Solid Oxide Technology
Role in Energy Applications

Benchmarking Water Splitting Technologies Workshop

21September 23

S. Elangovan and Team

OxEon energy
Beyond Current Potential

Company Background

N. Salt Lake, Utah

R&D/Manufacturing – Founded 2017

Team: SOFC/SOEC for 35 years

Aerospace and Commercial Terrestrial Applications

- OxEon's core technology was flight proven through NASA aboard the Mars Perseverance Rover
- Department of Energy for projects in sustainable fuel production for terrestrial applications
- NASA for continued development for space applications
- Department of Defense funding for programs power and fuels production
- Commercial contracts for fuel, power and electrolysis systems

Solid Oxide Technology for Space Exploration

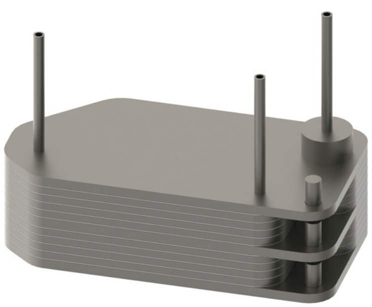
NASA funded flight program

- Only flight qualified SOEC stack in history
- Only TRL9 SOEC device in history
- First production of oxygen from the Mars Atmosphere

MOXIE SOXE TEAM:

- **MIT:** Program Prime and Science Team Lead
- **JPL:** Systems integration
- **OxEon:** Stack development and production
  - **TRL3 to 6 in 18 months!!**
  - Hermetically sealed, ruggedized stack capable of withstanding launch, entry, descent and landing

Image credit NASA/JPL-Caltec



Projects with NASA for Next Generation

- **Mars:** Oxygen and Methane Production from co-electrolysis
- **Lunar:** Liquid Propellants for LH_2/Lo_x-Fueled Cislunar Transport
- **SBIR**: Cathode Development for Redox Tolerance

Flight Test Success – First Ever ISRU Demonstration

- 16 total operation cycles completed on Mars at time of presentation (Mission Life Success!)
- >99.6% Oxygen purity
- Operations have spanned the climactic extremes of the Mars' year.
- All cycles performed as predicted: lab & models
- The MOXIE Mission continues through Sept 2023
- Basis for a Lunar and a Martian ISRU

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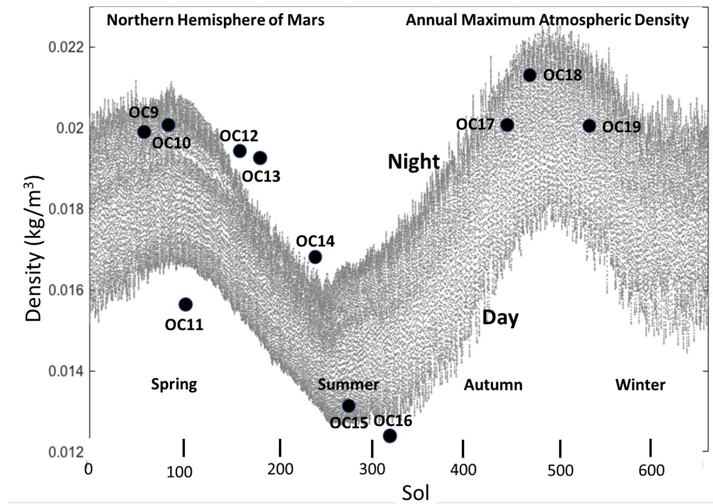
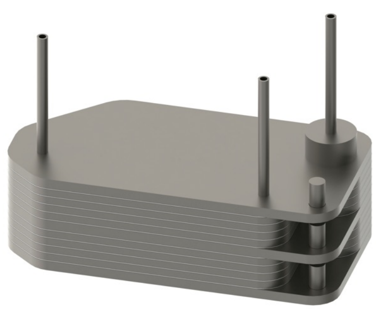




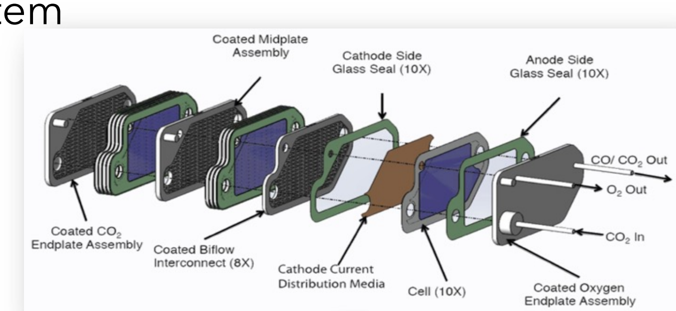
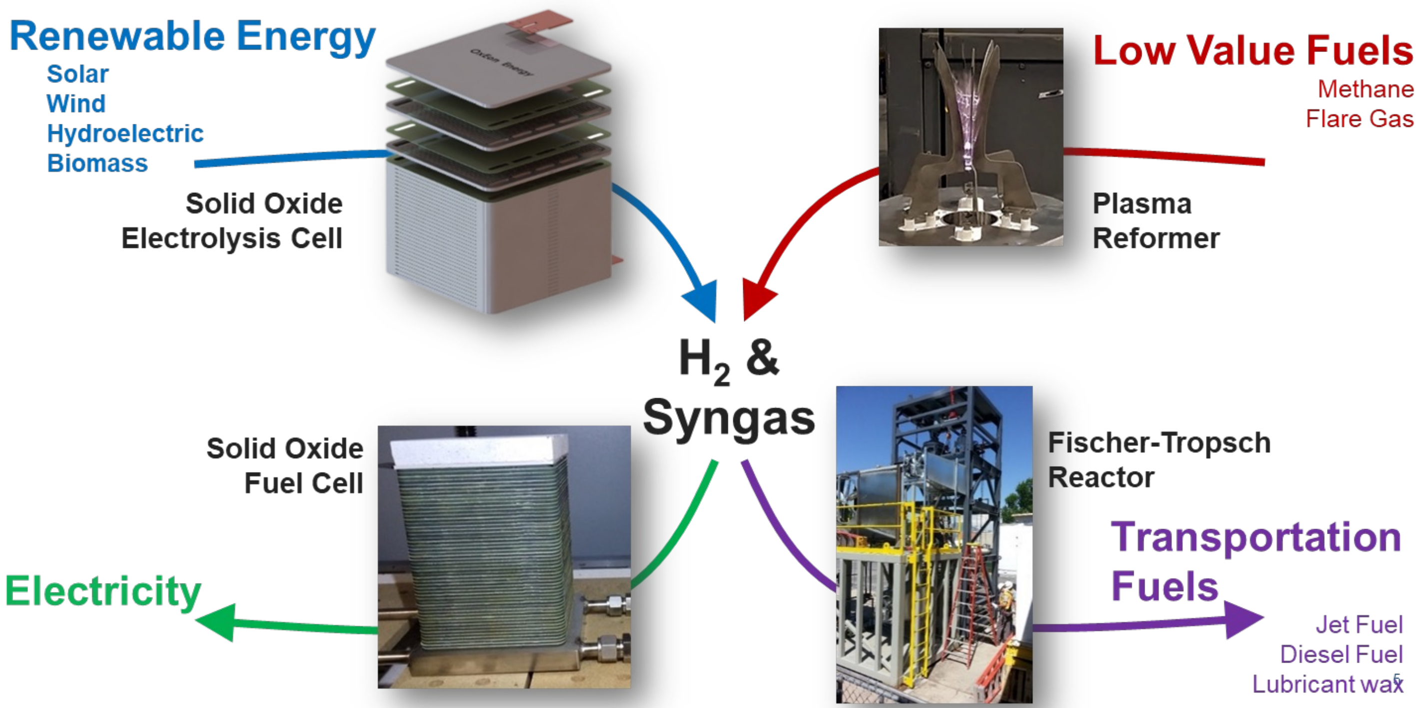


Image credit NASA/JPL-Caltech

OxEon Focus

Enabling Cross-Sector Energy Conversion

SUSTAINABLE AVIATION FUEL | IN SITU RESOURCE UTILIZATION PROPELLANTS | BIOGAS PROCESSING



SOXE For Space

- **MOXIE:** Flight demonstration aboard the Mars Perseverance Rover producing O_2 and CO/CO_2 from the Mars ambient air (Dry CO_2 Electrolysis)
- **NextSTEP:** Oxygen and methane production from co-electrolysis for full-scale Martian Mission (Co-Electrolysis)
- **Tipping Point**: Liquid propellant production for LH_2 /LO_x cislunar transport (Steam electrolysis)
- **SOFC**: Same stack run in reverse as fuel cell for power production

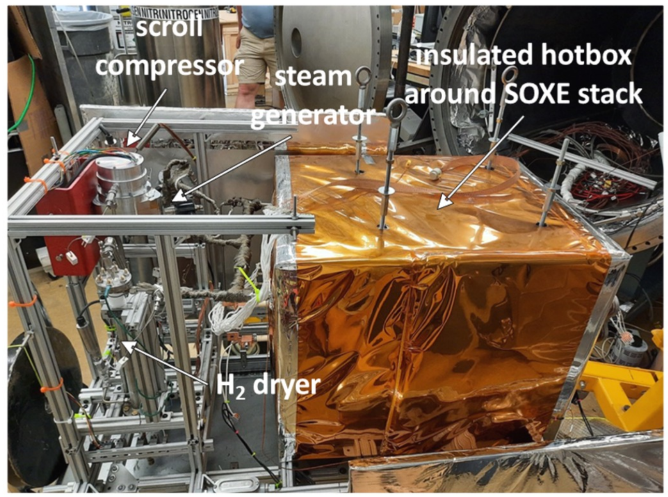
Lunar ice processing demonstration unit sponsored by a Tipping Point award to OxEon and Mines through NASA's Moon to Mars Technologies initiative

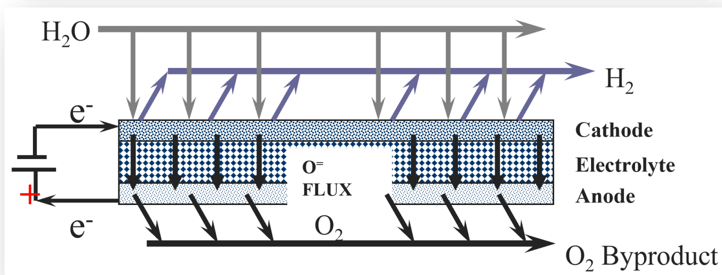
Objectives

Demonstrate high temperature SOXE propellant production from H_2O

Thermally integrated BOP

System architecture optimization and technoeconomic analysis





Program Accomplishments

Integrated breadboard system tested at relevant conditions

Moved technology from a TRL 4 to TRL 5

TEA indicates economically viable propellant production

NASA Contract: 80LARC20C0001

Program Accomplishments (Testing Completed 30 June 2022)

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Demonstrated system performance metrics:

- H_2 production at ~**2.8 kg/day** (stack current = 49 A, H_2O conversion = **99%**)
  - Exceeded performance threshold of 1.5 kg/day by nearly 90%!
- O_2 produced at pressures up to **3.6 bara**
  - Exceeded target threshold of 1 bara
    - **O_2 production to 22.8 kg/day**, nominal at peak current
- System specific power **average 46.5 kWh/kg H_2 for 2 hours** (excluding heat tracing steam lines)
- Demonstrated an **ISRU stack scale-up of 33x** over MOXIE stack

NASA Contract: 80LARC20C0001

Martian Demonstration System: Program Objectives

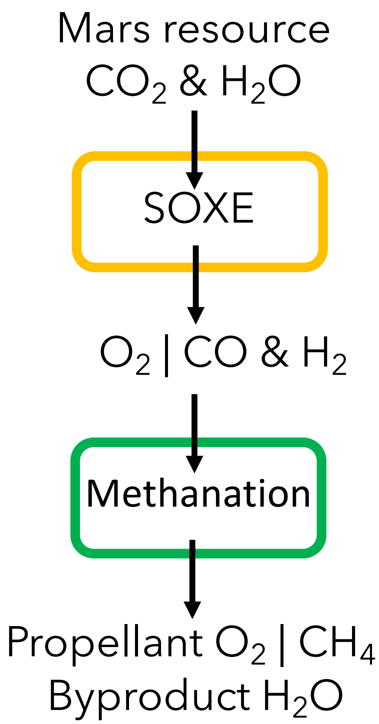
Martian ISRU demonstration system sponsored by a NASA Next STEP award and tested at Jet Propulsion Laboratory

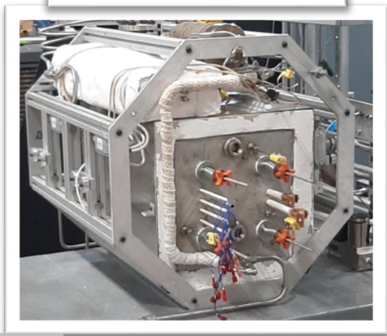
Objectives

Design integrated system to produce high purity O_2 and methane from CO_2 and H_2O

Operate SOXE for dry CO_2, water electrolysis, and co-electrolysis of steam and CO_2

Design ISRU variant stack with internal O_2 collection port





Program Accomplishments

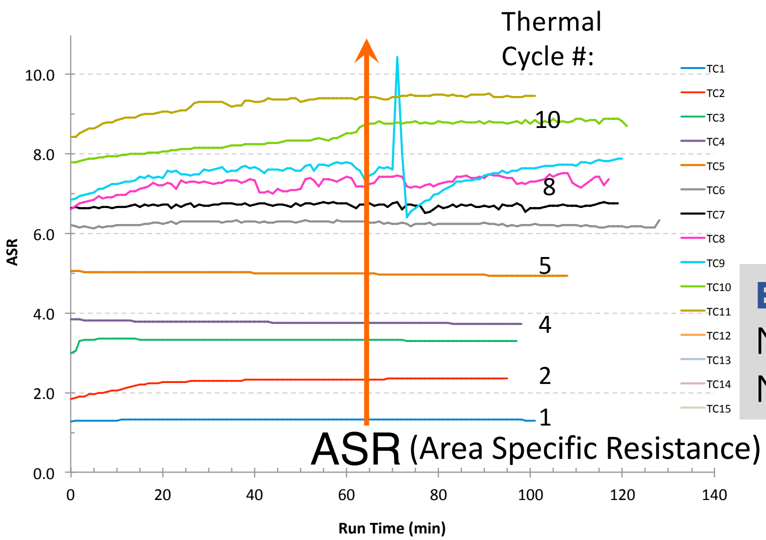
Design mission scale stacks with capacity for 675 g/hr O_2 with purity >99.6%

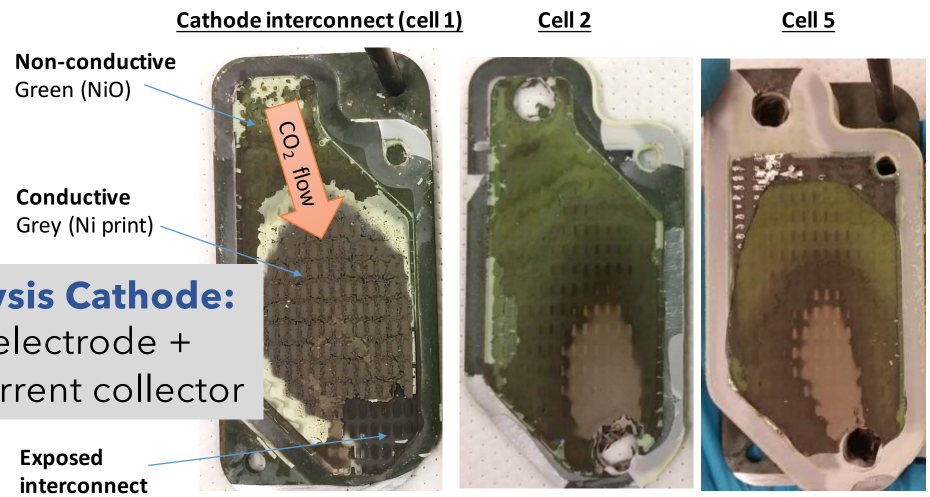
Design full scale methanation reactor for CH_4 production rate of 169 g/hr

Integrated SOXE/methanation prototype test in JPL Mars chamber for TRL6

NASA Contract 80HQTR19C0006

Cathode Challenge for MOXIE: Oxidation in dry CO_2





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

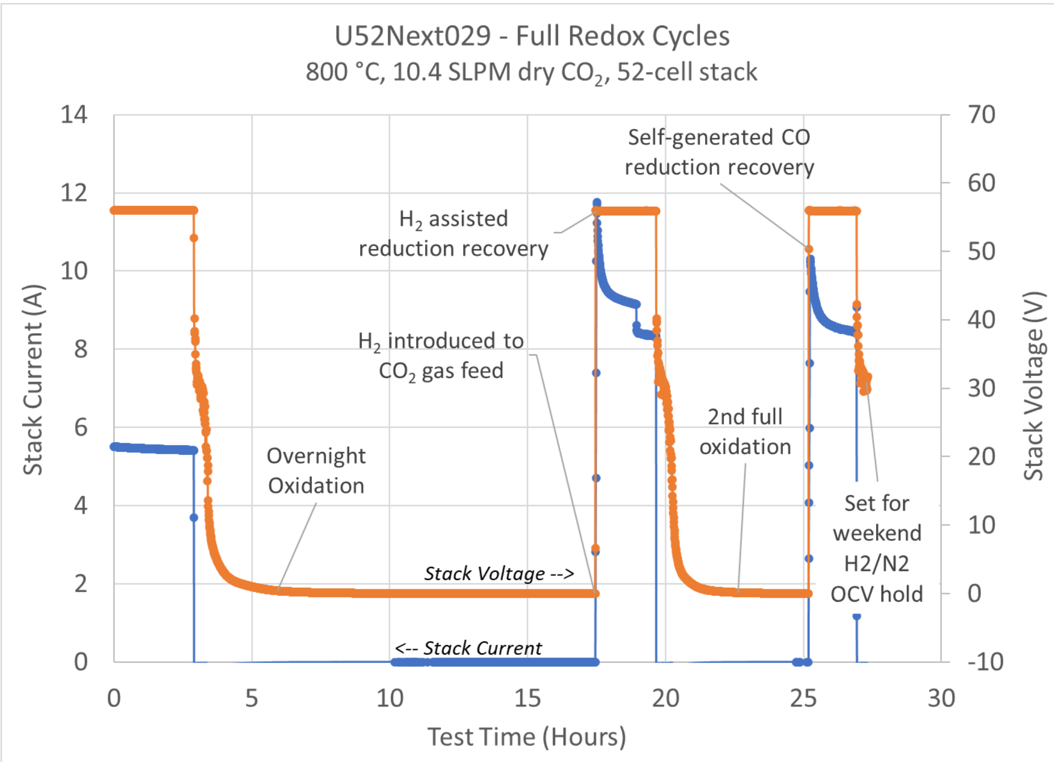
- Early MOXIE Test Stack:
  - 15 operational cycles - full thermal cycle with 120 min operation on dry CO_2
  - Dry CO2 → O2 production ~12% of initial

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

Cathode Challenge for MOXIE: Oxidation in dry CO_2



- 52-Cell Stack: kW class – CO_2 Electrolysis
- Full Recovery after overnight oxidation in CO2
- No difference in performance with and without H2 in the feed gas

NASA SBIR contract: 80NSSC19C0114

NASA Contract 80HQTR19C0006

Ongoing Other Activities

NASA:
- Post MOXIE Funding supporting Lunar and Martian applications
- Materials Development for redox tolerance, performance stability
  - Redox tolerance for CO2 electrolysis

Air Force Research Laboratory:
- STTR Phase II for eVTOL application (ammonia/air)
- Fuel Cell for Space Vehicles (unconventional fuel and oxidant)

Naval Research Laboratory:
- On ship jet fuel production from sea water (CO_2 capture + H_2 → JP fuel)

Department of Energy
- Electrolysis demonstration projects with INL Multiple solid oxide fuel cell and electrolysis development programs
- Redox tolerance, pressurized operation
- Full technology suite system for conversion of biomass CO_2 to fuel

Commercial:
- Microgrid applications
- Chemical weapons destruction

Ongoing Advances in SOEC Technology

2023 DOE HTWS Benchmarking Workshop

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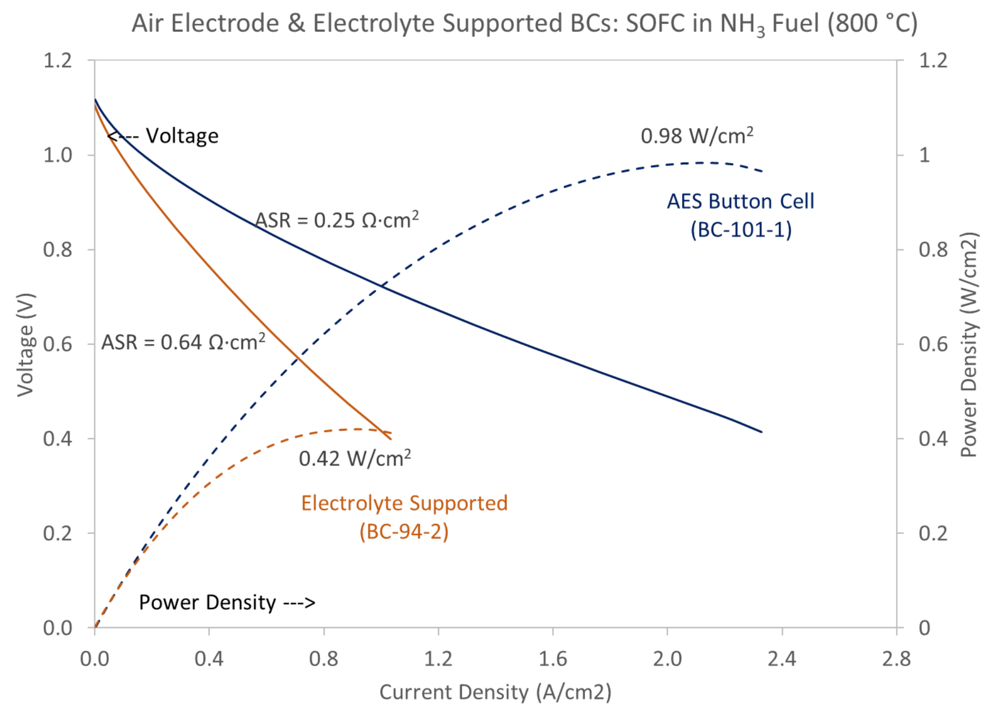
Air Electrode Supported Button Cell Testing (Lightweight Focus)

AES Button cell for Weight Reduction (eVTOL); ammonia fuel

- Screen printed anode
- Infiltrated cathode barrier layer + LSCF
- ~70 µm ScSZ electrolyte

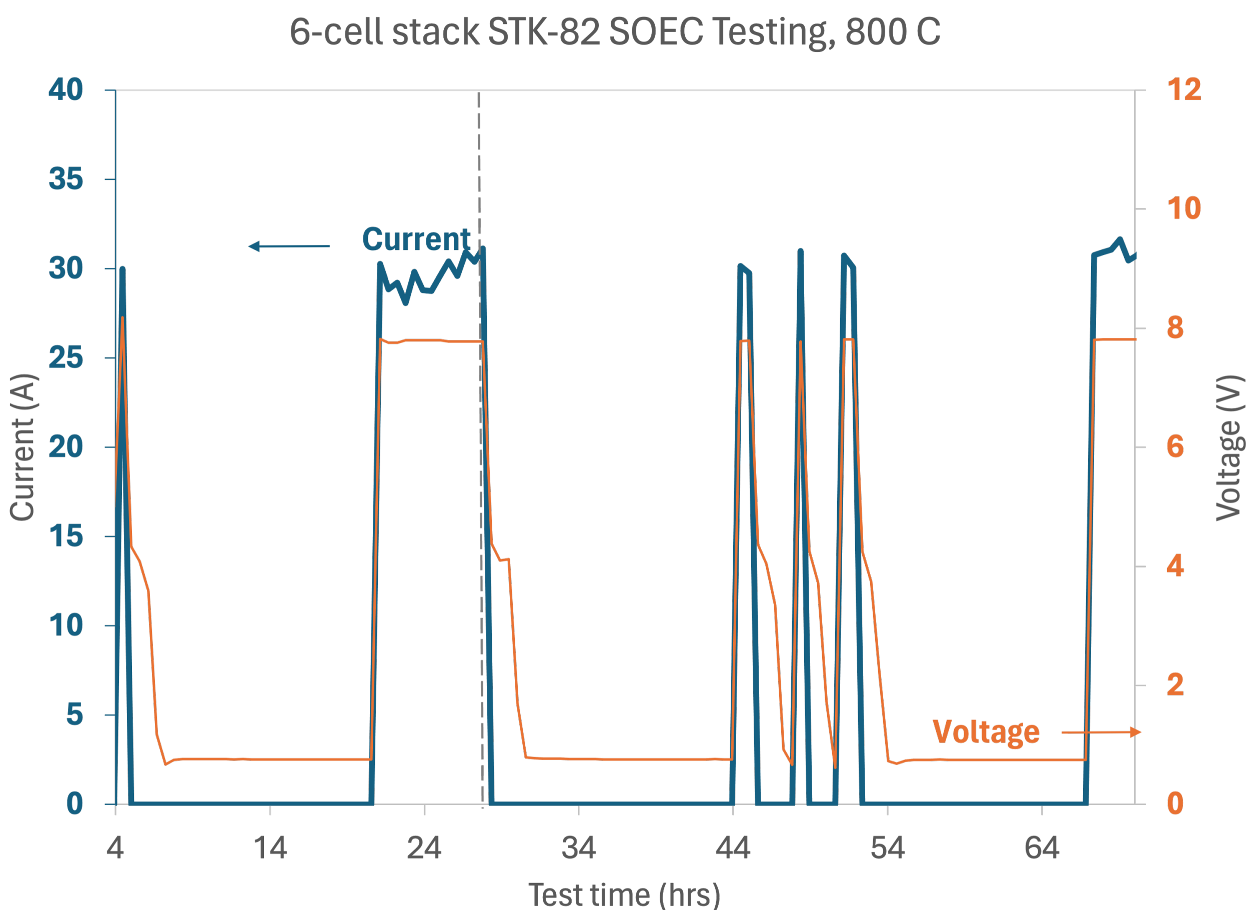
Fuel Feed (sccm)	Current Density (mA/cm^2)	ASR ($\Omega \cdot cm^2$)	Ro ($\Omega \cdot cm^2$)	Rp ($\Omega \cdot cm^2$)
30 H_2 /30 N_2	890	0.29	0.14	0.14
45 H_2 /15 N_2	1040	0.25	0.14	0.11
60 NH_3	1100	0.25	0.14	0.11
45 H_2 /15 N_2	845	0.34	0.22	0.12

Gamry potentiostat measurements taken at 0.7 V



Air Force STTR: FA864922P0792
Research Institution: PNNL
CRADA Partner: DOE-NETL

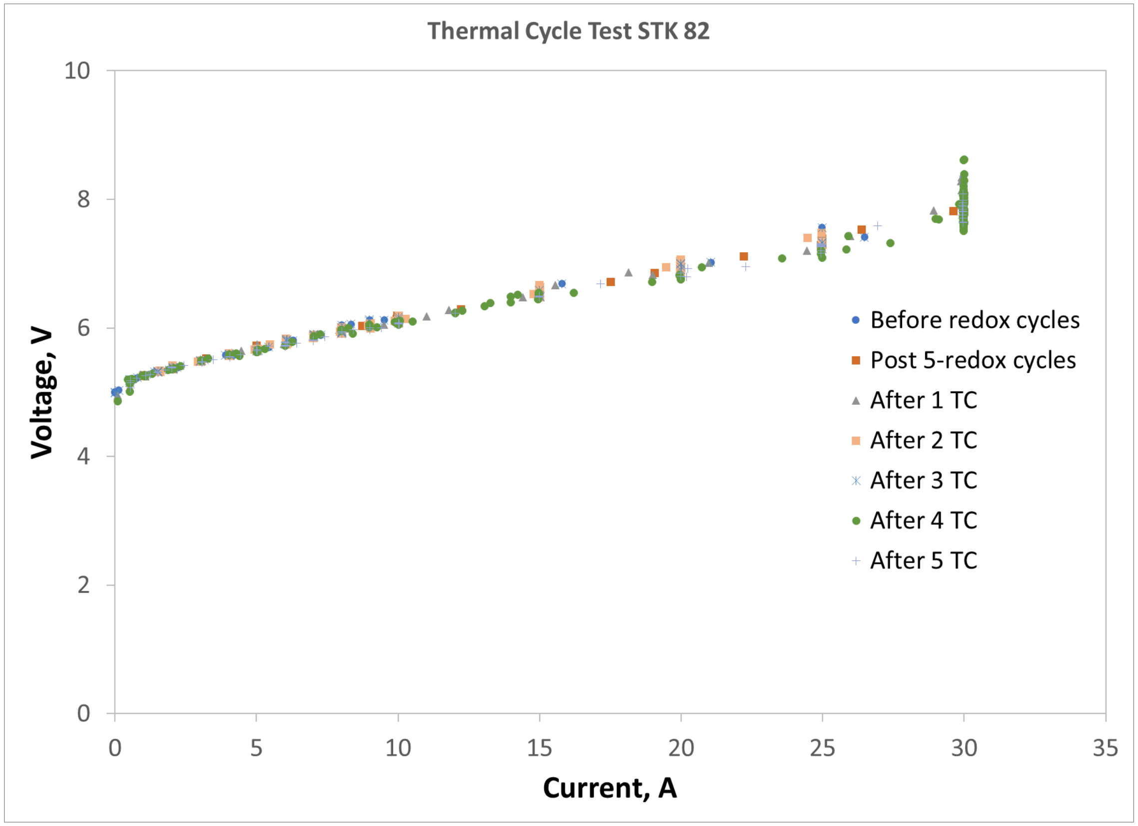
Redox Cycling



- H2 in feed is turned off after initial testing
- Stack left at OCV for oxidation of Ni-cermet electrode (overnight)
- Voltage drop indicated electrode oxidation
- Applied voltage (1.3 V/cell) without adding hydrogen
  - Complete recovery of performance

DOE-NETL Contract: DE-FE0032105

Thermal Cycling



Stable performance after deep thermal cycles

Performance recovery after thermal cycling demonstrates robustness of the stack and seals.

DOE-NETL Contract: DE-FE0032105

Additional Reversibility Testing + Final Redox

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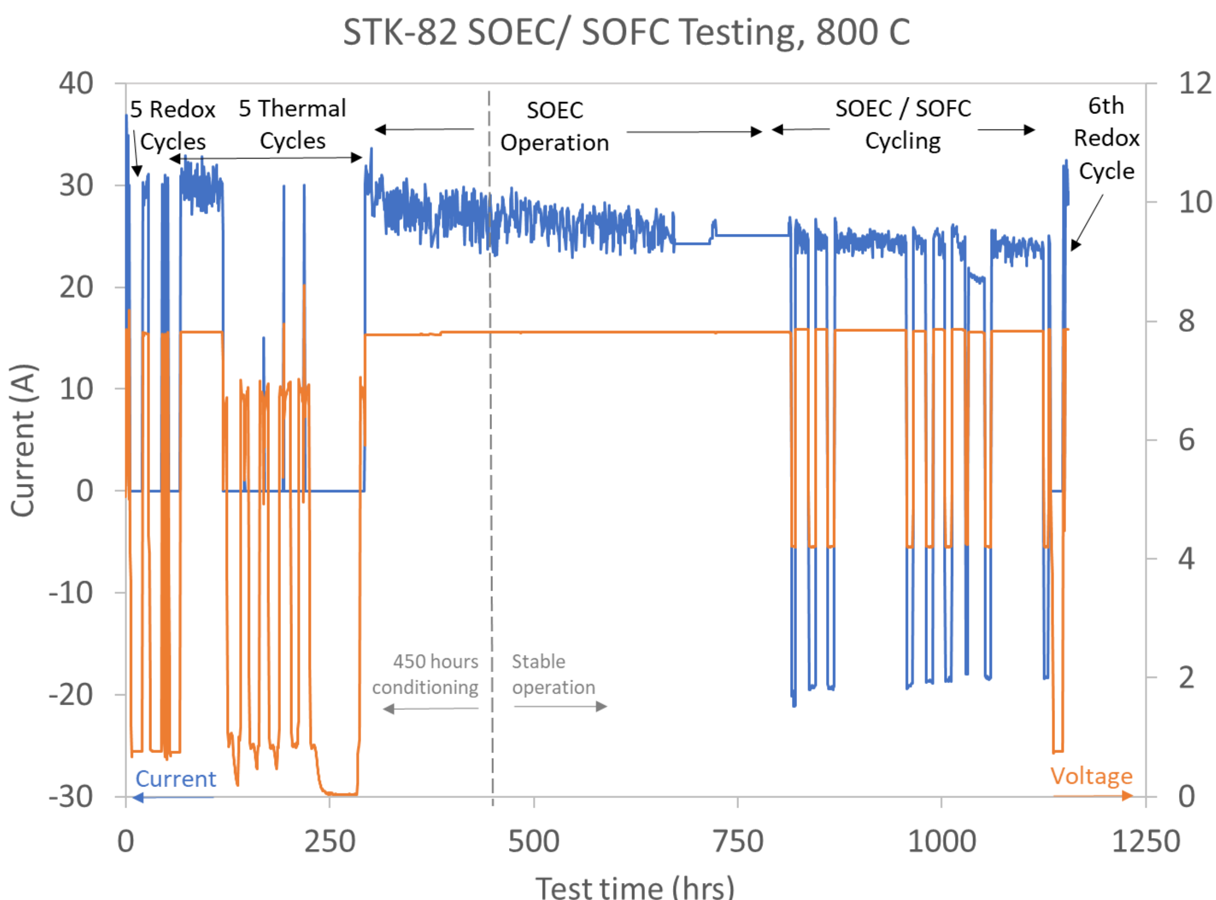


Higher degradation after 5 thermal cycles

Reversibility testing showed stability

Final Redox – back to initial performance

DOE-NETL Contract: DE-FE0032105

Pressurized Testing

GC Results (%)								
Pressure Condition	2 barg O2, 2 barg fuel		2.2 barg O2, 2 barg fuel		2 barg O2, 2.5 barg fuel		2 barg O2, 3 barg fuel	
GC Type	**Oxygen**	**Fuel**	Oxygen	**Fuel**	**Oxygen**	Fuel	Oxygen	Fuel
H2	-	85.81	-	84.84	-	84.08	0.010	85.40
O2	99.84	~~0.160~~	98.58	~~0.131~~	99.46	~~0.149~~	99.58	~~0.23~~
N2	0.161	14.03	1.39	15.03	0.54	15.77	0.410	14.36

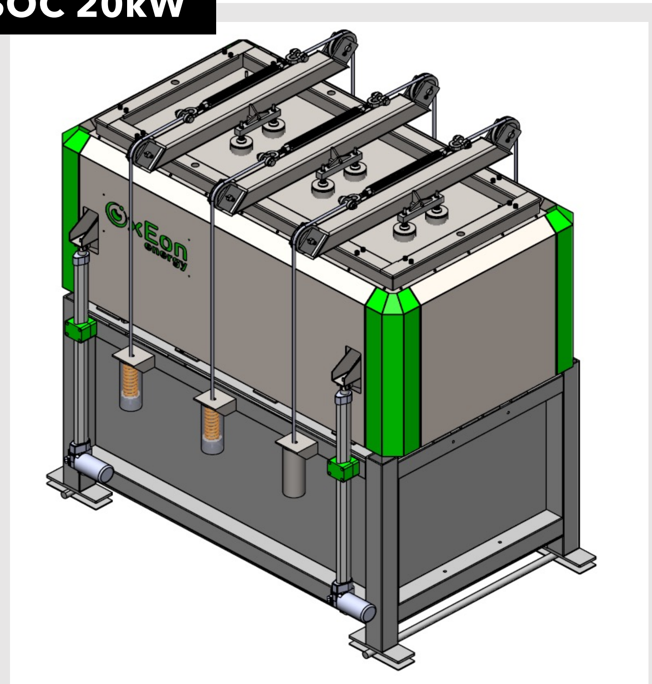
- Pressurized H2 (3 barg) and O2 (up to 3 barg) production (stack 83)
- 1 bar differential pressure achieved
- External to stack is ambient (no pressure chamber)

DOE-NETL Contract: DE-FE0032105

rSOC Program Overview

Ongoing system design and validation with commercial and DOE partners

rSOC 20kW



Farm Microgrid

Electrolysis:
- Renewable energy supports generation of H2
- Production rate at 20kW
- Initial H2 storage capacity 100kg at 350 bar

Fuel Cell:
- On-site H2 storage to generate electricity at night
- Production rate at 10kW

Idaho National Laboratory (Prime)

Electrolysis:
- Steam electrolysis production rate at 30kW

Fuel Cell:
- Production rate at 20kW

Fischer Tropsch Overview

Syngas ($CO + H_2$)

Fischer-Tropsch produces liquid hydrocarbon fuels from syngas

$$(2n+1)\,H_2 + n\,CO \rightarrow C_n H_{(2n+2)} + n\,H_2O$$

$$H_2 + CO \rightarrow \text{liquid hydrocarbon fuels}$$

Catalysts (Fe, Co) and process conditions facilitate the reaction and determine the hydrocarbon product.

Advantages

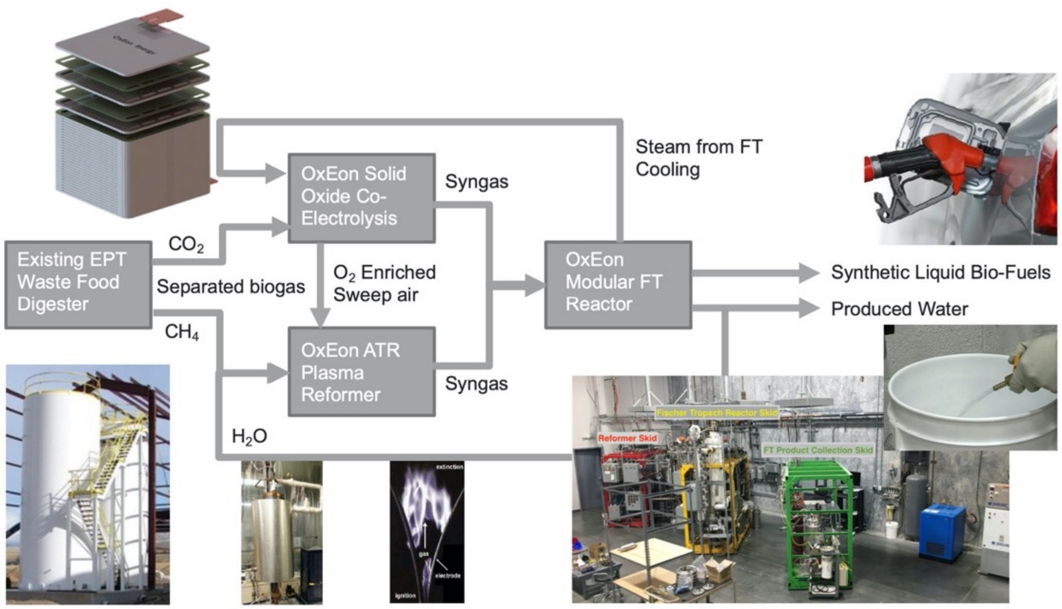
- Biogas / biomass conversion produces **sustainable transportation fuels**
- **Modular design** reduces capital costs to start up and expand system
- FT is an established technology that produces syncrude, which can be converted to standard fuels with upgrading.

Transportation Fuels

Jet Fuel
Diesel Fuel
Lubricant wax

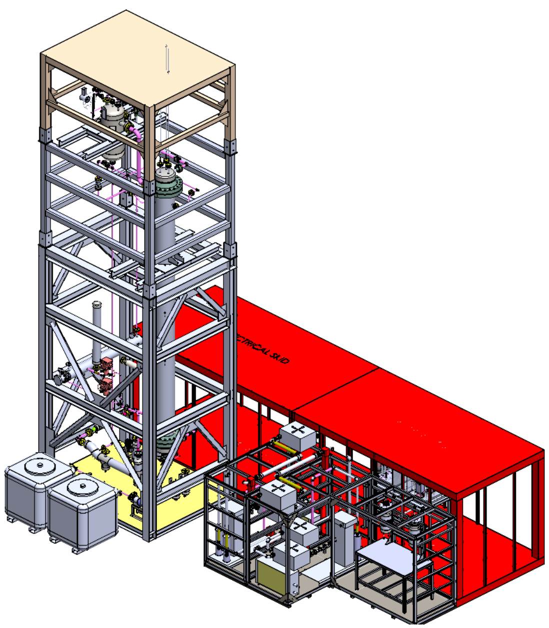
Fischer Tropsch – Program Overview

- **Engineering-scale demonstration for production of liquid hydrocarbon fuels using both methane and carbon dioxide generated by a food waste digester**
- **Three key elements:**
  - **Solid Oxide Electrolysis Cell (SOEC) –** Converts steam and CO_2 to syngas
  - **Plasma Reformer –** Syngas production from methane with steam and water
  - **Fischer-Tropsch (FT) Reactor –** Liquid fuel production from syngas



DOE-BETO Contract: DE-EE0008917

Fischer Tropsch – Subsystem Verification Test Results



Criteria	Target	Overall Averages 10/21-10/29 and 10/30-11/3		Overall Averages 10/21-11/3	2020 Results
CO Conversion	>80%	84.2%	86.1%	84.9%	92%
H_2 Conversion	>80%	93.4%	93.8%	93.6%	92%
CO Selectivity to C5+	>76%	80.2%	75.9%	78.6%	73.2%
Overall CO to C5+ (Conversion*Selectivity)	>67%	67.4%	65.4%	66.7%	67.2%
Mass balance closure	>92% on C	95.8%			98.80%
Product Distribution C_n peak	>C9	SimDis product peak at C9-C10		C9-C10	C8-C9

Thank you

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SOLID OXIDE FUEL CELLS
SOLID OXIDE ELECTROLYSIS CELLS
FISCHER-TROPSCH REACTOR
PLASMA REFORMER

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