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 m³)
• 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

<table>
<thead>
<tr>
<th>Stack Performance Metrics</th>
<th>Proposed ARPA-E Targets</th>
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</thead>
<tbody>
<tr>
<td>Size (kW)</td>
<td>1</td>
</tr>
<tr>
<td>Operating Temperature Range (°C)</td>
<td>300-500</td>
</tr>
<tr>
<td>Open Circuit Voltage (V/cell)</td>
<td>1.0-1.1</td>
</tr>
<tr>
<td>Current Density at 70% Nernst (A/cm²)</td>
<td>≥0.2</td>
</tr>
<tr>
<td>Electric Efficiency at Rated Power (%)</td>
<td>≥54</td>
</tr>
<tr>
<td>Startup Time (minutes)</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Transient Response, 10-90% (minutes)</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>
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*)
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$_2$O$_3$ (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$_2$O$_3$ 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

**Diagram Details**

- **Stagnation Flow**
  - Primary Flow Measurement
  - H₂ to MFC
  - Back Pressure Regulator
  - Vent
  - He to MFC
  - Gas Chromatograph

- **Flow-Through**
  - Feed
  - Gasket
  - Explosd View not to Scale
  - Bulk leak (external)
  - Bulk leak (internal)
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**
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 Thickness Optimization for Increased OCP

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

Most recent results:
OCV @ 500°C = 1.02 V
**M2.1.1: Cathode ASR ≤0.7 Ω-cm² at 500°C**

- 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**

- LSM-ESB cathode & SNDC/DWSB electrolyte
- Captures:
  * Heterogeneous catalysis
  * Electrochemistry
  * Temp. dependence of materials

**Bilayer / leakage current model**

**Expanding model to full stack for design optimizations**

Graphs and diagrams showing the distribution of temperature and stack edge conditions across different channels.
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/cm² peak, ~0.28 W/cm² @ 0.7 V)
- Other configurations (not shown) have achieved >1 V at 500°C, & ~0.55 W/cm² at 525°C
Thank You

Questions?