A Transformational Natural Gas Fueled Dynamic SOFC for Critical Datacenter In-Rack Power

(The first 6-month progress report)

DE-FE-0031671
Primary: University of South Carolina
In collaboration with Atrex Energy

2019 Annual SOFC Review Meeting
April 30, 2019
Outline

• Datacenter power challenges
• Fe-bed SOFC technology
• Objectives of the project
• Recent results
• Summary
• Acknowledgement
Datacenter Market Size and Key Requirements

• $18.5 billion global market (2018)
• Expected to grow to $32 billion by 2023
• 9.04% compound annual growth rate (CAGR)
• $6 billion market in the US alone
• Representing 2-3% of the total energy consumption in the US and Canada

Keys requirements: reliability, efficiency, cost and load following
The Challenges

Fossil fuel

100 kW_h fossil to thermal power plant
30 kW_e delivered to the data center
16 kW_e delivered to the server
9.5 kW_e delivered to the application

Can Conventional SOFCs Be Applied for Datacenters?

- Designed for baseload power applications at constant fuel and air utilizations
- Poor overload tolerance – causing local fuel starvation, Ni-oxidation and cracks in anode
- Slow fuel supply response system – mass flow controller
- Lack of robust control algorithms
The Fe-Bed SOFC Technology

Cathode reaction: \( \text{O}_2 + 4e^- \rightarrow 2\text{O}^{2-} \)
Anode reaction: \( 2\text{H}_2 + 2\text{O}^{2-} \rightarrow 2\text{H}_2\text{O} + 4e^- \)
Fe-bed: \( \text{H}_2 + \text{FeO} \leftarrow \text{H}_2\text{O} + \text{Fe} \)

*Energy & Environmental Science, 4 (2011), 4942; 9 (2016), 3746 – 3753*
Robust Performance

Energy & Environmental Science, 9 (2016), 3746 – 3753
Remaining Issues

Before testing

Fe-rich dense skin

After testing

Close-end

Fe-rich dense skin

Open-end
Project Objective(s)

• **Overarching objective**: to develop a new generation of dynamic SOFC system operated on NG for datacenter applications
  ✓ **Primary objective -1**: to develop robust metal-bed design and compositions
  ✓ **Primary objective -2**: to demonstrate the new cell technology at pilot-scale
Optimizing Fe/ZrO$_2$ Ratio
Segmented Bed Design

Fuel injector

Fe-X1

Fe

Fe-X2

%H₂O

3%  80%

Z
FeCoO$_x$-ZrO$_2$ Phases

Oxide form

Intensity (a.u.)

2-Theta (deg.)

Fe:Co=50:50
Fe:Co=60:40
Fe:Co=70:30
Fe:Co=80:20
Fe:Co=90:10
Fe:Co=100:0

Fe$_2$O$_3$ PDF#33-0664
CoFe$_2$O$_4$ PDF#79-1744
ZrO$_2$ PDF#49-1642

Alloy form

Intensity (a.u.)

2-Theta (deg.)

FeCo Alloy PDF#48-1817
ZrO$_2$ PDF#49-1642
ZrO$_2$ PDF#37-1484
TPR @ Different Ramping Rates
Studying FeCoO$_x$ Reduction Kinetics by TPR

\[
\ln\left(\frac{\varphi}{T^2_m}\right) = -\frac{E}{RT_m} - \ln\left(\frac{E}{AR}\right) + C
\]

\[
A = \frac{-E}{RT_m^2} \times \frac{\varphi e^{E/RT_m}}{d\frac{df(\alpha)}{d\alpha}}_{T=T_m}
\]

\[
f(\alpha) = k(T)t = (1 - (1 - \alpha)^{1/3})^2
\]

\[k(T) = Ae^{-E/RT}\]
TPO/TPR Alternate 50 Cycles

Graphs showing TCD Signal (a.u.) over time (min) for Fe:Co=50:50.
Oxygen Concentration Cells: Measuring $a_{Fe}$

$$ (Fe) + \frac{1}{2} O_2 = FeO $$

$$ P_{O_2} = 0.21 \exp \left( -\frac{4EF}{RT} \right) $$

$$ a_{Fe} = \frac{1}{KP_{O_2}^{1/2}} $$

$$ -RT \ln K = \Delta G^0 $$
Fe-Activity in Fe-Co Alloys

EMF vs T

OCV (V)

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>Theoretical OCV (V)</th>
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<tbody>
<tr>
<td>600</td>
<td>1.045</td>
</tr>
<tr>
<td>650</td>
<td>1.027</td>
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<tr>
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<td>1.008</td>
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<tr>
<td>750</td>
<td>0.989</td>
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<tr>
<td>800</td>
<td>0.971</td>
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</table>

Raoult's law

a_{Fe} vs X_{Fe}
Conclusions

• Fe$_2$O$_3$:ZrO$_2$ molar ratio can be increased to 9:1

• Adding Co into Fe makes Fe(Co)O$_x$ reduction easier

• It is also confirmed for Fe-Co alloys that $a_{Fe} < 1$ at $X_{Co} < 0.4$, above which $a_{Fe} > 1$ below 700 °C
Next Steps

- Finishing EMF study for all Fe-Co alloys
- Expanding EMF study to Fe-Ni alloys
- Down selecting Fe-X compositions for pilot-scale testing at Atrex

Acknowledgement

- DOE NETL for supporting this work under award DE-FE-0031671
- Dr. Diane Madden is the project manager and Dr. Shailesh Vora is the program director
A New Isostructural Bilayer Cathode Tolerant to Cr
A New Isostructural Bilayer Cathode Tolerant to H$_2$O and CO$_2$

**H$_2$O Effect**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Graph 1</th>
<th>Graph 2</th>
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</thead>
<tbody>
<tr>
<td>550°C</td>
<td><img src="image1" alt="Graph" /></td>
<td><img src="image2" alt="Graph" /></td>
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<tr>
<td>600°C</td>
<td><img src="image3" alt="Graph" /></td>
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<td>650°C</td>
<td><img src="image5" alt="Graph" /></td>
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<tr>
<td>700°C</td>
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**CO$_2$ Effect**

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<tr>
<td>700°C</td>
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