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

Project Start: October 1, 021

Contract Number: DE-FE0032105

OxEon Energy, LLC

North Salt Lake, UT 84054

PI: Dr. S Elango Elangovan

Subcontractor: Pacific Northwest National Laboratory

PNNL Technical Lead: Dr. Olga Marina

November 18, 2021

Pacific Northwest NATIONAL LABORATORY

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2021 SOFC Project Review Meeting – Virtual

OxEon Technology Background

OxEon Energy Company Overview

- North Salt Lake, UT R&D and Pilot Manufacturing Facility
  - New 24,000 ft^2 office, lab, and production areas
    - Material synthesis, Tape casting, cell and stack production, and testing; Synthetic fuel pilot plant
- 34 employees and growing
- Founded in 2017

  - Employee Owned and led by Joseph Hartvigsen and Dr. S. Elango Elangovan
    - 30+ years experience in OxEon's core technology development

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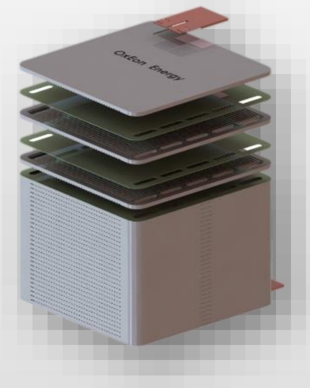


Solid Oxide Fuel Cell and Electrolysis Stacks

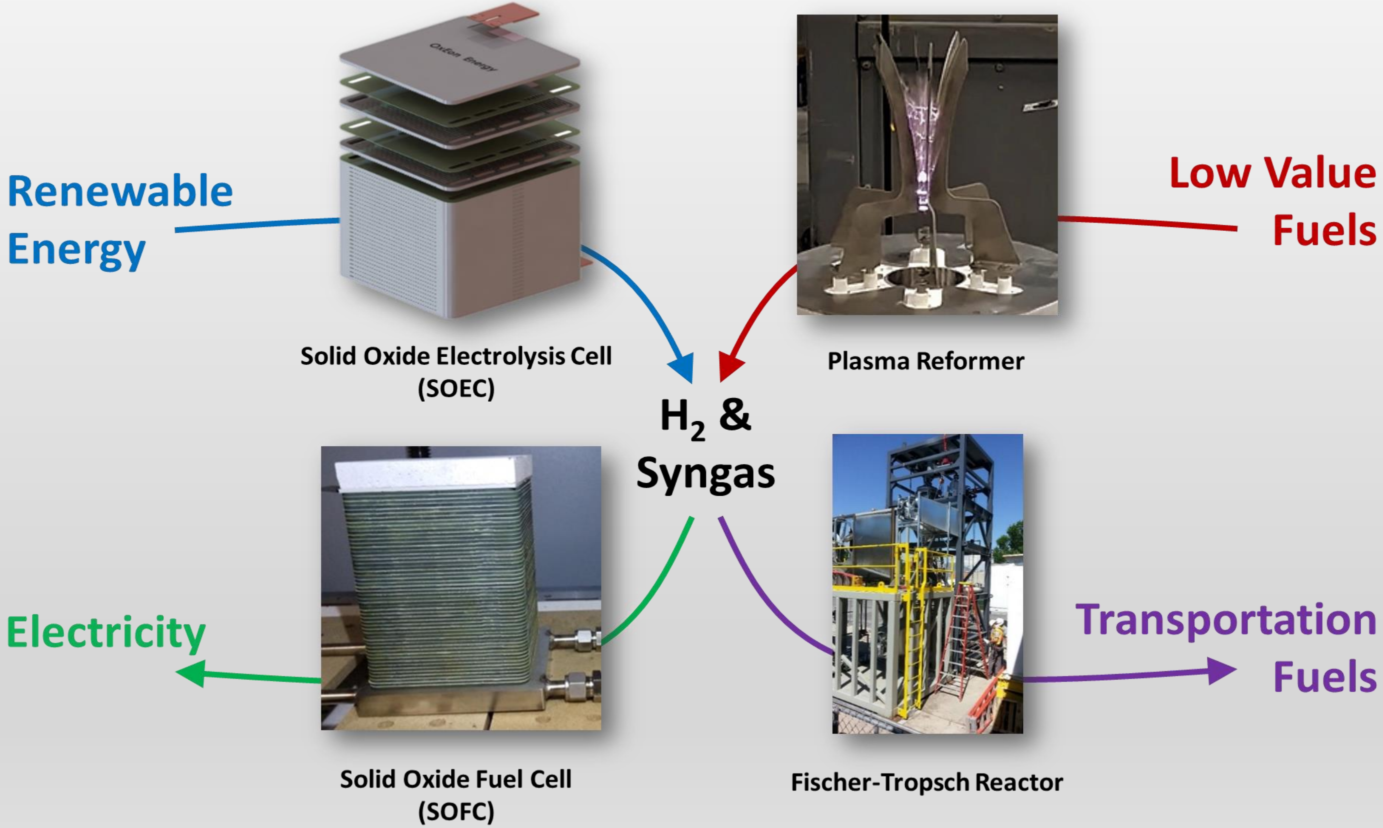
- Longest running solid oxide fuel cell & electrolysis group
- Only flight qualified, TRL 9 SOEC unit in history
- 30kW/10kW reversible system test program in process

Fuel Reformation and Generation

- Plasma Reformer – H_2 and Syngas for flare curtailment
- Fischer-Tropsch Reactors – Modular design for transportation fuel production from H_2 and Syngas

End-to-end **power to synfuels pilot plant** in operation

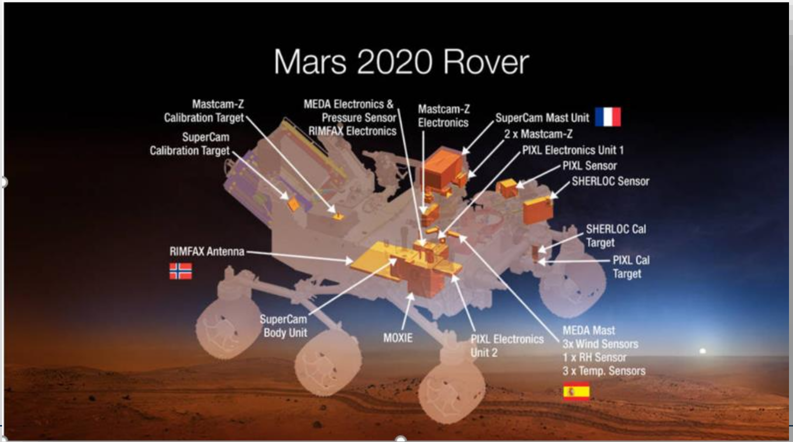
Energy Cross-Sector Coupling

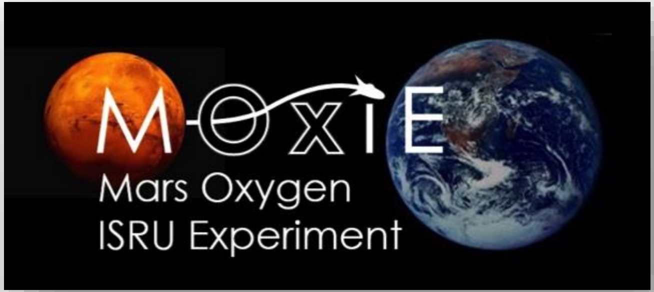


OxEon Technology Space

SOEC for Space Applications

MOXIE: Solid Oxide Electrolysis on Mars





1 of 7 major experiments to fly on the $2.1 billion Mars 2020 Mission

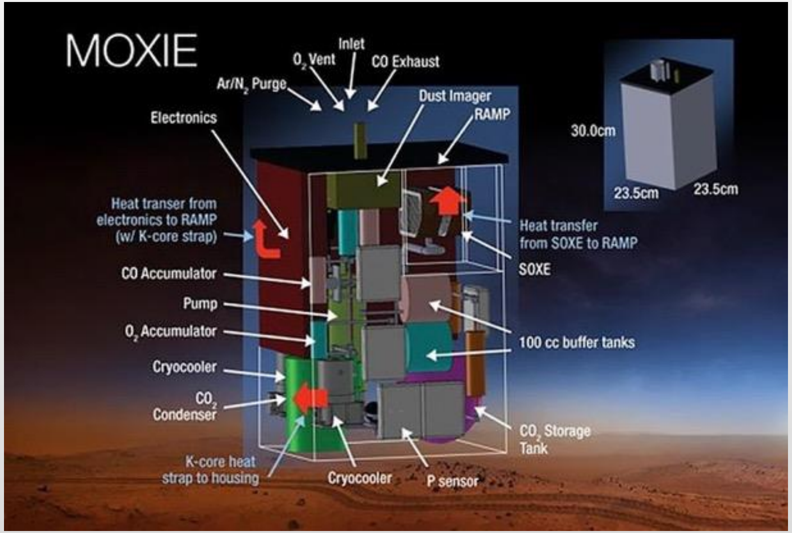
Demonstration of In-Situ Resource Utilization (ISRU) technologies to enable propellant and consumable oxygen production from the Martian atmosphere

First oxygen production on 20 Apr 2021. Four additional tests to-date matching model/lab results

TRL 6 to 8 in 24 months. With successful Mars Operations, **TRL 9 reached** for first time in SOEC

Propelled OxEon's manufacturing capabilities and interest from aerospace and defense markets

MOXIE's Formidable Technical Targets



- 20+ full operational cycles – 10 preflight, 10+ mission - Op cycle = 2 hr heat up from ambient to 800 °C; 1 hr operation; and cool down
- 60 full operational cycles for proof of extensibility
- Oxygen Purity: 99.6%+ at end of life
- Seals operating against Mars near vacuum
- Capability to cycle to -65°C proof temperature
- Withstand 8 kN compressive force
- Withstand flight shock and vibe requirements (PF +3dB)
- Operate with dry CO_2 and avoid carbon

Completed five operational cycles on Mars meeting oxygen purity target

Project Objectives

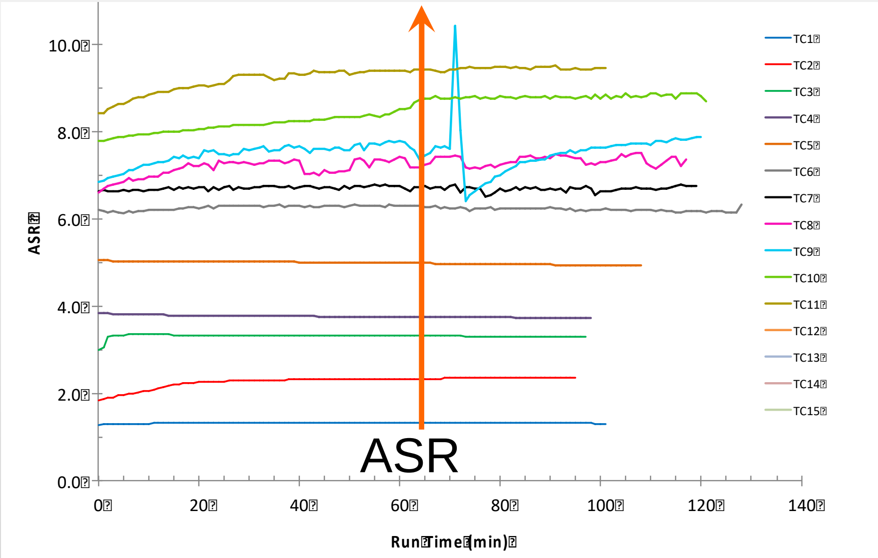
DE-32105 Started on 01 Oct 2021

- Improve performance and reduce degradation through modification to baseline materials
- Demonstrate thermal cycling capability of stacks
- Demonstrate fuel electrode redox tolerance
- Evaluate oxygen electrode contamination effect
- Evaluate fuel electrode contamination effect
- Demonstrate hydrogen production at ~ 2 barg pressure
- Task integration with recent/on-going projects

NASA SBIR Project Foundational Results

- Relevant to Dry CO_2 Electrolysis
  - Demonstrated redox recovery without the use of reducing gas
  - Rapid thermal cycle capability
  - Combined redox-thermal cycle capability

Consequences of Oxidation – early MOXIE stack test



- STK-007 Operational History
  - 15 cycles, full thermal cycle with 120 min operation on dry CO2
  - Dramatic degradation suggestive of progressive oxidation front

15 cycles in dry CO2 => performance ~12% of initial

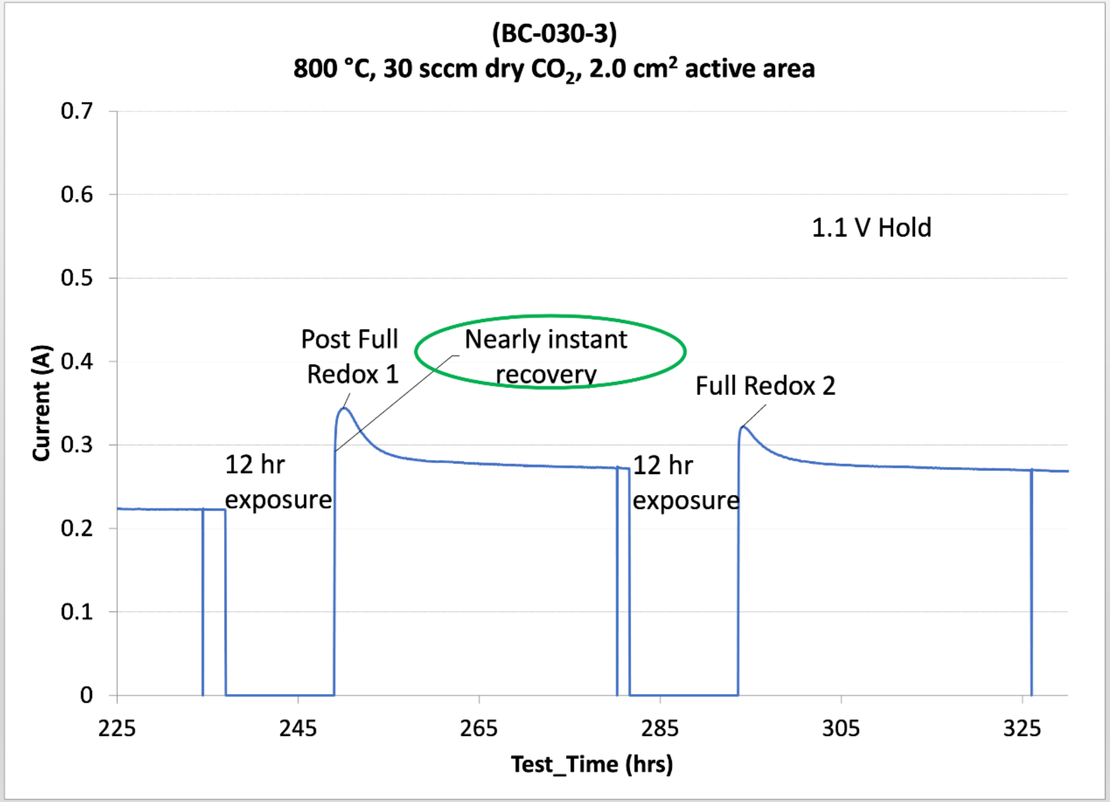
- STK-007 Post Test Examination
  - Progressive oxidation front confirmed
  - Non-conductive cathode and current distribution layers

Product CO recycled in MOXIE

Steam/CO_2 Redox Tolerance Approach

- Use of catalytic Ni based fuel electrode
  - Ni-ceria cermet
  - Inhibit coarsening by steric hindrance
  - Redox tolerance by alloying for enhanced reducibility
  - Surface catalyst for augmented electrochemical performance
- This combination also improved thermal cycle capability

Oxidized Cathode Instantaneous Recovery



- Cathode exposed to dry CO_2 for 12 hours
- Near instant recovery upon application of voltage
  - No reducing gas provided
- Similar recovery after short term (20 min) exposure to dry CO_2

Performance recovery without external reducing gas

Button Cell Rapid Thermal Cycling and Redox Capability

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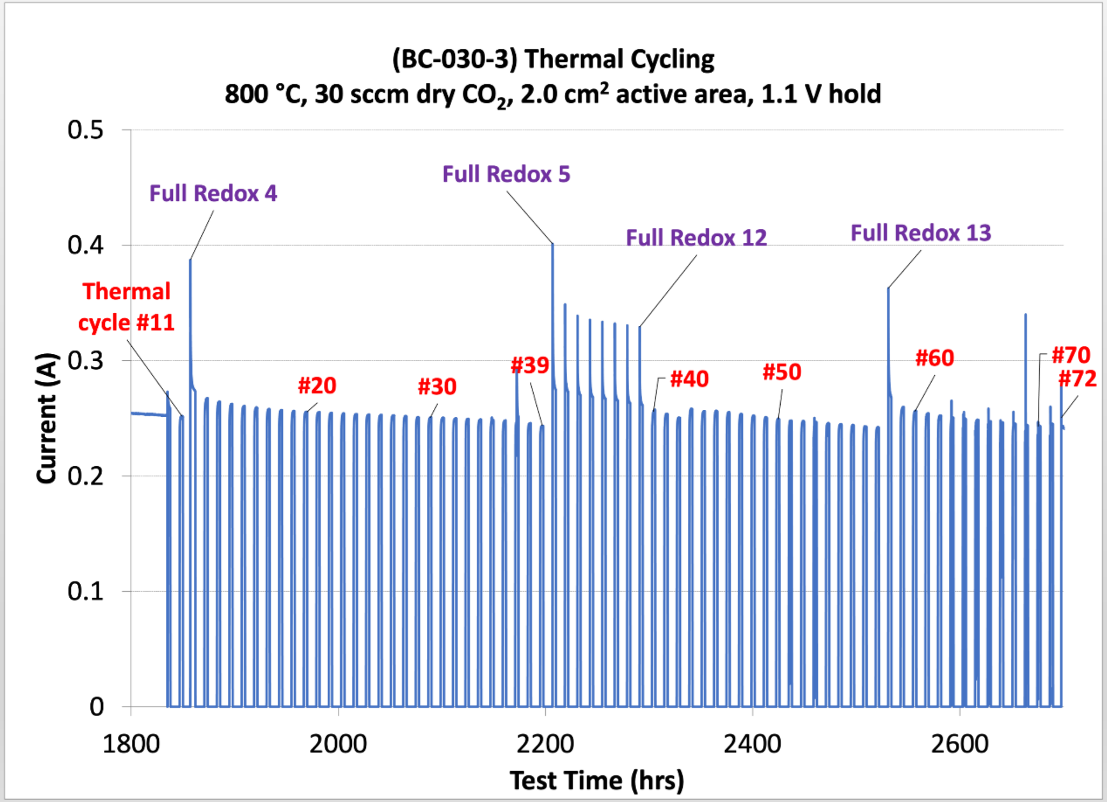
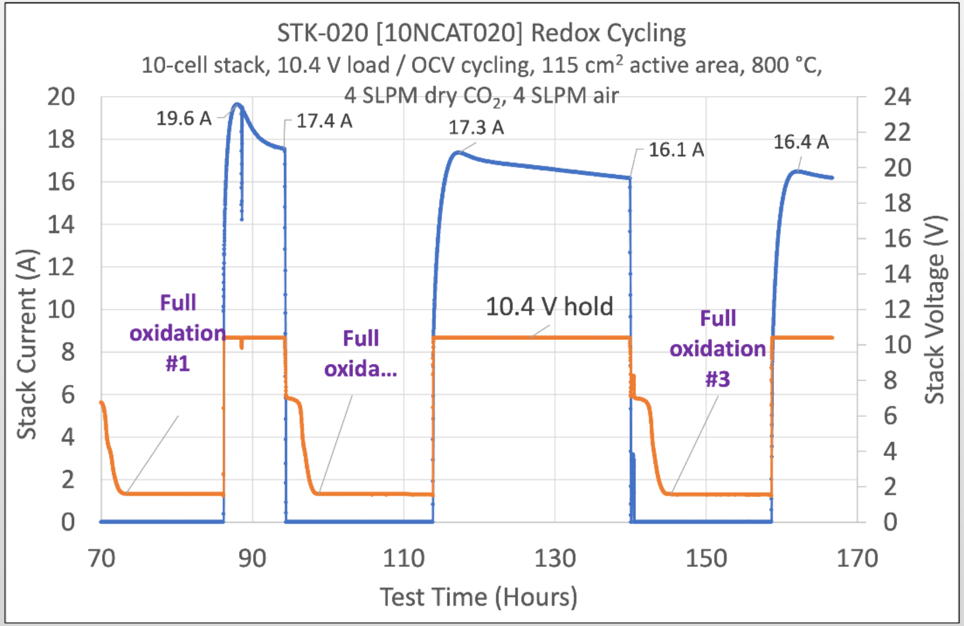


- Thermal cycle at **15 °C/min heating rate**
- Total 72 rapid thermal cycles
- Only CO_2 flow during thermal cycle
- 13 Full redox cycles (long exposure to CO_2 and application of voltage for recovery)

Time dependent degradation will be addressed in this project

10-cell stack: Redox recovery



Stack performance recovers after redox cycle in dry CO_2 without using a reducing gas

Thermal/Redox Cycles in CO_2 - Stack

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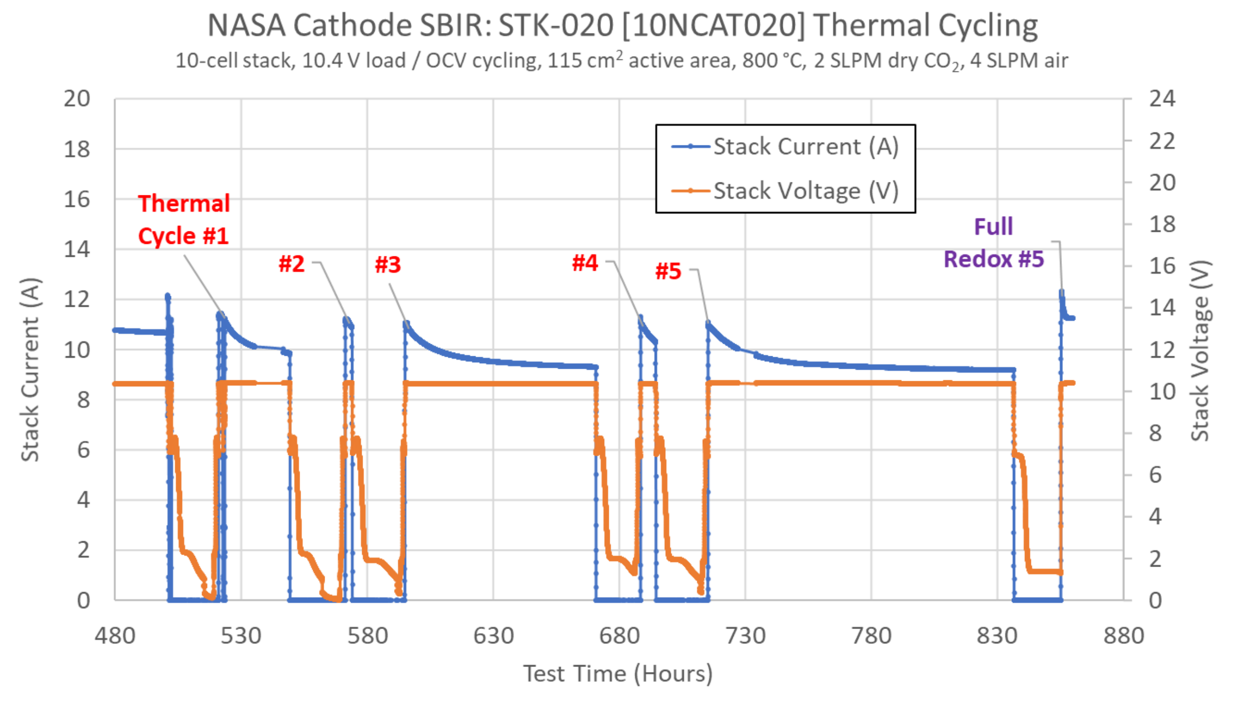
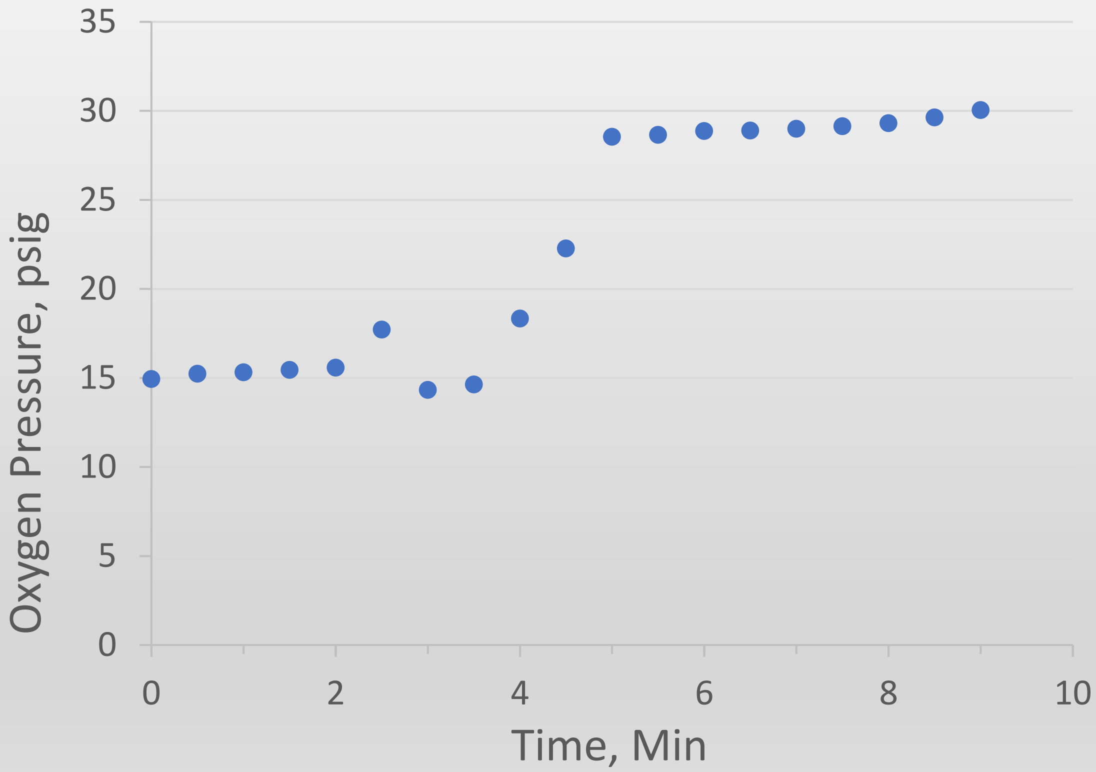


Stack stability demonstrated

- 400-hour test sequence
- 5 thermal cycles (in dry CO_2)
- 5 redox cycles

Thermal cycle in dry CO_2 also introduces redox cycles

Seal Capability at Pressure



- Steam electrolysis
  - (NASA Lunar application)
    - Electrochemical Compression of Oxygen to 2 barg
  - Mars MOXIE stack
    - ~ 1 bar inside stack and 7 millibar outside the stack
    - O_2 production ~100% purity

Project Objectives (DE-32105)

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Objective	DOE Project Focus
Improve performance and reduce degradation	Extend fuel and oxygen electrode advances from ongoing projects
Demonstrate thermal cycling capability of stacks	Button cells and stack testing
Demonstrate fuel electrode redox tolerance	Extend dry CO_2 capability to steam electrolysis
Evaluate oxygen electrode contamination effect	Cr tolerance of oxygen electrode
Evaluate fuel electrode contamination effect	Effect of Si from the seal
Demonstrate hydrogen production at ~ 2 bar	Eliminate need for first stage compressor

DOE project tasks integrate with recent/on-going projects (NASA SBIR Phase II-E awarded)

Project Schedule

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01 Oct 2021

Task	Task List	Year 1				Year 2			
		Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
1	Program Management and Planning	■	■	■	■	■	■	■	■
2	Electrode Characterization	■	■	■	■				
	Oxygen Electrode / Current Collector Evaluation								
	Interface Improvement								
	Fuel Electrode / Current Collector Evaluation								
3	Electrode Catalyst Evaluation				■				
4	Button Cell Characterization – Effect of Operating Condition					■	■		
5	Fuel Electrode Redox Testing					■	■	■	■
6	Button Cell Thermal Cycling					■	■		
7	Short Stack Testing							■	■
	Long term Testing								
	Pressurized Operation								
	PNNL Tasks								
1	Pressurized Testing (Button Cells)		■	■	■				
2	Fuel Electrode Contaminant Effect				■	■	■		
3	Oxygen Electrode Contaminant Effect					■	■	■	
4	Redox Characterization						■	■	■

Proposed Milestones

Quarter	Milestone
Y1-Q2	Selection of electrodes, catalyst compositions and processing conditions to achieve degradation rate of 1%/1,000 hours
Y1-Q4	Determination of effect of operating conditions on cell degradation
Y2-Q2	Redox and thermal cycle testing confirm performance loss <1% after 5 cycles each
Y2-Q3	P&ID, HAZOP document and photos of the test stand modifications
Y2-Q4	Stack degradation of <2%/1,000 hours. Hydrogen production at elevated pressure
Y2-Q4	Report detailing 2 – 3 barg hydrogen production

Thank You

Additional Info:
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