Washington State University

» Land grant Institution founded in 1890
» 29,686 Students (20,043 at Pullman Campus)

Set among the scenic Palouse hills
How does pressurization affect performance?
Are there alternative system configurations that enable pressurized operation?

How do we incorporate the slower transients of high temperature fuel cells with energy storage to meet local demands?

What role can solid oxide technology and the hydrogen economy play in sustainable systems?
Why Pressurized SOFC/SOEC?

- Higher FC operating voltage (also with pure O₂ cathode)
- Potential for low energy H₂ recovery, ammonia co-production, integrated carbon capture & liquefaction
- Reduce/eliminate high temperature air heat exchangers (with pure O₂ cathode)
- Potential for continuous H₂ production in both modes (integrate with H₂ liquefier being developed at WSU)

What will CESI lab test?

- Pre-commercial SOFC cells (100mm X 100mm) at 0-150psig
- Operation at elevated pressure with pure O₂ cathode
- Indirect/direct internal reforming
- Participation of CO in electrochemistry
- O₂ purge cycle for closed-end cathode (requires additional hardware installation)
Oxy-FC can provide ultra-efficient, carbon neutral, fertilizer production

- Pressurized, pure O₂ cathode and higher anode H₂ concentration increases efficiency
- Waste heat captured in chemical potential of H₂
- Air separation yields O₂ for FC and liquid N₂ for the carbon liquefaction and H₂ recovery
- Exhaust N₂ and H₂ streams pass over a catalyst bed to form NH₃ (Haber-Bosch)
- Ammonia production consumes 5% of the world’s natural gas (<50% efficient)
- Combined system co-produces electricity + ammonia + liquid CO₂ at +80% efficiency
Copper cored electrodes

Shielded thermocouples

Shielded voltage wire
  > Missile wire rated to 2000F

1 kW Load bank
  > 200 amps
  > 10 voltage measurements

Humidifier Control

Furnace Control
» **Cathode:**
  > 150psig rated MFC for N$_2$ delivering 0.2$\rightarrow$10slpm
    + Expandable to 125slpm
  > 150psig rated MFC for O$_2$/Air delivering 0.2$\rightarrow$10slpm

» **Anode**
  > 150psig rated MFC for H$_2$ delivering 0.1$\rightarrow$5slpm
  > 150psig rated MFC for CO & CO$_2$ delivering 0.002$\rightarrow$0.1slpm

» **Humidifier**
  > Pressurized D-I water reservoir and liquid MFC for H$_2$O delivering 0.2$\rightarrow$10gpm

» **Gas cabinets / regulators**
  > 4 X GasGaurd bottle cabinets with continuous exhaust
  > 3 X dual bottle 200 psig regulators with automatic switchover
  > 1 X 200 psig regulator for inert & control air
6kW furnace rated to 1000°C and 150psig

- Top-hat style so top+ sides lift off to expose working area
- Bottom mounted to stand

1 kW anode humidifier
High Pressure Furnace
Test volume: Diameter = 300mm
Height = 300mm

Anode heat exchanger plate
Ceramic tubes supporting weight
Concentric supply/return tubes

» 5 pass throughs in bottom of furnace

Aerospace multi-sensor pass through
> Sensor diameter 0.1”
> Pressure rating 150psig
> Up to 28 sensors
» Cathode plate A: raised channels with contact paste
» Cathode plate B: recessed channels with metallic foam for current collection
» Anode plate A: counter-flow, Nickel mesh current collector
» Anode Plate B: cross-flow, Nickel mesh current collector
» Bi-polar Plate = Cathode B + Anode B
Machining and Post-Treatment

» Anode & Cathode heat exchangers machined from ½” Inconel plate
  > Plates aluminide coated & brazed together
  > Post-machining of a moat to create a strong Inconel-Inconel weld

» Anode A & B, Cathode A & B, and bi-polar plates machined from 0.12” SS-430
  > Anode plates aluminide coated via thermal spray
  > Cathode plates spinel coated with Mn1.5Co1.5O4

» Water-jetting process for small anode/cathode channels to reduce machining time
## SOFC Materials

<table>
<thead>
<tr>
<th>Support</th>
<th>Anode</th>
<th>Cathode</th>
<th>Thickness (μm)</th>
<th>Rated Voltage @ 0.5A/cm²</th>
<th>Cell Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolyte</td>
<td>NiO-GDC</td>
<td>LSM-GDC</td>
<td>250</td>
<td>0.7</td>
<td>$360</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>Ni-YSZ</td>
<td>LSM</td>
<td>150</td>
<td>0.73</td>
<td>$225</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>Ni-YSZ</td>
<td>LSM</td>
<td>150</td>
<td>0.75</td>
<td>$250</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>Ni-GDC</td>
<td>LSCF</td>
<td>160</td>
<td>0.8</td>
<td>$280</td>
</tr>
<tr>
<td>Anode</td>
<td>3 layers</td>
<td>2 layers</td>
<td>700</td>
<td>0.85</td>
<td>$160</td>
</tr>
<tr>
<td>Anode</td>
<td>GDC</td>
<td>LSC</td>
<td>250</td>
<td>0.9</td>
<td>$270</td>
</tr>
</tbody>
</table>
Test Stand Investment ($153,154)

- Electrical & Controls: 9%
- Gas Handling Components: 50%
- Heating & Humidification: 22%
- Fittings & pass throughs: 6%
- Machining & Post-treatment: 13%
Pressurized SOFC/SOEC has a number of applications:
- FC-GT hybrids
- Oxy-FC with ammonia co-production
- Electrolysis with methanation

Published data for pressurized operation is scarce.

CESI lab’s test stand will evaluate commercial scale cells and small stacks up to 1kW at up to 150psig, and test with a pure O₂ cathode.

Off-the-shelf furnace + pressure vessel is extremely expensive and large, custom option may actually save costs.

Water-jet machining is a good option for lab test interconnects, but commercialization requires stamping.

Mass flow controllers rated for 150psig are the bulk of the test stand cost.

There is considerable spread in the cost to researchers of pre-commercial SOFC.