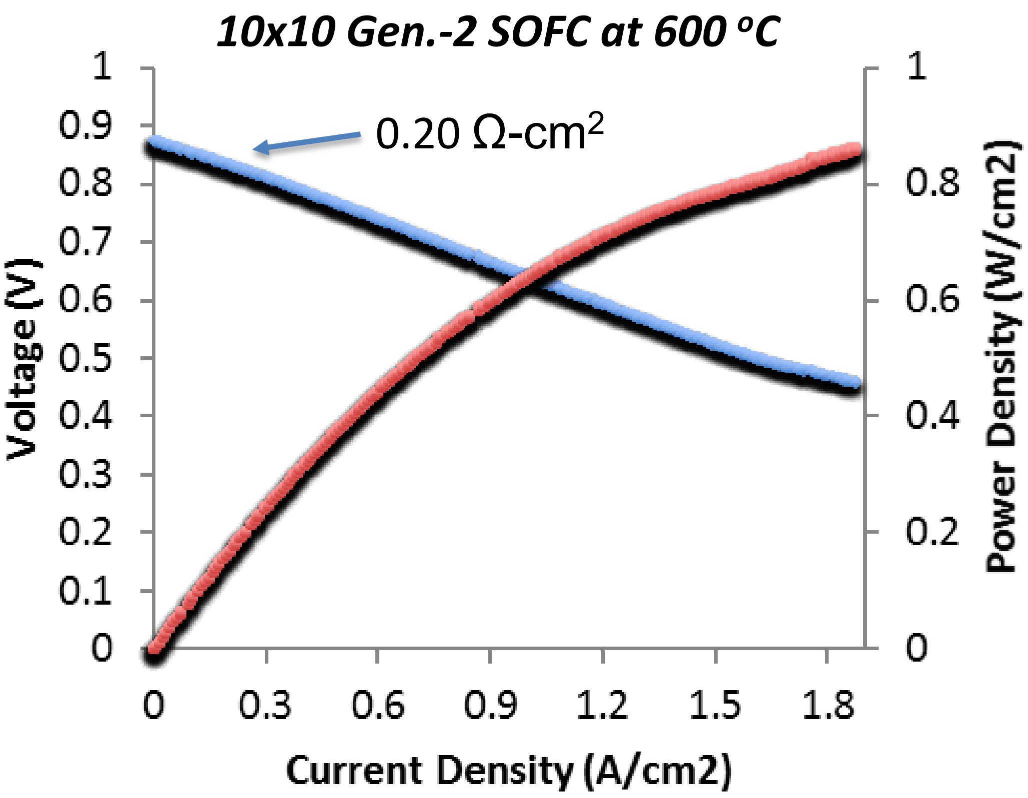
- **2.0. Design & Optimization of High Performance Electrodes**
  - Increased as-fabricated anode porosity without compromising mechanical strength
    - Modified composition for 2x increase in mechanical strength of Gen.-2 (porous) anode vs. Gen.-1 (non-porous anode)
    - New anode composition phase and morphological stability confirmed after ~1,000 h of operation
  - Infiltrate nanoparticle catalysts into porous anode and cathode
    - Open circuit voltage improved by as much as 50 mV with infiltration
    - Custom infiltration system developed to selectively infiltrate cathode and anode, and scaled to 10 cm x 10 cm cell production
    - Infiltrate demonstrated to retain fine structure after ~1,000 h of operation

SEM of anode intentionally fractured surface



Accomplishments and Progress

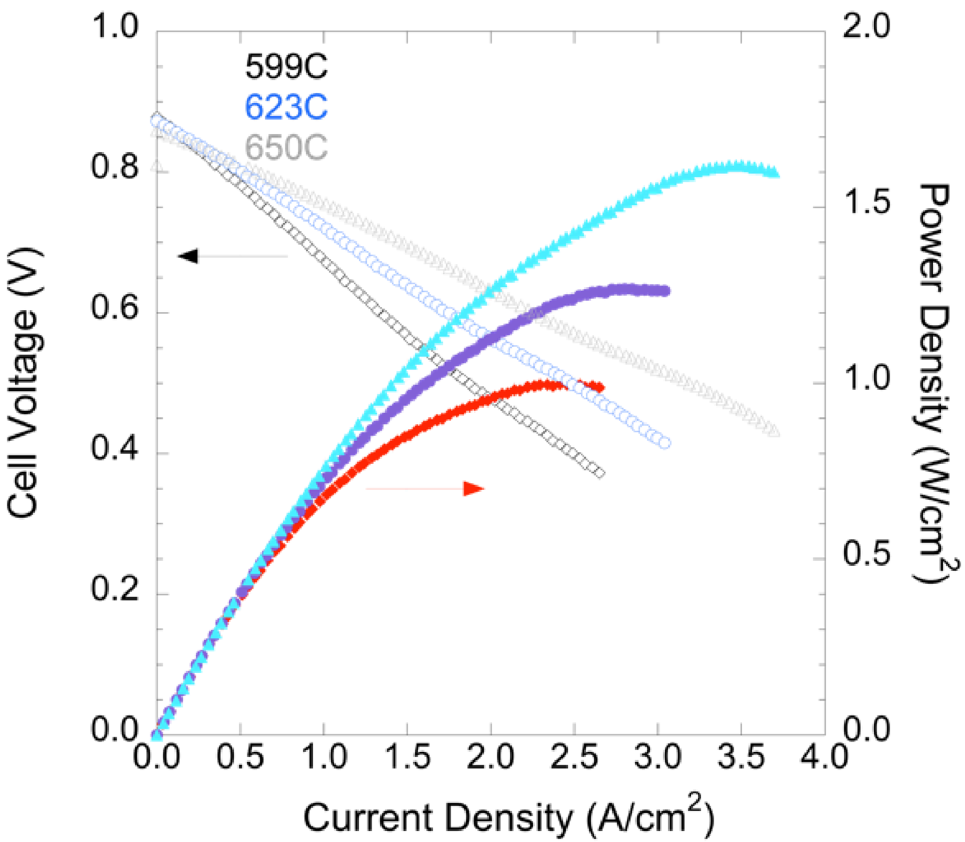
- **2.0. Design & Optimization of High Performance Electrodes**
  - **Achieved M2.2:** 10x10 Cell ASR ≤ 0.2 Ω-cm^2 at ≤ 600°C



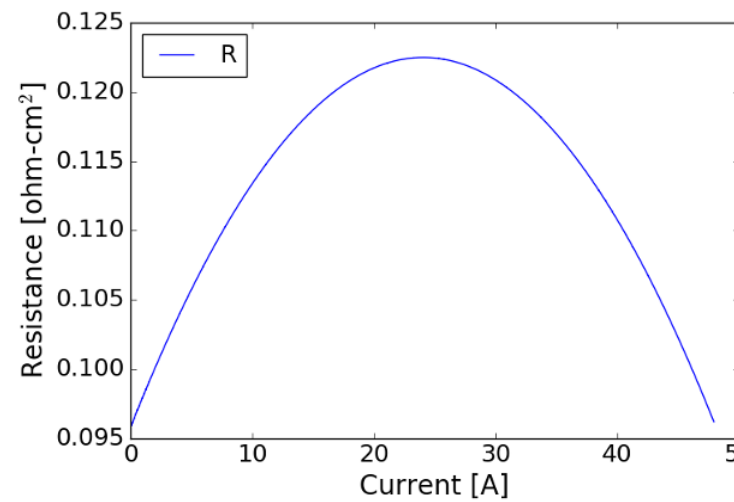
Accomplishments and Progress

- **2.0. Design & Optimization of High Performance Electrodes**
  - **Additional M2.2 Progress:** 5x5 Gen.-2 SOFC evaluation

1.6 W/cm² with Gen.-2 5x5 at 650 °C
1 W/cm² at 600 °C



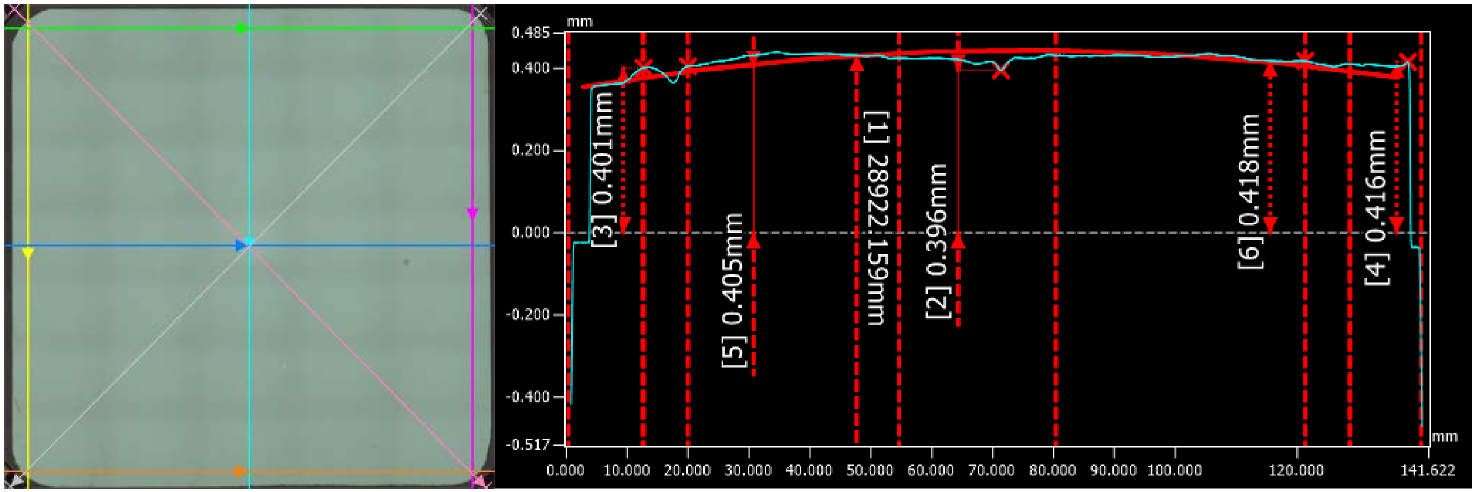
~0.1 Ω-cm² ASR of 5x5 Gen.-2 at 650 °C



Accomplishments and Progress

- **2.0. Design & Optimization of High Performance Electrodes**
  - **Additional M2.2 Progress:** Gen.-2 half-cell camber and scale-up

Low camber of 10 cm x 10 cm Gen.-2 cells achieved with optimized firing and composition

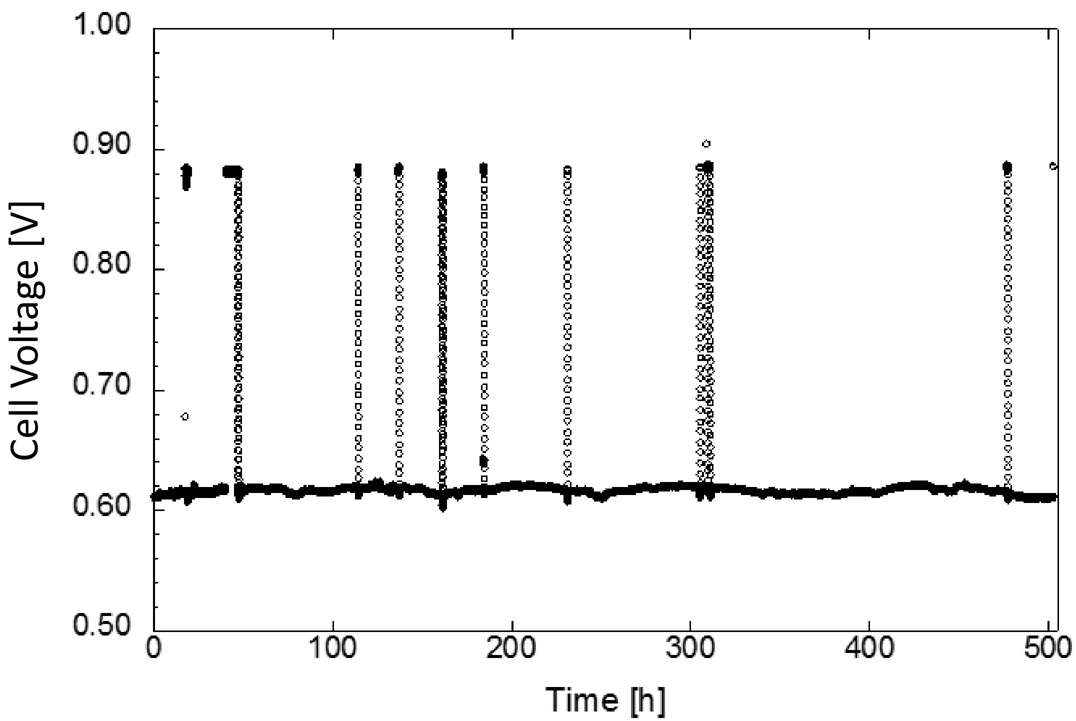


- Production partners successfully fabricated >7,500 sq. in. of Gen.-2 anode tape
- >24 15 cm x 15 cm green half-cells produced and from these >16 5 cm x 5 cm cells fabricated at in-house and production partner facilities
- Multiple ready to test Gen.-2 10 cm x 10 cm half-cells also produced

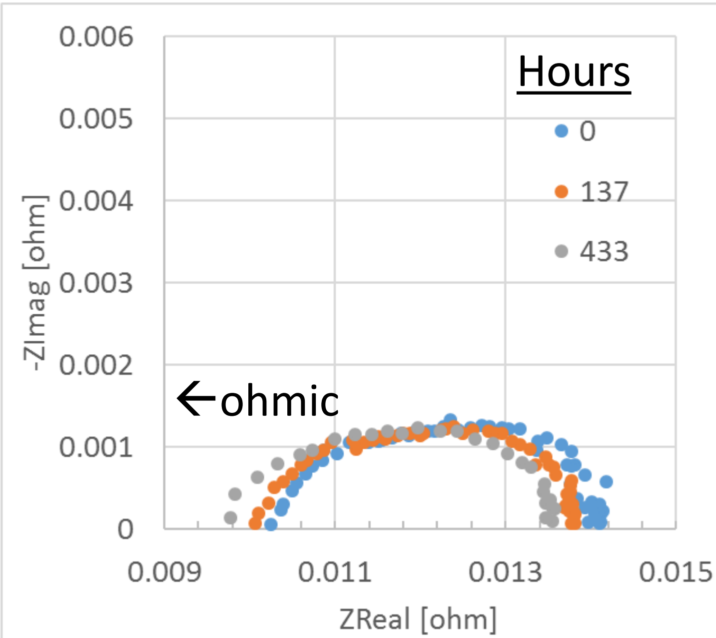
Accomplishments and Progress

- **2.0. Design & Optimization of High Performance Electrodes**
  - **Achieved M2.3:** Achieve degradation rate ≤ 2% per 1,000 h at ≤ 600°C with 10x10 cells (minimum of 300 h tested)

No voltage degradation after 500 h at 600 °C for 5 x 5 Gen.-2 cell



Decrease in ohmic ASR with time, no increase in non-ohmic ASR over ~500 h at 600 °C

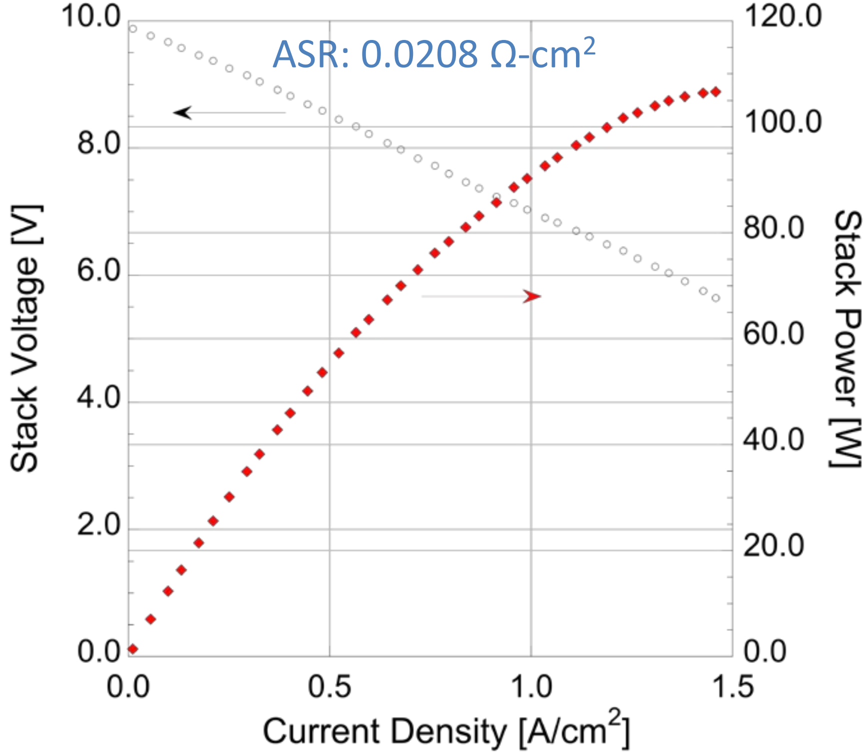


10 cm x 10 cm Gen.-2 SOFC also exhibited increase in voltage under load at 600 °C over >60 h of operation

Accomplishments and Progress

- **4.0 Stack Demonstration**
  - **Achieved M4.2:** Demonstrate Full Stack Under CHP Conditions

Successfully fabricated and tested a 12 cell Gen.-2 5x5 stack at 600 °C with dry H_2 fuel



- Power density of stack similar to 5x5 and 10x10 single cell tests (for a given current density)
- Open circuit voltage and ASR slightly less than single cells – possibly due to temperature variations within stack

Collaborations

EERE Project Collaborators

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

Redox Additional Partnerships

- Large *datacenter player (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*)

Technology Transfer Activities

- Redox has developed an ISO 9001 SOFC cell manufacturing and development chain over the past five years
  - Gen.-1 and Gen.-2 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 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)™ cost analysis of fuel cell systems & energy devices
    - Cell and stack model updated, with system 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**
  - to improve the performance/durability of Redox technology ~600 °C through development of an optimized Gen.-2 porous anode based solid oxide fuel cell
  - guided by a custom multiphysics model, culminating in an operating stack demonstration under combined heat and power (CHP) conditions.
- **Relevance**
  - High energy efficiency reduces hydrocarbon consumption, pollution, & 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 Gen.-2 porous anode, GDC electrolyte, cell for 600 °C stack CHP demo.
- **Accomplishments**
  - Achieved ASR ≤ 0.2 Ω-cm^2 at 600 °C with 10x10 porous anode (Gen.-2) cells
  - Achieved 12 and 3 cell 5x5 Gen.-2 stack tests with performance comparable to 10x10 and 5x5 single cell tests, demonstrating scalability
  - Achieved 1.6 W/cm^2 and 1.0 W/cm^2 5x5 Gen.-2 cell power densities at 650 °C & 600 °C, respectively
- **Collaborations**
  - **EERE** project leverages strong group of academic (**UMD**, UCI, CSM), manufacturing & commercialization (**Trans-Tech**, **MTech,** SA), & end-user partners beyond core EERE team.