Hybrid SOFC/Turbogenerator for Aircraft
Christopher Cadou, University of Maryland

Project Vision:
Exploit the high specific power of turbomachinery and the high conversion efficiency of fuel cells to create a synergistic system offering unprecedented fuel to electrical conversion performance (power/weight and fuel economy).
Brief REEACH Phase 1 Project Overview

Context/history of the project: Prior Work
Aluminum Combustor Powered Sea Horse

High Efficiency Hybrid SOFC-Turbogenerator
Team: Cadou, Jackson, Kee, Wachsman, Lents

Performance:
- ~100 kW power output
- < $1000/kW capital cost
- 72% overall efficiency

Technology:
- Integrated CPOx/SOFC
- Turbine engine
Brief REEACH Phase 1 Project Overview

Context/history of the project: Prior Work Continued

High Efficiency, Low Cost & Robust Hybrid
SOFC/IC Engine Power Generator
PI: Rob Braun; Colorado School of Mines

Performance:
~100 kW power output
< $1000/kW capital cost
70% overall efficiency

Application: Distributed power generation

Technology:
Pressurized metal-supported SOFC modules
IC engine
Novel power conditioning

Unifying Theme: Realize a synergistic integration where the advantages of one component
offset the disadvantages of others - and vice versa.
Brief REEACH Phase 1 Project Overview

Proposed System

Predicted ESPG Performance
Ni-YSZ/LSM-YSZ MEA
No anode recycle

<table>
<thead>
<tr>
<th>Metric</th>
<th>Targets</th>
<th>Actual</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Energy</td>
<td>3</td>
<td>3.42</td>
<td>kWh/kg</td>
</tr>
<tr>
<td>Specific Power</td>
<td>0.75</td>
<td>1.19</td>
<td>kW/kg</td>
</tr>
<tr>
<td>Fuel cost</td>
<td>0.15</td>
<td>0.13</td>
<td>$/kWh</td>
</tr>
<tr>
<td>Capital cost</td>
<td>1000</td>
<td>&lt;1000</td>
<td>$/kW</td>
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Ultimate success criteria: Be able to see a turbine/SOFC hybrid in the Smithsonian Air and Space Museum 20 years from now.
Proposed System

- **Key components:**
  - High power density redox-tolerant SOFC
  - Integrated autothermal reactor (ATR) solid oxide fuel cell (SOFC) stack

- **Success criterion, Phase I:**
  - Projected stack-level specific power > 1.6 kWₑ/kg at 0.75 V/cell
    - Ni-GDC cells
    - Simulated reformate
    - Stack T up to 650 °C
    - Stack pressure up to 15 bar
    - At least 5 cells with 16 cm² active area
    - Projected stack specific power based on 100 cell stack of 10 cm × 10 cm cells.
  - 1 kWₑ ATR/SOFC at 0.75 V/cell
    - Commercial GDC cells
    - Stack pressure up to 15 bar
    - Stack degradation rate < 2%/1000 hr projected from 200 hr run
    - Three thermal cycles from 300 °C to operating T.
# Team

<table>
<thead>
<tr>
<th>Team member</th>
<th>Location</th>
<th>Role in project</th>
</tr>
</thead>
<tbody>
<tr>
<td>Christopher Cadou</td>
<td>University of Maryland</td>
<td>PI; Overall system modeling, pressurized ATR/SOFC testing</td>
</tr>
<tr>
<td>Eric Wachsman</td>
<td>University of Maryland</td>
<td>High power density fuel cell development</td>
</tr>
<tr>
<td>Greg Jackson</td>
<td>Colorado School of Mines</td>
<td>Co-I; ATR/SOFC design and modeling</td>
</tr>
<tr>
<td>Robert Braun</td>
<td>Colorado School of Mines</td>
<td>ATR/SOFC design and modeling; Technoeconomic analysis</td>
</tr>
<tr>
<td>Tyrone Vincent</td>
<td>Colorado School of Mines</td>
<td>ATR/SOFC controls</td>
</tr>
<tr>
<td>Charles Lents</td>
<td>Raytheon Technology Research Center</td>
<td>Large-scale ATR/SOFC testing, turbomachinery modeling and design, business development</td>
</tr>
</tbody>
</table>
Innovation

▶ Key component-level innovations
  – Redox-tolerant high power GDC solid oxide fuel cells
    • Up to 2 W/cm² with Ni/GDC anodes as compared to up to 1 W/cm² for Ni-YSZ
  – Tightly integrated autothermal reactor / solid oxide fuel cell
    • Innovative flow paths and wiring schemes reduce ATR/SOFC weight by up to 50%

▶ New tools being developed to support this work
  – Pressurized SOFC test rig
  – High-fidelity ATR/SOFC models
  – Control model for ATR/SOFC
Overall Technical Approach: Main Goals

- Develop high power Ni-GDC SOFC 25-cm² cells and demonstrate a pathway to 100-cm² high power redox-tolerant cells.

- Demonstrate a 1.0 kWₑ integrated SOFC/ATR using COTS stacks
  - Specific power > 1.2 kWₑ/kg at 0.75 V/cell
  - $p ≤ 15$ bar
  - $T ≤ 650 ^\circ C$
  - Degradation rate < 2%/hr over 6 hrs.
Overall Technical Approach: High Power Density Redox Tolerant SOFCs

- Developed multiple cell chemistry/microstructure approaches to high power density lower-temperature - solid oxide fuel cells (LT-SOFCs)

  - Ultra-high-power ceria/bismuth-oxide electrolyte LT-SOFC
  - Higher stability high-power cathode-modified ceria-based LT-SOFC
  - Redox tolerant anode

- Based on model defined system requirements down-select approach and optimize high power density LT-SOFCs
- Scale cell size and demonstrate performance in multi-cell stacks
Overall Technical Approach: Pressurized SOFC Testing

- Internal Dimensions: ID = 10 in; Internal length = 24 in
- Operating conditions: $p_{\text{max}} = 50$ bar at $260^\circ$C
- Temperature and pressure control
RTRC maintains several labs with access to high pressure (up to 27 bar) high temperature air, that will be used to simulate the gas turbine conditions at interface points with SOFC subsystem.
Overall Technical Approach: ATR/SOFC Modeling

- **Mines ATR/SOFC modeling will lead design/optimization to guide system integration & testing**
  - Mines’ team has existing SOFC modeling tools and reduced-order system-level models.
  - GDC cell gPROMs models will be used to design flow paths/interconnects for $\geq 1.2 \text{ kW}_e/\text{kg}$.
  - Non-isothermal ATR design in gPROMs will target $\geq 50\%$ CH$_4$ reforming with $T_{\text{out}} < 700^\circ\text{C}$.
  - Integrated ATR/SOFC model will assess how pressure impacts stack performance.
  - ANSYS-Fluent CFD models will optimize flow and pressure field around ATR /SOFC to ensure good flow distribution, minimal leak risks, and anode exhaust recycling with ejector

**Systems**: modeling, process systems engineering, optimization & techno-economics
Overall Technical Approach: Full-Scale System Model

Adapt existing GT/SOFC system model

Features
- Electrochemistry (Mines’ models)
- ‘Down the channel’ pressure and heat loss
- Dusty gas MEA transport model
- Realistic turbomachinery maps
- Turbomachinery and fuel cell mass estimation

Required modifications:
- Add generator; update electrochemical and turbomachinery models
## Risks and Challenges

<table>
<thead>
<tr>
<th>#</th>
<th>Risk</th>
<th>Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Unable to integrate high power density stack with SOFC and ATR in a thermo-mechanically robust manner</td>
<td>Design ATR/SOFC to minimize temperature gradients; Add air plenum between ATR and SOFC; Develop compliant ATR/SOFC fluidic connections</td>
</tr>
<tr>
<td>2</td>
<td>Unable to achieve sufficient power density with redox tolerant anodes</td>
<td>Several design approaches are possible. If one doesn’t work, then will move on to second etc.</td>
</tr>
<tr>
<td>3</td>
<td>Inadequate control of anode exhaust recycling to provide thermal control of ATR/SOFC</td>
<td>Add dampers between ATR and SOFC and/or in recycling loop.</td>
</tr>
<tr>
<td>4</td>
<td>CTE mismatches in integrated ATR/SOFC lead to excessive anode flow path leakage</td>
<td>Unique stack design eliminates rigid seals and tolerates leaks; Cathode leaks don’t matter; Reduce $\nabla T$ using high velocity flow around stack; Adopt standard rigid glass seals if anode leaks.</td>
</tr>
<tr>
<td>5</td>
<td>Active component failure due to stress at seals during operation and transients</td>
<td>Change operating conditions based on results of stress sensitivity analysis; Improve cell flatness and seal area design (Phase II).</td>
</tr>
<tr>
<td>6</td>
<td>Debris from ATR/SOFC failure damages turbomachinery</td>
<td>Install protective screens and catch basins in flow path.</td>
</tr>
<tr>
<td>7</td>
<td>Adoption risk: Concept is perceived as too high-risk by aircraft manufacturers</td>
<td>Demonstrate insignificant deterioration over 600 hr and project to longer run times; Education campaign; buy in from RTRC.</td>
</tr>
<tr>
<td>8</td>
<td>Adoption risk: Capital and maintenance costs are too high compared to existing technology to encourage future development.</td>
<td>Design for simplicity of manufacture; Explore rapid prototyping to lower cost of ATR/SOFC; ID cost reduction strategies with industry partners.</td>
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</tbody>
</table>
Initial Risk Assessment

**Likelihood**
- Almost Certain
- Likely
- Moderate
- Unlikely
- Rare

**Consequences**
- Insignificant
- Minor
- Moderate
- Major
- Catastrophic

<table>
<thead>
<tr>
<th>Risk (start of project)</th>
<th>#</th>
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</thead>
<tbody>
<tr>
<td>ATR/SOFC Integration</td>
<td>1</td>
</tr>
<tr>
<td>High power density AND redox tolerance</td>
<td>2</td>
</tr>
<tr>
<td>Inadequate anode exhaust/thermal control</td>
<td>3</td>
</tr>
<tr>
<td>Excessive anode leakage</td>
<td>4</td>
</tr>
<tr>
<td>Component failure due to CTE mismatch</td>
<td>5</td>
</tr>
<tr>
<td>ATR/SOFC failure debris damages turbomachines</td>
<td>6</td>
</tr>
<tr>
<td>Manufacturers perceive concept as too risky</td>
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</tr>
<tr>
<td>Capital and maintenance costs too high</td>
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Task Outline & Technical Objectives

1. **ESPG System Modeling**: Develop models for predicting the performance of the full-scale system and bench demonstrator (Phase II)
   - RTRC Turbomachinery/generator models
   - UMD ATR/SOFC models
   - Sensitivity analysis of SP, SE, fuel cost
   - ID appropriate performance targets for cells and stacks in subsequent milestones

2. **High Power cell development**: Develop high power 25-cm² SOFC cells for ≤ 700°C operation.
   - Ni-GDC cell performance benchmarking – button cell
   - Cell manufacturing – develop 25-cm² cell manufacturing processes and demonstrate scalability to 100 cm².
   - Develop pressurized SOFC test rig and use it to measure performance of commercial GDC 81-cm² and Ni-GDC 25-cm² SOFC cells and stacks.

3. **ATR/SOFC modeling and design**
   - Design ATR and SOFC stack
   - Design low mass SOFC interconnects
   - Design integrated ATR/SOFC
Task Outline & Technical Objectives

4. ATR/SOFC Test Article Fabrication and Demonstration
   • Validate low mass interconnect design/sealing performance in 100-cm² commercial cells by building and testing a short stack (~3 cells) in UMD’s pressurized flow rig. Anode to cathode cross leaks < 1% at 400°C and 15 bar.
   • Manufacture ATR/SOFC test article (100-cm² commercial cells)
   • Develop interface for RTRC flow bench
   • Test 1.0 kWₑ ATR/SOFC in pressurized flow rig at RTRC
     ≥ 1.2 kWₑ/kg using commercial GDC cells and model-optimized interconnect plates
     Degradation < 2%/1000 hr

5. Technology to Market
   • T2M plan
   • Technoeconomic analysis – ESPG cost model
   • Develop IP strategy based on patent search
Technology-to-Market Approach

Commercialization plan

- Spin out unit of Ion Storage Systems (ISS). ISS, founded by Prof. Wachsman, is manufacturing ceramic solid-state batteries and looking to expand into SOFCs using similar fabrication techniques in its 20,000ft² facility.
  - Initial market: integrated power generation/storage
- RTX will own the integrated propulsion system and turbo-machinery, integrating an ISS SOFC product into a final product. RTX will provide the path to market through its Pratt and Whitney business.

<table>
<thead>
<tr>
<th>First Markets</th>
<th>Long-Term Markets</th>
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<tbody>
<tr>
<td><strong>Description</strong></td>
<td><strong>Primary power unit replacing a traditional APU on an SoA tube &amp; wing aircraft</strong></td>
</tr>
<tr>
<td>Integrated solid-state batteries</td>
<td>Central power plant for distributed &amp; AC integrated propulsion 150 pax single aisle</td>
</tr>
<tr>
<td>Backup generators (kW-scale)</td>
<td>Utility-scale power (MW-scale)</td>
</tr>
<tr>
<td>UAV and AAM propulsion</td>
<td></td>
</tr>
<tr>
<td>20 -50 PAX regional series turbo-electric power plant</td>
<td></td>
</tr>
<tr>
<td><strong>Performance Requirements</strong></td>
<td><strong>0.75 kWₑ/kg</strong></td>
</tr>
<tr>
<td>0.75 kWₑ/kg</td>
<td>0.75 kWₑ/kg</td>
</tr>
<tr>
<td><strong>Capital Cost Requirements</strong></td>
<td><strong>$1000/kW</strong></td>
</tr>
<tr>
<td>$1000/kW</td>
<td>$1000/kW</td>
</tr>
<tr>
<td><strong>Fuel Cost Requirements</strong></td>
<td><strong>$0.15/kWh</strong></td>
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<tr>
<td>$0.15/kWh</td>
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</tr>
<tr>
<td><strong>Time of Market Entry</strong></td>
<td><strong>6-10 years from inception</strong></td>
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<tr>
<td>4-6 years from inception</td>
<td></td>
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</table>
Needs and Potential Partnerships

‣ Anticipated needs following the completion of the award.
  – RTX capability to develop a multi-megawatt machine is not being addressed in this program but could provide further significant performance improvements.
  – Power electronics to integrate and regulate voltage and current from SOFC and generator.

‣ Capabilities that could be useful for other REEACH teams.
  – High power density SOFC technology
  – Pressurized fuel cell testing
  – Fuel cell and system modeling
https://arpa-e.energy.gov
## Power Density Summary

<table>
<thead>
<tr>
<th>Development Stage</th>
<th>Stack power density [W/cm²]</th>
<th>Specific power [kWₑ/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full System design</td>
<td>--</td>
<td>≥ 0.75</td>
</tr>
<tr>
<td>Phase I 25 cm² high power density short stack</td>
<td>2.0 @ 0.75 V/cell</td>
<td>≥ 1.6</td>
</tr>
<tr>
<td>Phase 1 Ni-GDC commercial cells for 1.0 kW demonstration stack</td>
<td>1.5 @ 0.75 V/cell</td>
<td>≥ 1.2</td>
</tr>
</tbody>
</table>