An Intermediate Temperature Metal-Supported Proton-Conducting Solid Oxide Fuel Cell Stack

18th Annual SOFC Workshop
June 14, 2017
Stack Concept

*Metal supported p-SOFC with internal CH$_4$ reforming*

<table>
<thead>
<tr>
<th>Feature</th>
<th>Lead Organizations</th>
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<tbody>
<tr>
<td>Proton-Conducting Oxide</td>
<td>Northwestern, University of Maryland, UConn</td>
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<tr>
<td>Metal Support</td>
<td>ElectroChem Ventures, UConn, United Technologies Research Center</td>
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<tr>
<td>Internal Fuel Reforming</td>
<td>United Technologies Research Center</td>
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</table>
CHP System Concept & Efficiency

**Assumptions**
- Methane Conversion: 90%
- H₂ Utilization: 80%
- OCV (V/Cell): 1.05
- ASR (Ωcm²): 1
- Current Density (mA/cm²): 200
- Parasitic Power / Stack Power: 9%
- Inverter Efficiency: 95%
- Heat Recovery Temp: 75 °C

**Overall stack efficiency:** 27%

**Net electric efficiency:** 59%

**Inverter losses:** 5%

**Waste Heat Recovery:** 25%

**Total Output:** 75%

**Effective Electric Efficiency (57%)**
PCO-Electrolytes: Exceed Target Conductivity

**Graph:**
- **X-axis:** $1000/T$ (K$^{-1}$)
- **Y-axis:** Conductivity ($\sigma$, S/cm)
- **Legend:**
  - comp 1: 1.91
  - comp 2: 1.78
  - comp 3: 1.66
  - comp 4: 2.00
  - target: 1.5

**Data Points:**
- $p_{H_2O} = 0.031$ atm
- Balance $N_2$

**Note:**
- Conductivity is extrapolated to $T = 500$°C.
Cathode: BaZrYO$_3$ - BaPrYO$_3$

Typical spectra
Pr-rich, fixed composition
Vary diameter

Observation: strong composition dependence, slight diameter dependence
Anode Supported Button Cell Performance in H2

Cathode sintered at 1000 °C

<table>
<thead>
<tr>
<th>ACIS</th>
<th>ohmic, Ωcm²</th>
<th>Non-ohmic, Ωcm²</th>
<th>Peak PD Ωcm⁻²</th>
</tr>
</thead>
<tbody>
<tr>
<td>T (°C)</td>
<td>#1</td>
<td>#2</td>
<td>#1</td>
</tr>
<tr>
<td>700</td>
<td>0.179</td>
<td>0.142</td>
<td>0.050</td>
</tr>
<tr>
<td>600</td>
<td>0.295</td>
<td>0.213</td>
<td>0.265</td>
</tr>
<tr>
<td>500</td>
<td>0.461</td>
<td>0.338</td>
<td>1.420</td>
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</table>
Cell Performance Stability Evaluation

@ 0.5 V

$T = 550 \, ^\circ C$

- Test period $\approx 700 \, h$
- Degradation rate $\approx 0$
  $< 2 \times 10^{-3} \%/h$ target

0.72 A cm$^{-2}$

Current Density (A cm$^{-2}$)

Time (h)

humidified H$_2$ / cell / air
Excellent Stability in CO₂

Long-term OCV measurement

Anode gas: humidified H₂; humidified 90% H₂, 10% CO₂
Further Performance Improvement Demonstrated

Without PLD

With PLD

Decreased ohmic loss

Cathode PLD layer

Electrolyte
Operation under Methane: 1\textsuperscript{st} Attempt

<table>
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<tr>
<th>Temperature (°C)</th>
<th>Ohmic (Ω cm(^2))</th>
<th>Non-ohmic (Ω cm(^2))</th>
<th>Peak power density (W cm(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>650</td>
<td>0.139</td>
<td>0.132</td>
<td>0.548</td>
</tr>
<tr>
<td>600</td>
<td>0.197</td>
<td>0.345</td>
<td>0.332</td>
</tr>
<tr>
<td>550</td>
<td>0.277</td>
<td>0.992</td>
<td>0.181</td>
</tr>
<tr>
<td>500</td>
<td>0.369</td>
<td>2.833</td>
<td>0.094</td>
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</table>

Ru on anode, 28.2%CH\(_4\)+71.8%H\(_2\)O

@ 600 °C
Metal Support Design

(1) Metal Porous Sheet  
(substrate for p-SOFC trilayer)

(2) Metal C-Ring Inserts/Orifices  
(3 out of 4 visible)

(3) Metal Foam  
(substrate for reforming catalyst)

(4) Metal Stamped Dish

(5) Insulator Couplings  
(2 out of 4 visible)

Enabling Fabrication Approach: Reactive Spray Deposition Technology (RSDT)
Cell Manufacturing Process: RSDT

- atomizing nozzle
- secondary spray
- quench gas
- 2.7 cm square
- Cathode: 5-10μm
- Electrolyte: 2-5μm
- Anode: 5-10μm
- Support: 177 μm
- 3 cm square

Temperature (K) vs. x (cm)

- P1, T1
- V1, V2, P2
- droplets
- oxidant gas
- flame zone
- vapor
- nucleation
- surface growth
- cluster formation
- coalescence
- nanoparticles
- aggregation
- agglomeration

United Technologies Research Center
Northwestern
University of Maryland
UCONN
ElectroChem Ventures
Cell Deposition on Metal Support by RSDT

- Demonstrated thin dense electrolyte (leak rate $\sim<0.05$ ml/min/cm$^2$ at 1” H$_2$O)
- Challenges in anode deposition on porous metal:
  - Adherent layer
  - Able to bridge large pores
Recent Progress Made in RSDT Full Cell Deposition

5 x5 cm$^2$ metal supported cell
Technoeconomic Analysis of 5-kWe System

- 8 major system components
- Key operating conditions:
  - Stack mean $T = 500 \, ^\circ C$; Cell area = 100 cm$^2$
  - $H_2$ utilization = 80%; $CH_4$ reforming conversion = 90%

<table>
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<tr>
<th>ASR $[\Omega , cm^{-2}]$</th>
<th>Stack temp. $[\circ C]$</th>
<th>$i$ $[A , cm^{-2}]$</th>
<th>Power Density $[W , cm^{-2}]$</th>
<th>Stack cost $[$/kWe]$</th>
<th>System cost $[$/kWe]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>500</td>
<td>0.2</td>
<td>0.17</td>
<td>916</td>
<td>2005</td>
</tr>
<tr>
<td>0.5</td>
<td>600</td>
<td>0.2</td>
<td>0.19</td>
<td>764 (-16%)</td>
<td>1323 (-34%)</td>
</tr>
</tbody>
</table>
Summary

- Progress
  - Cell materials
  - Stack design
  - RSDT fabrication process

- Next Steps
  - Further improvement of cell deposition
  - Performance demonstration of metal supported cell
  - Continue material development
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<table>
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<tr>
<th>Organization</th>
<th>Team Members</th>
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<tr>
<td>Northwestern</td>
<td>Sossina Haile, Sihyuk Choi, Chris Kucharczyk, Daekwang Lim</td>
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<td>ElectroChem Ventures</td>
<td>John Yamanis</td>
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<tr>
<td>UCONN</td>
<td>Radenka Maric, Tim Myles, Ryan Ouimet</td>
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<tr>
<td>University of Maryland</td>
<td>Ichiro Takeuchi, Xiaohang Zhang, Yangang Liang</td>
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<tr>
<td>United Technologies Research Center</td>
<td>Tianli Zhu, Justin Hawkes, Sean Emerson, Neal Magdefrau, Xian Tang</td>
</tr>
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Grigorii Soloveichik, Scott Litzelman, John Tuttle, John Lemmon
Back Up
Proton Conducting Oxide

High-Throughput Material Evaluation Approach

![Graph showing proton conductivity vs. temperature](image)

- doped CeO$_2$
- doped BaZrO$_3$
- CsH$_2$PO$_4$
- CsHSO$_4$
- Zr$_{0.9}$Sc$_{0.1}$O$_{1.95}$
- Zr$_{0.9}$Y$_{0.1}$O$_{1.95}$
- LSGM = La$_{0.9}$Sr$_{0.1}$Ga$_{0.9}$Mg$_{0.1}$O$_{2.35}$
- PBI = polybenzyimidazole

1.5 \times 10^{-2} \ \Omega^{-1}\text{cm}^{-1}

1000/T (K$^{-1}$)

Temperature (°C)

Substrate
Mask
1ML

Repeat
Plume
B
A

ElectroChem Ventures

Northwestern University
University of Maryland
UCONN
**CO₂ stability of Gen-2 Electrolyte**

- No carbonate detected by diffraction
- No weight gain under flowing CO₂
### System Concept

**5 kW Residential CHP System**

**Exhaust**
- Exhaust: 12.8 g/s, 35 °C
- Burn In Cath: 12.7 g/s, 385 °C
- Anode Out: 0.7 g/s, 463 °C
- Cath In: 12.6 g/s, 463 °C
- Boil Out: 12.7 g/s, 385 °C
- Rec. H2O: 0.6 g/s, 35 °C

**Building/Potable Water Heating/Cooling Sub-System**
- Recovered Water Pump

**Recuperator**
- Air Inflow: 12.6 g/s, 15 °C
- HEX Hot In: 13.4 g/s, 598 °C

**Stack Afterburner**
- HEX Hot Out: 13.4 g/s, 246 °C

**Cathode**
- PC SOFC Stack
- SR & Anode

**Performance Summary**
- Net DC Power (W) = 5000
- Net AC Power / Methane LHV = 51%
- Recovered Heat / Methane LHV = 25%
- Effective Electric Efficiency = 57%

**5 kW Residential CHP System**

**Boiler**
- Steam: 0.6 g/s, 463 °C

**Fresh Fuel & Steam Mixer**
- Natural Gas

**Recuperator**
- Air Cooled Exhaust Condenser

**Air Inflow**
- 12.6 g/s, 15 °C

**Building/Exhaust**
- 12.8 g/s, 35 °C

**Recovered Water Pump**
- 13.4 g/s, 80 °C

**Recuperator**
- 13.4 g/s, 246 °C

**Stack Afterburner**
- Burn In Cath: 12.7 g/s, 385 °C
Better Cathode/Electrolyte Interface via PLD Layer

Sintered without PLD 900 °C

Sintered at T 950 °C with PLD

Sintered at 1000 °C