Development of Stable Solid Oxide Electrolysis Cells for Low-cost Hydrogen Production

Contract Number: DE-FE0032105

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Support: NASA, DOE

23rd Annual Solid Oxide Fuel Cell (SOFC) Project Review Meeting
Pittsburgh, PA
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DOE Project Manager: Drew O’Connell
Company Background

Utah, USA R&D/Manufacturing - 2017
• Office, laboratory, and manufacturing facility (24,000 ft²)
• NASA, DOE, DOD and commercial contracts
• Tape casting, cell and stack production, and testing
• End-to-end power to synfuels pilot plant

Solid Oxide Fuel Cell and Electrolysis Stacks
• Longest running solid oxide fuel cell & electrolysis group in world
• Only flight qualified, TRL 9 SOEC unit with active NASA demonstration on Mars
• 30kW/10kW and 20kW/10kW reversible SOC system test programs

Fuel Reformation and Generation
• Plasma Reformer - H₂ or syngas from flare gas; digester gas conversion; clean-up bio-gasification
• Fischer-Tropsch Reactors - Modular design for sustainable fuel production from H₂ and syngas
- A solid oxide electrolysis cell (SOEC) stack in a laboratory test bed
  - show improved performance over baseline stacks
    - robustness,
    - reliability,
    - endurance,
    - hydrogen purity, and
  - produce hydrogen at elevated pressure of 2 to 3 bar.
Project Goals

• **Improved performance over baseline**
  • Reproducibility and lower polarization by electrode modification

• **Long term stability**
  • Projected lifetime of > 40,000 hours

• **Robustness**
  • Capability for thermal cycling of a stack
  • Redox cycling of fuel electrode in a stack
  • Production of hydrogen at elevated pressure
Robustness

Redox Tolerant Fuel Electrode - Background
Mars OXYgen ISRU Experiment aka “The Oxygenator”

\[ \text{CO}_2 \rightarrow \text{CO} + \text{O}_2 \]

First of any kind of demonstration of In-Situ Resource Utilization (ISRU) technologies to enable propellant and consumable oxygen production from the Martian atmosphere - Currently onboard Perseverance Rover

MOXIE is a ~0.5% scale prototype of expected final O\textsubscript{2} production rate

TRL 9 SOEC unit

Solid Oxide Electrolysis (SOXE) Development Team

Supported by NASA through the Jet Propulsion Laboratory (JPL)
Flight Qualification

Baseline Performance
• 21 consecutive stacks built with aerospace quality standards and traceability having a maximum baseline performance of 1.6 ohm-cm² dry CO₂ and 99.9%+ O₂ purity

Cycling Performance
• 3 stacks with 21 cycles of identical test procedure having varying cycle-to-cycle flow rates and final cycle averages of 10.11 g O₂/hr production and 99.8% purity – Targets exceeded
• 1 stack to cycle 61 with >99.6% purity at a controlled production rate of 6 g/hr at 55g/hr feed

Structural Stability Testing
• No leak or significant performance change after 10kN crush testing
• Stacks tested to 25kN force with no crossover or external leakage
• Load to failure required 62.2kN (>30 margin of safety from design)

Shock/Vibe Testing
• Stacks vibrated at JPL and post vibe tested at OxEon
• No leak or significant performance change post vibe!
• No leak after shock testing, no significant performance change!

Cryo-Cycling
• Vibe stack cryo-cycled to -40°C (40 cycles), -55°C (3 cycles), -65°C
• Stack performance and purity unchanged in operational cycling post test
• Early MOXIE Test Stack:
  • 15 operational cycles - full thermal cycle with 120 min operation on dry CO₂
  • Dry CO₂ → O₂ production ~12% of initial

Electrolysis Cathode:
Ni-ceria electrode + Ni felt current collector

Dramatic degradation resulted from progressive oxidation front
Oxidation of Ni to NiO causes ~24% vol expansion, and in this case, irreversible damage to the electrode & current collector

MOXIE implemented recycle of produced CO to prevent cathode oxidation

NASA Support through JPL
Flight Test Success – First Ever ISRU Demonstration!

First 100 Sols!

- **Sol 5 “Aliveness Test”** Mon Feb 22, 2021
- **Sol 13 First run with Run Control Table (RCT)**
- **Sol 14 “Health Check” of heaters and compressor**
- **Sol 59-60 April 20, First Oxygen**
  - Produced 5.4 g O₂ pre-dawn, peak rate of 6 g/h (2 A current)
- **Sol 81 May 12, 2nd Oxygen**
  - Nighttime (early AM) operation
  - Produced 7 g O₂, 8 g/h peak
- **Sol 100 May 31 3rd Oxygen**
  - Mid-day operation with lower atmospheric density
  - Extended 8 g/h operation

11 Successful high purity (>99.6%) oxygen production runs on Mars to-date

NASA Support through JPL
Redox Tolerance for CO$_2$ Electrolysis (NASA SBIR)

Ni-based electrode
**Down-selected Composition**  
Ni-Ceria based (N85)

- Full Redox Cycle = 12 hours off load with dry CO₂ only feed
- kept at 800 °C to nearly fully oxidize the cathode material (Ni metal → Nickel-oxide)
- Load is reapplied
- No external reducing gas
• **Stack**: Short (20 min) and long (12 hrs) exposure to CO₂
• **Application of voltage** – full recovery of performance

NASA SBIR Funded
Cell test at PNNL using Redox Tolerant fuel electrode:

- Steam oxidation overnight
- Application of 1.3 V
- No external H₂ feed
- Full recovery of performance
Stack test at Colorado School of Mines:

- Stack in Lunar vacuum

- Power supply problem
  - Recycle H₂ stopped
  - Current to zero
  - Voltage dropped
  - Restored power supply
  - Stack performance recovery
Electrode Improvement - DE-FE0032105

Focus: Address known/suspected degradation mechanisms
# Integrated Approach to Addressing SOEC Degradation

<table>
<thead>
<tr>
<th>No.</th>
<th>Degradation mechanism</th>
<th>Effect</th>
<th>SOEC component</th>
<th>Activity</th>
<th>Project Support</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cr transport from interconnect</td>
<td>Poisons active electrochemically sites</td>
<td>O₂ electrode</td>
<td>Poisoning Effect (PNNL) Spinel Coating</td>
<td>DOE/NETL NASA Phase II-E</td>
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<tr>
<td>2</td>
<td>Perovskite composition instability over time</td>
<td>Catalytically inactive and electrically resistive grains/Non-catalytic secondary phases</td>
<td>O₂ electrode / current collector</td>
<td>Composition modification</td>
<td>DOE/NETL NASA Phase II-E</td>
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<tr>
<td>3</td>
<td>SiO₂ migration from seal</td>
<td>Contaminates electrodes</td>
<td>O₂ electrode Fuel electrode</td>
<td>Poisoning Effect (PNNL)</td>
<td>DOE/NETL NASA Phase II-E</td>
</tr>
<tr>
<td>4</td>
<td>Cation diffusion</td>
<td>Formation of more resistive phases</td>
<td>Electrolyte CeO₂ barrier</td>
<td>Process modification</td>
<td>DOE/NETL NASA Phase II-E</td>
</tr>
</tbody>
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Oxygen Electrode Interface Improvement

SDC Barrier layer

- Improve sinterability to lower sintering temperature
- Eliminate interface reaction between ceria and zirconia
- Additional modification underway

Standard SDC  >150 °C Reduction

This Project + NASA SBIR
• Post-sintering surface treatment by infiltration
  • Fuel electrode polarization varies with type of treatment

Work done at Yildiz Group (MIT)
Oxygen electrode surface modification by infiltration (MIT, OxEon - Non-Federal project)
Interim Validation: 10 cell stack

Incorporating Barrier Layer/ Electrode Modification

Non-Federal Support

- Low degradation after ~ 800 hrs
- <1% / 1000 hr
Button Cell Operation at Elevated Pressure

- PNNL
  - Test fixture construction is complete.
  - SOP was sent out for review.
  - Fixture validation to begin after SOP is approved.

- Elevated pressure BC tests will start with PNNL house-made cells after SOP approval and system verification.
- OxEon Cell tests to follow
Oxygen Production (Seal Validation)

• **High Purity O₂ on Mars**
  • External to stack Mars ambient ~ 7 millibar

• **Oxygen production at pressure (steam electrolysis test at CSM in vacuum chamber)**
  • Stack in vacuum
  • H₂ production at 1 bar
  • O₂ production up to 3.6 bar via electrochemical compression
The effect of Cr impurities on the oxygen electrode in SOEC mode will be investigated.

- OxEon delivered cells to PNNL for testing
  - Two compositions of air electrode

- PNNL starting tests in presence of Cr
  - 1 cell of each set without Cr
  - 1 cell of each set with Cr
• **Process development for improving spinel density**
  • Ongoing
Multiple projects to provide complementary modification

Redox tolerance validated for steam electrolysis
- Oxidized Ni electrode recovery without the need for hydrogen in inlet

Electrode materials modification - validation in progress
- Composition to improve thermochemical stability
- Surface modification for improving catalytic property

Investigation of poisoning effect - ongoing

Pressurized tests: steam electrolysis
- button cells - to begin shortly
- Stack - in Year 2
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