Scale Up and Coupling of the MOXIE Solid Oxide Electrolyzer for Mission-Scale Lunar and Martian Applications

J. Hartvigsen, M. Hollist, J. Elwell, T. Hafen, J. Pike, and E. Elangovan

Beyond Current Potential

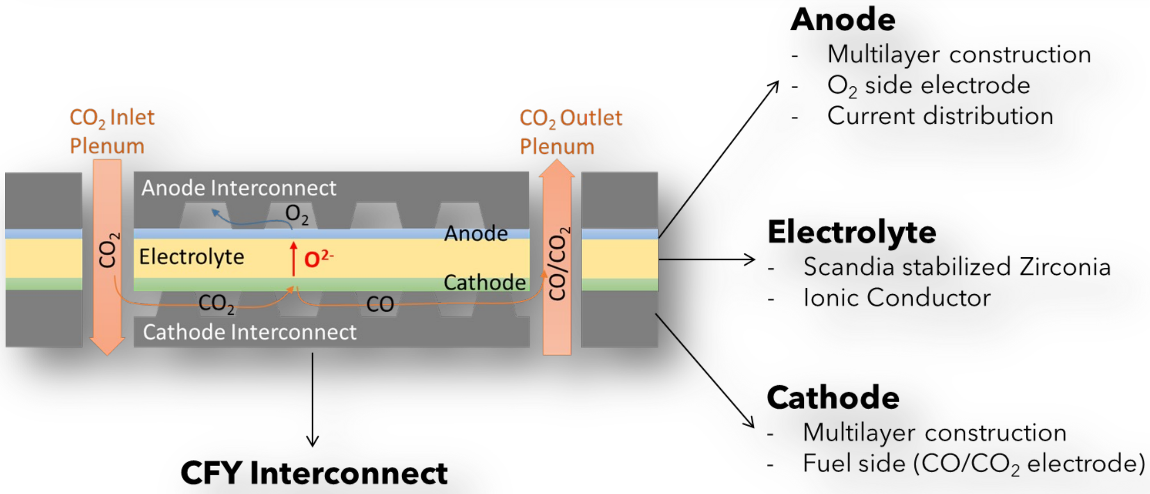
MOXIE: Mars Oxygen ISRU Experiment

NASA funded flight program

- Only space flight qualified SOEC stack in history
  - Shock, vibe, operational cycles, mechanical load
- Only TRL9 SOEC device in history
- First space ISRU demonstration
  - Produced oxygen from the Mars Atmosphere

MOXIE SOXE TEAM

- **MIT:** MOXIE Science Team Lead
- **JPL:** MOXIE System Integration & Qualification
- **OxEon:** SOEC/SOXE development and production
  - TRL3 to 6 in 18 months
  - Hermetically sealed, ruggedized stack capable of withstanding launch, entry, descent and landing
  - Capable of multiple operations cycles: rapid 2 hour heat up to 800 °C
  - 14 operational cycles on Mars to date



SOXE Development Since MOXIE

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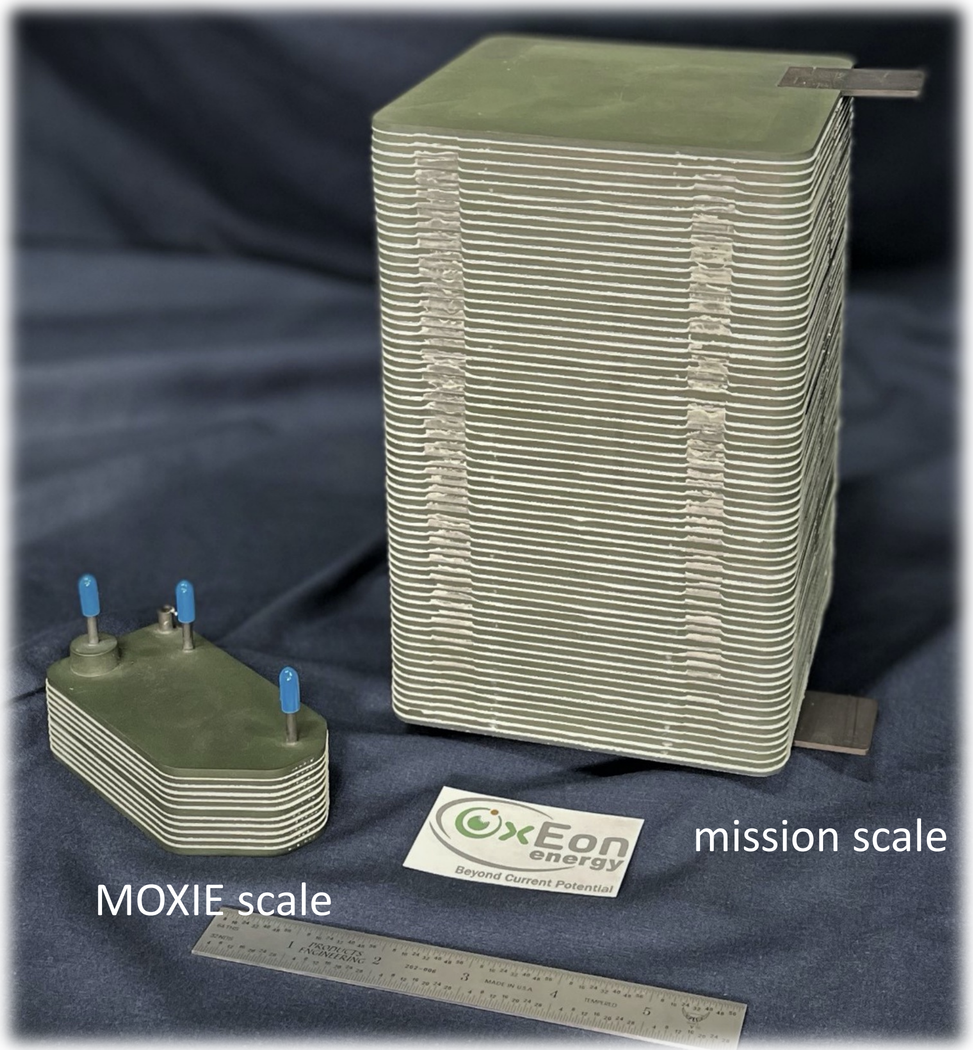
Scale-up of SOXE device

- 5x increase in cell area
- 6.5x increase in cells per stack
- Newest, mission-scale variants scaled 33x device used in MOXIE

6 mission-scale stacks (4+2 spares) capable of producing 30 tons propellant O_2 to fuel MAV in 19-month window from Mars landing to next launch

Demonstration systems built and relevant tested

- Lunar application–production of propellant H_2 and O_2 from Lunar PSR Ice
- Martian application–production of propellant O_2 and CH_4 from Mars CO_2 and H_2O



Scaled-up Interconnect

MOXIE system requirements moved SOXE stacks from open anode channel design to hermetically sealed anode

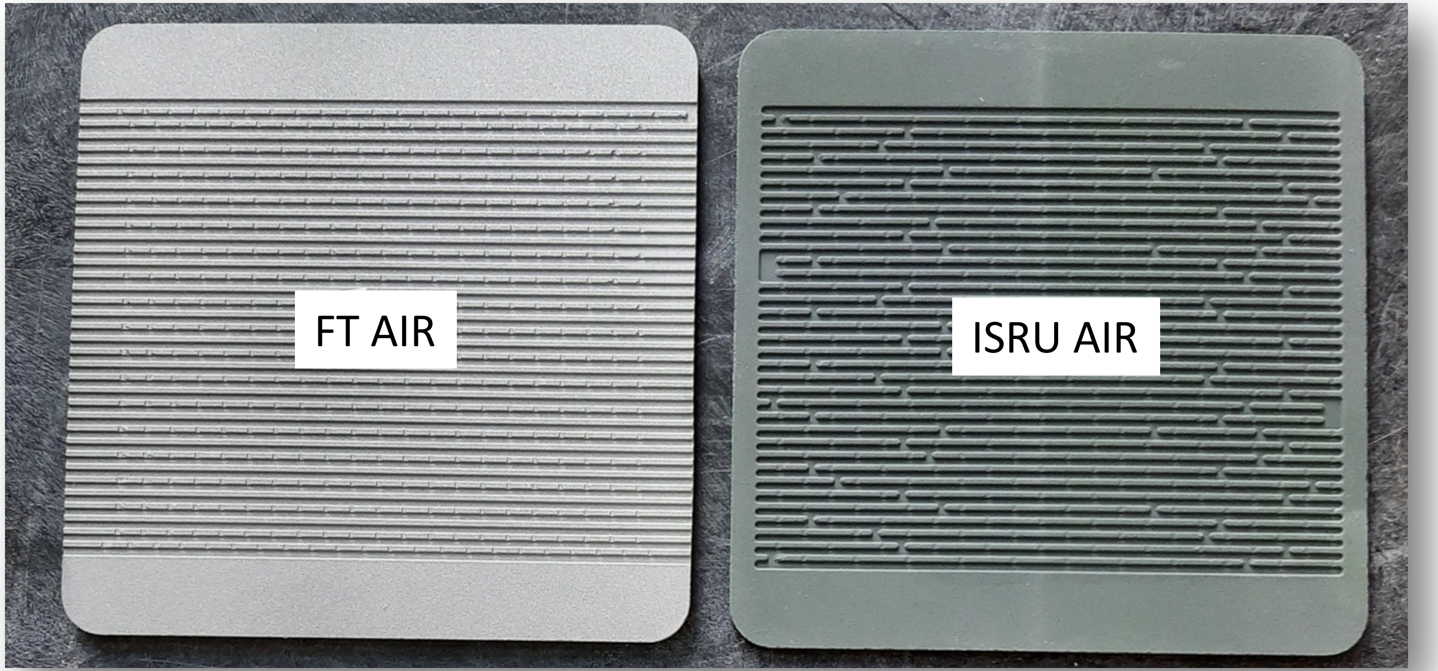
- Allow internal collection of O_2

Change in interconnect necessary for CTE material match

- Heritage SOXE stacks utilized stamped ferritic stainless steel
- ISRU stacks use high chromium (95CR-5Fe-Y_2O_3 CFY) interconnects

Scale-up limited by production presses available

- First ISRU interconnects were 50 mm x 100 mm (MOXIE)
- Scaled-up ISRU interconnects are 130 mm x 130 mm



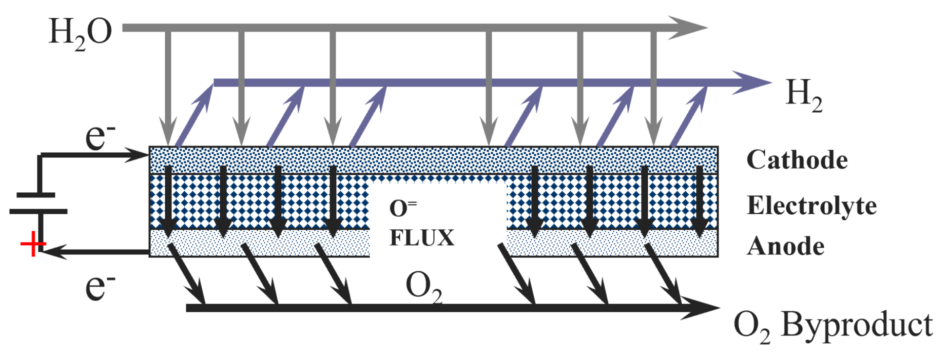
Lunar ice processing demonstration unit sponsored by a Tipping Point award to OxEon and Mines through NASA's Moon and Mars Technologies initiative

Objectives

Demonstrate high temperature SOXE propellant production from H_2O

Thermally integrated BOP

System architecture optimization and technoeconomic analysis



Program KPPs

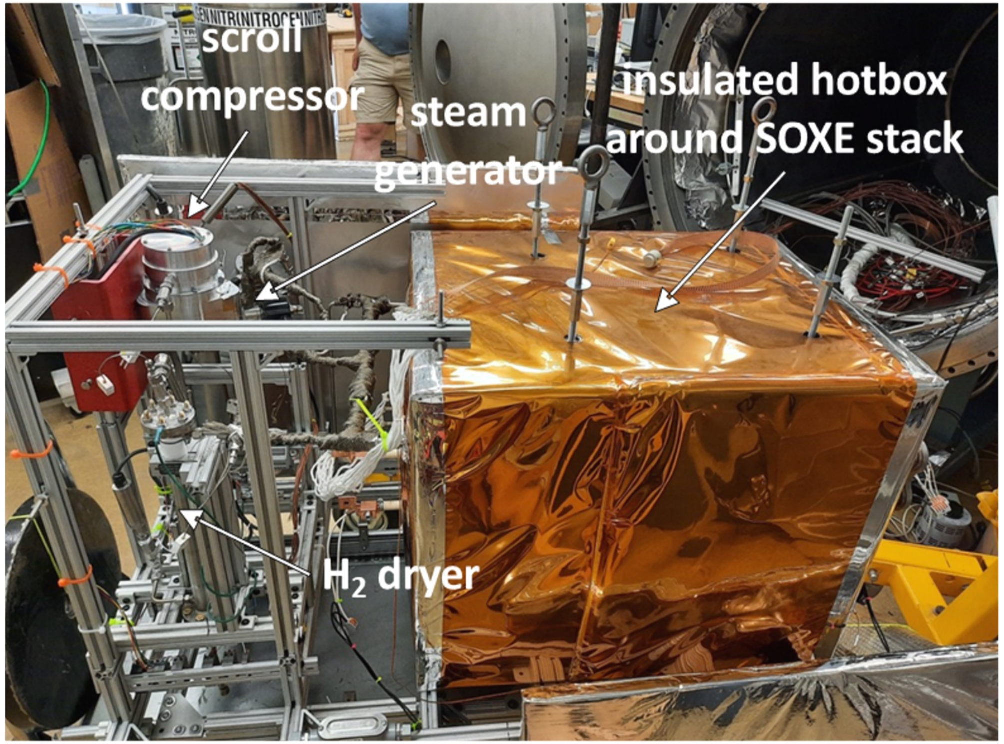
Integrated breadboard system H_2 production rate: Threshold/Goal = 1.5/1.8 kg/day

O_2 product pressure: Threshold/Goal = 1/2 bara

System specific power: Threshold/Goal = 50/46 kWh/kg H_2

Lunar Demonstration System: Program Accomplishments

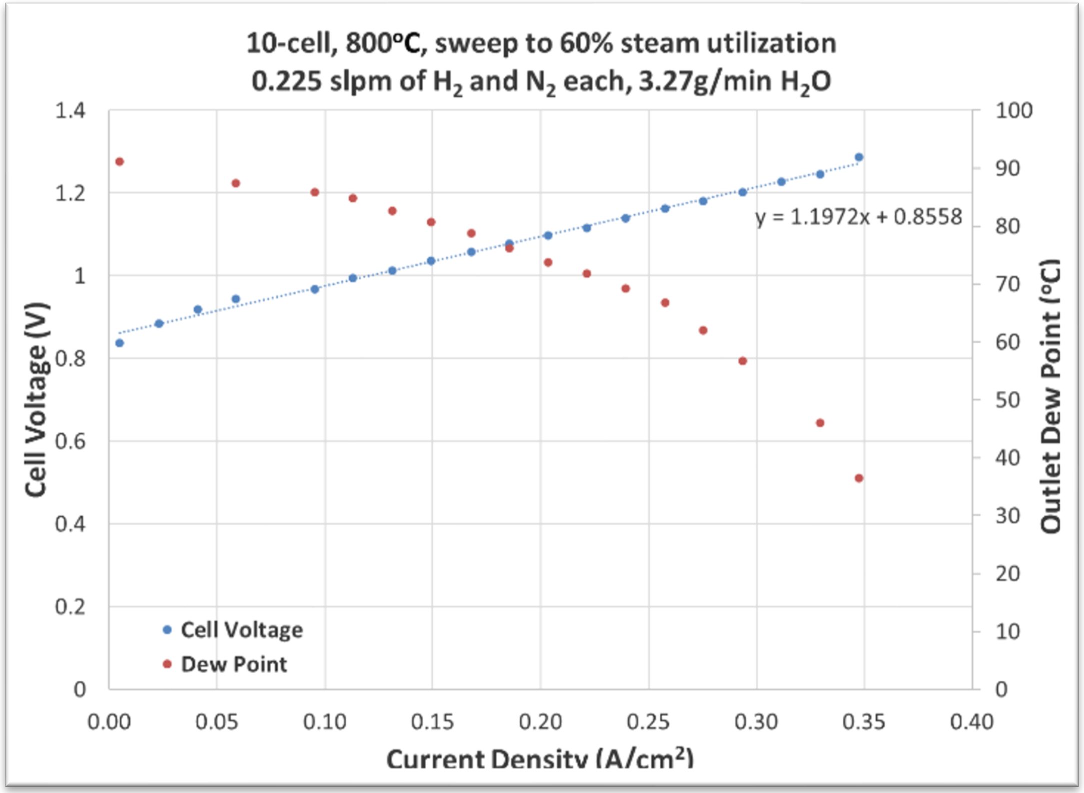
- ✓ Successful scale-up of ISRU from MOXIE
- ✓ Moved technology from a TRL 4 to TRL 5
- ✓ Met all 3 KPP threshold values
- ✓ Exceeded 2 of 3 KPP goal values
- ✓ TEA indicates economically viable propellant production



Lunar Demonstration System: Electrochemical Drying

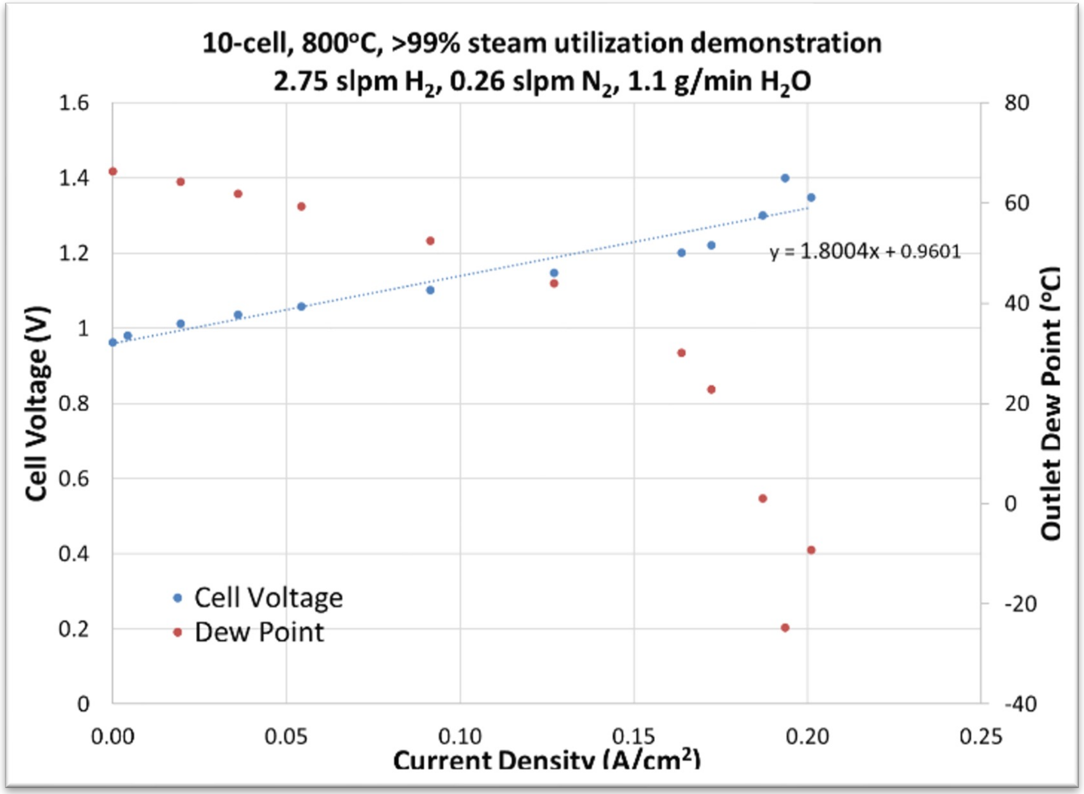
Two-stage electro-drying scheme

- First stack produces majority of H_2
- Second stack used to dry H_2 product
  - Eliminate need for additional processing to dry H_2 product



Short stack demonstration

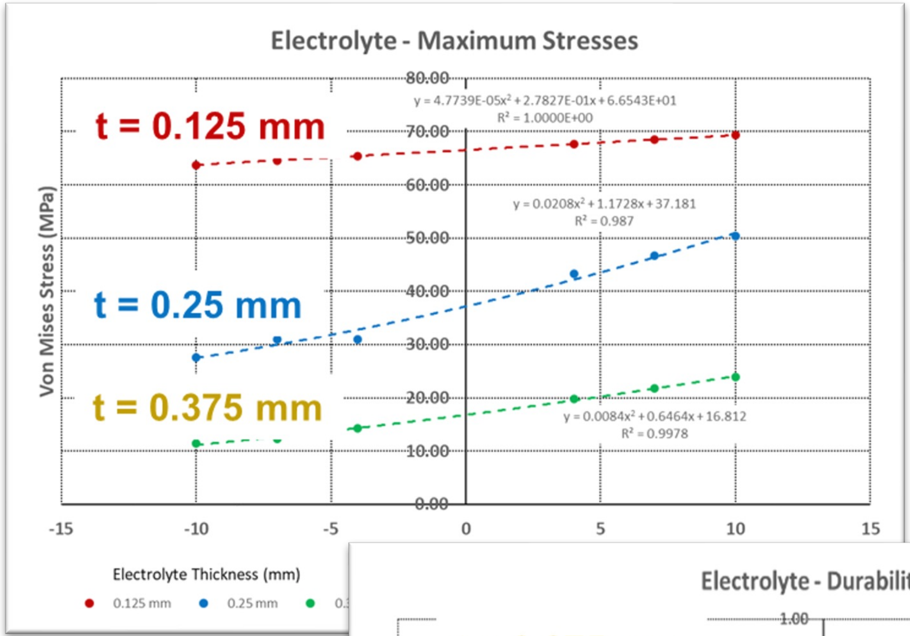
- Stack run at 60% H_2O utilization
- Inlet conditions adjusted to match outlet from first test
- Stack driven to outlet dew point of -20 °C (99.9% H_2O utilization)

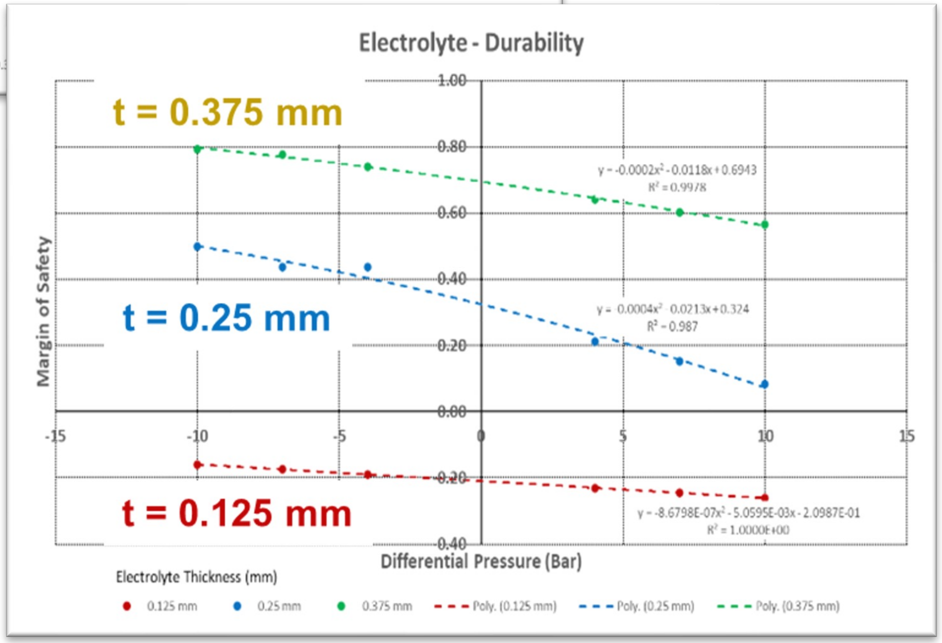


FEA study to evaluate electrolyte

- FEA to assess electrolyte stresses as a function of thickness/differential pressure
  - Three electrolyte thicknesses evaluated (0.125, 0.25, and 0.375 mm)
  - Differential pressure across electrolyte varied ±10 bar
- Highest stresses mimic pattern of interconnect

Representative electrolyte corner geometry mesh and plot von Mises stress (1.6M elements, 6 elements thick)





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

Mars resource
CO_2 & H_2O
↓
SOXE
↓
O_2 | CO & H_2
↓
Methanation
↓
Propellant O_2 | CH_4
Byproduct H_2O

Program Targets

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

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

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Modelling of SOXE stack operation and test verification

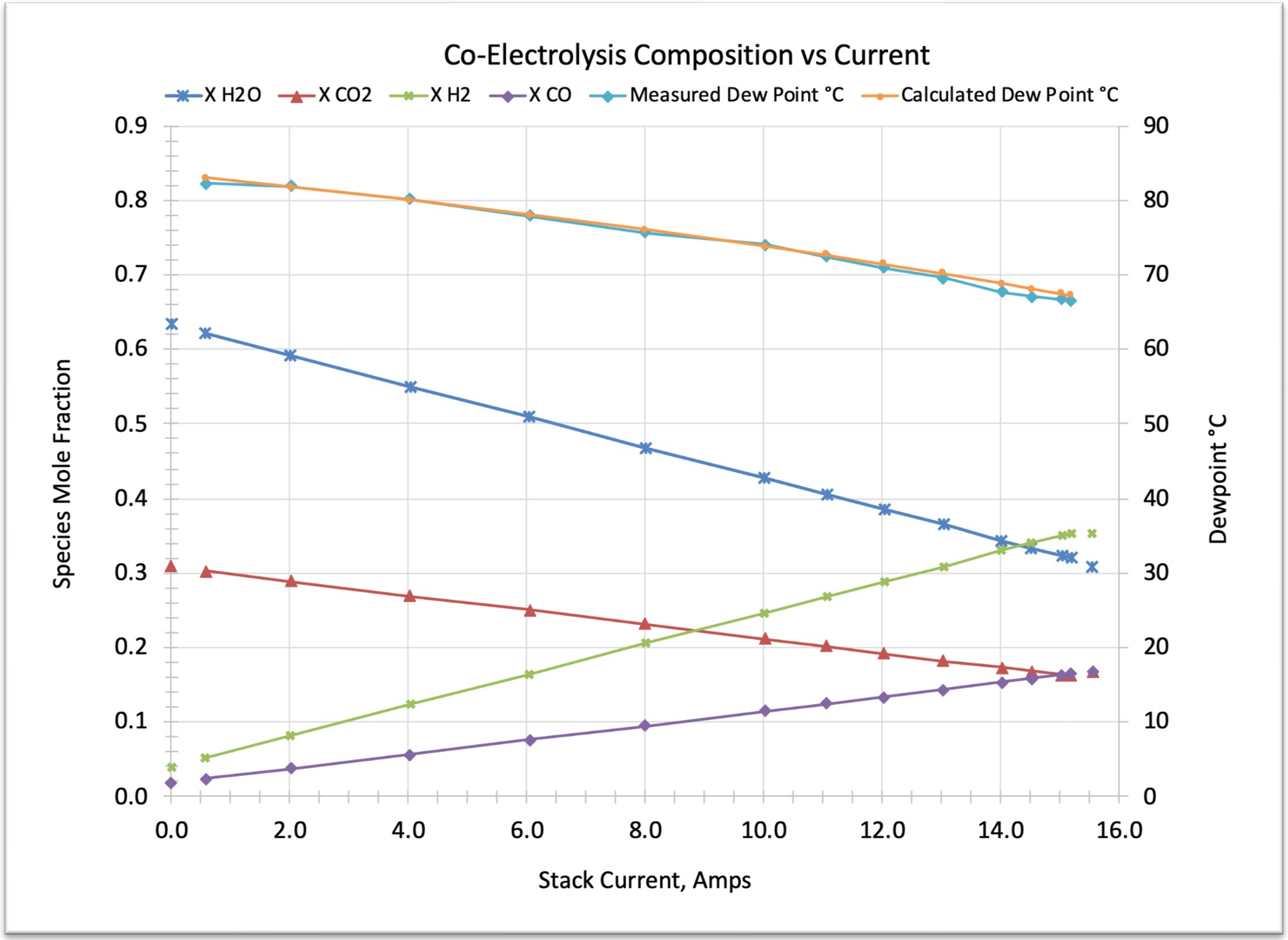
- Dry CO_2 electrolysis
- Steam electrolysis
- Co-electrolysis

Monitor steam source and conversion with dewpoint sensor

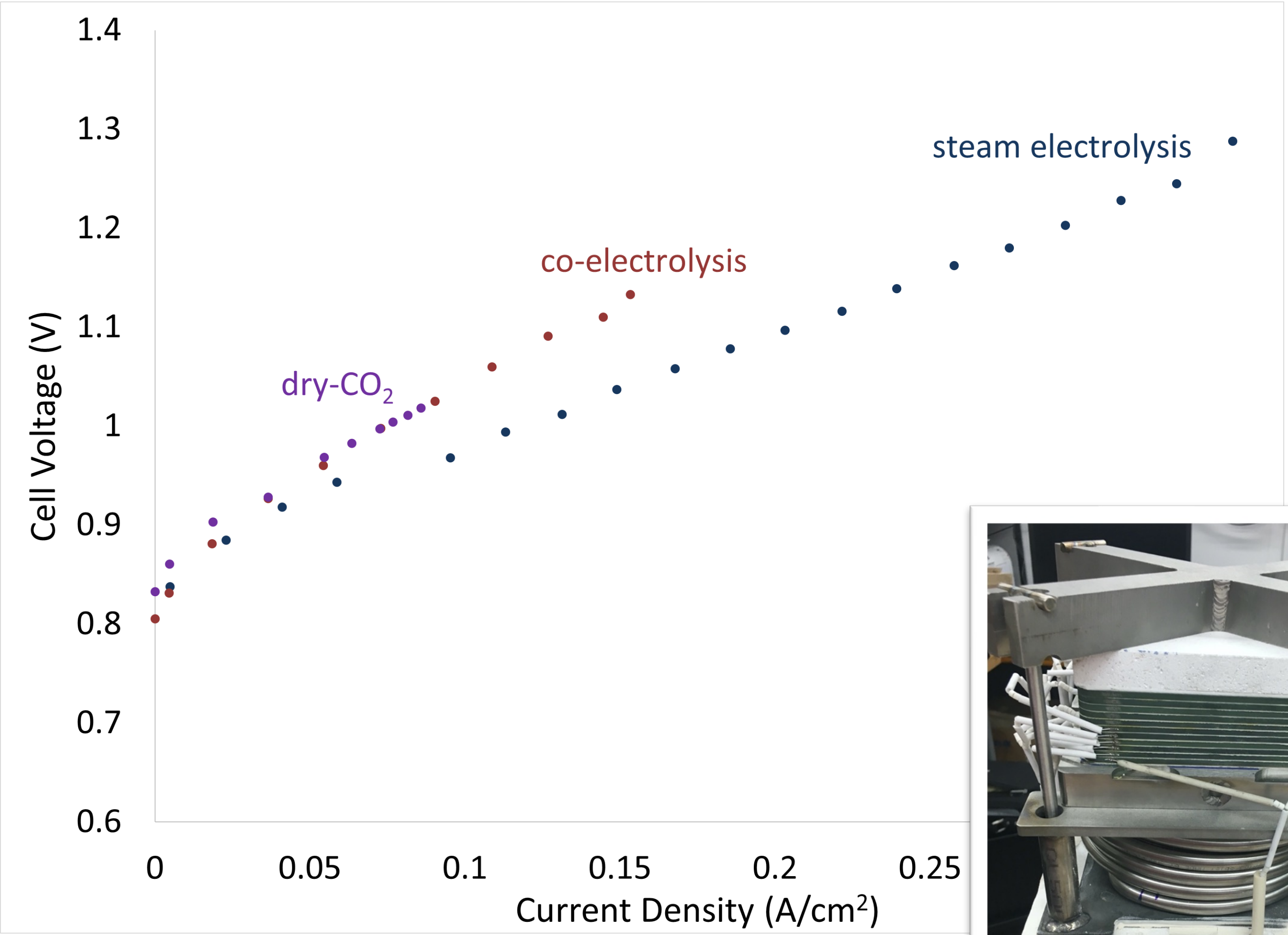
- Compare model composition with GC and DP data

Flexibility in feed composition to SOXE demonstrated

- Can vary inlet to match desired syngas composition



Mars Demonstration System: Electrolysis Testing



Steam electrolysis

- Higher productivity
- Multi-stage can achieve >99% steam utilization

Dry CO_2 electrolysis

- Limited by CO reduction potential

Co-electrolysis (steam and CO_2)

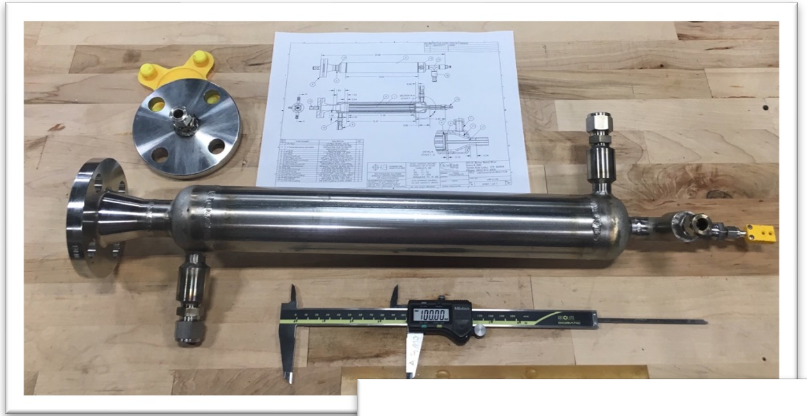
- Product H_2/CO ratio tracks inlet H_2O/CO_2 ratio
- Productivity nearer dry CO_2 than steam
- Modest performance dependence on H_2O/CO_2 feed ratio

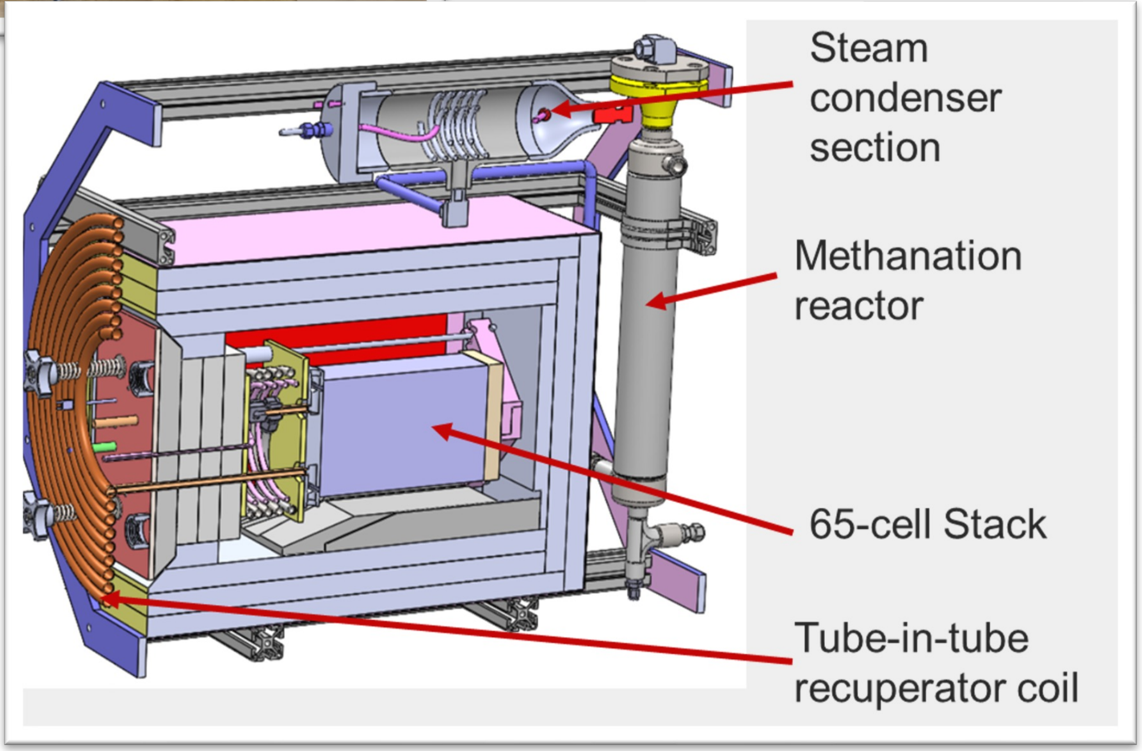
Methanation reactor design

- Schedule 10 stainless 1-1/2″ nominal pipe
- Aluminum fin insert for heat removal
- Centerline multi-point temperature probe
- 300 mm catalyst loaded length, 300 ml total
- Evaporative cooling jacket with condenser loop

System Integration

- SOXE generated sygnas cooled to remove unreacted H_2O
- Dry syngas fed to methanation reactor to produce CH_4



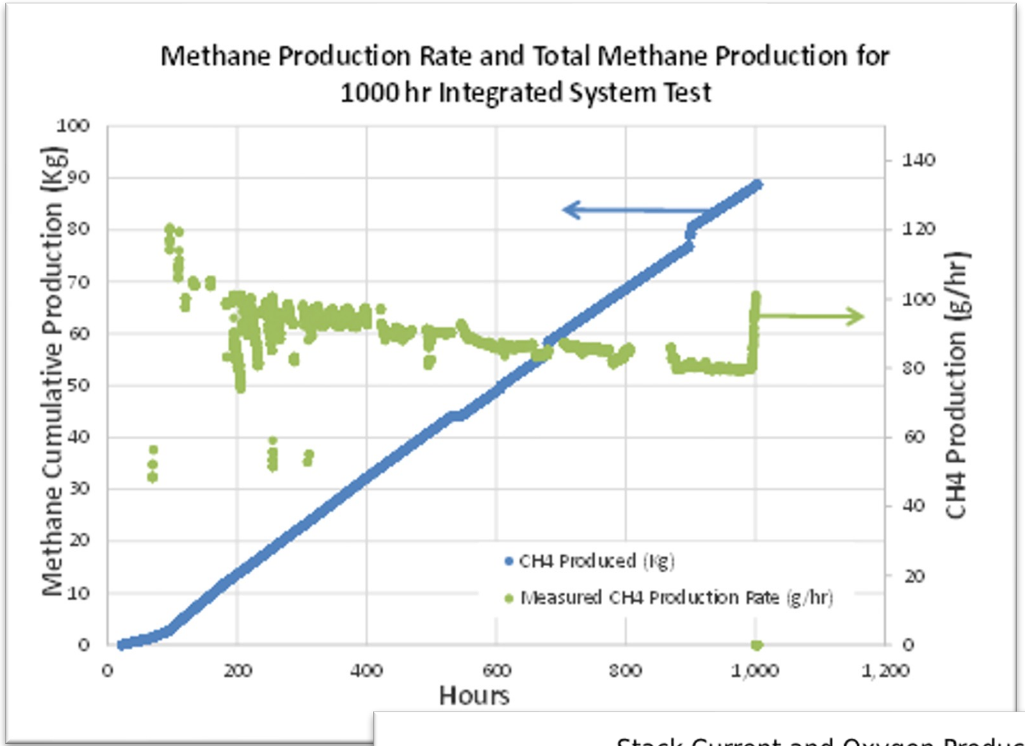


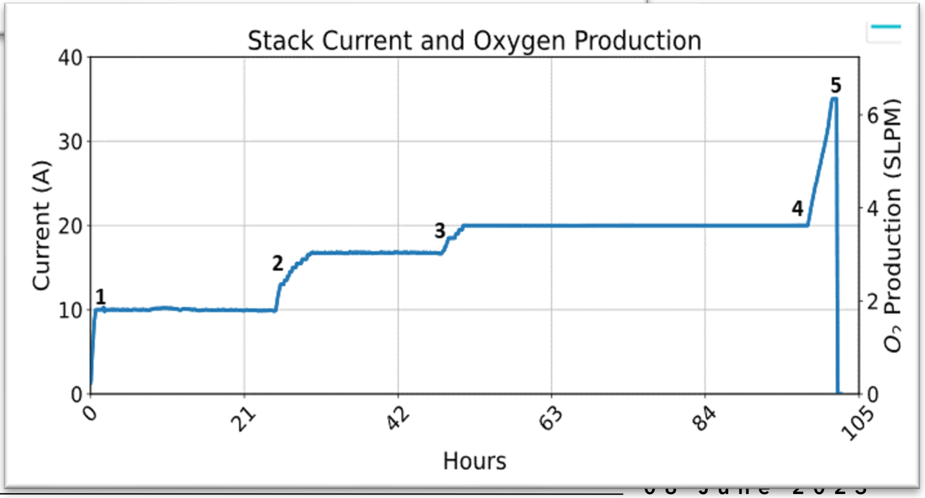
SOXE standalone test
- 1,000 hours
- Dry-CO_2, co-electrolysis, and steam electrolysis demonstrated with mission-scale stack

Methanation reactor standalone test
- 1,500 hours

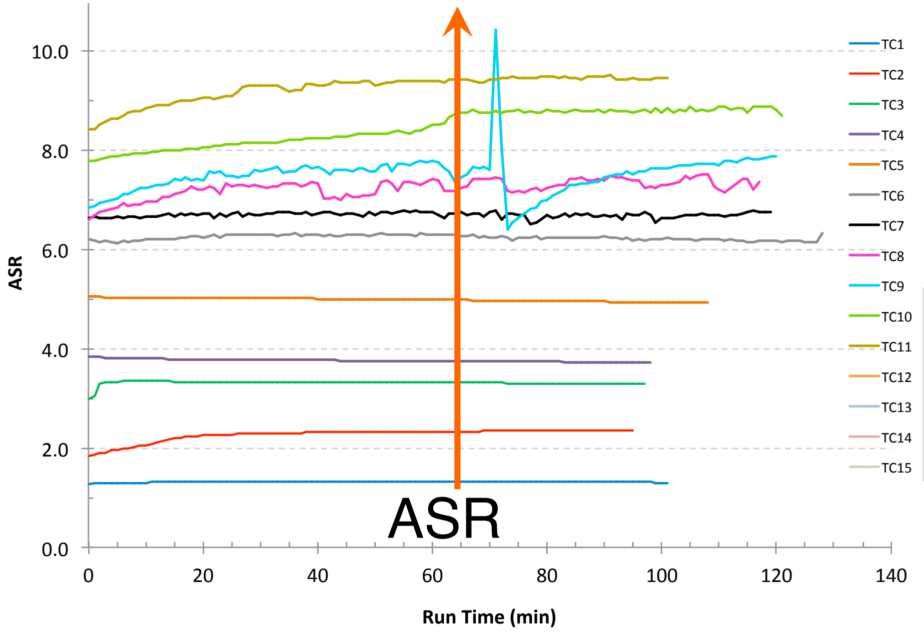
Integrated system test
- Ambient conditions for 1,000 hours
- Relevant condition test in JPL Mars chamber for 100 hours

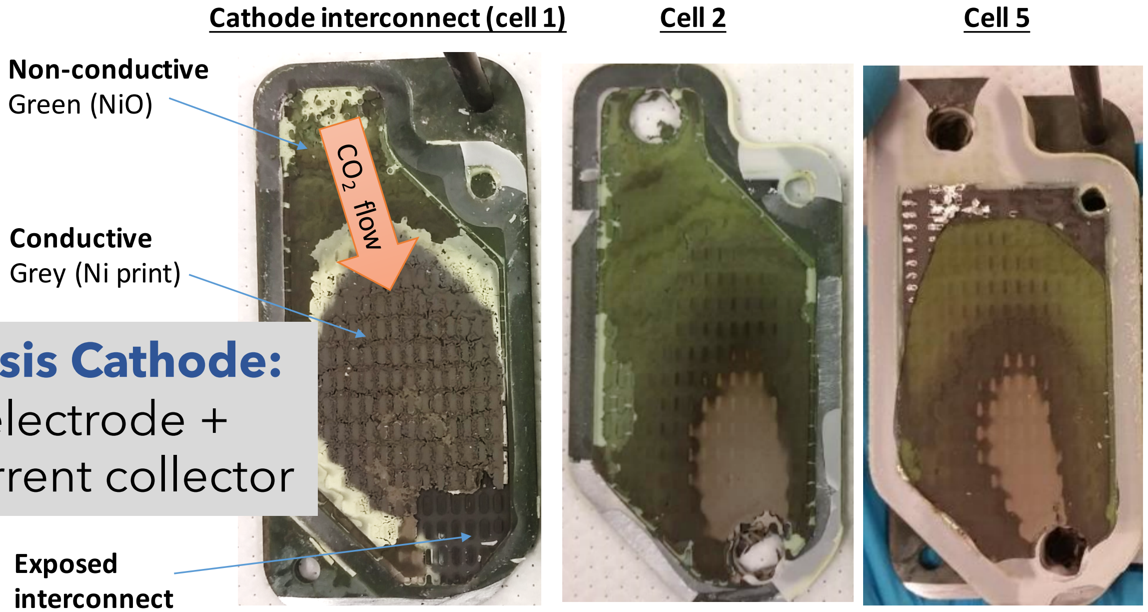
Mission Scale SOXE stack extended operation
- Three thermocycles demonstrated
- Total of 2,500 hours of operation
- Demonstrated target O_2 and CH_4 production rates, SOXE produced O_2 purity > 99.9%





Cathode Challenge: 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

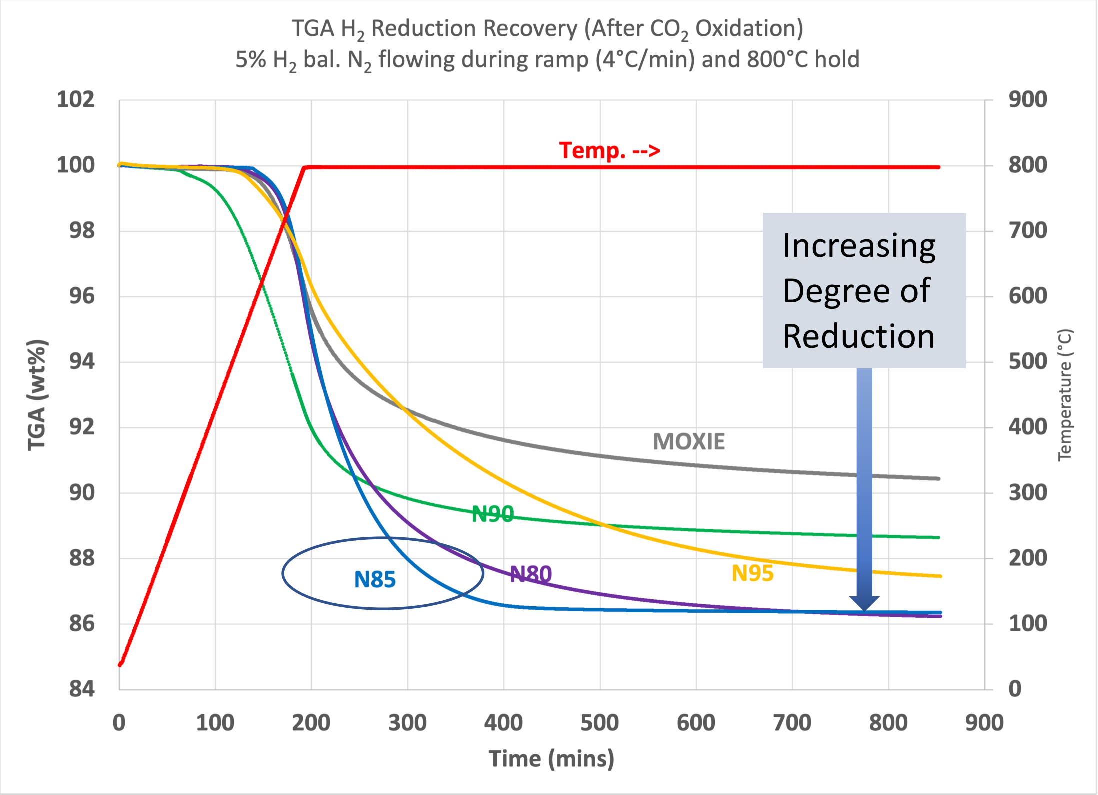
Reduction Kinetics: Thermogravimetry Analysis

Various levels of promoter to improve reduction kinetics were evaluated

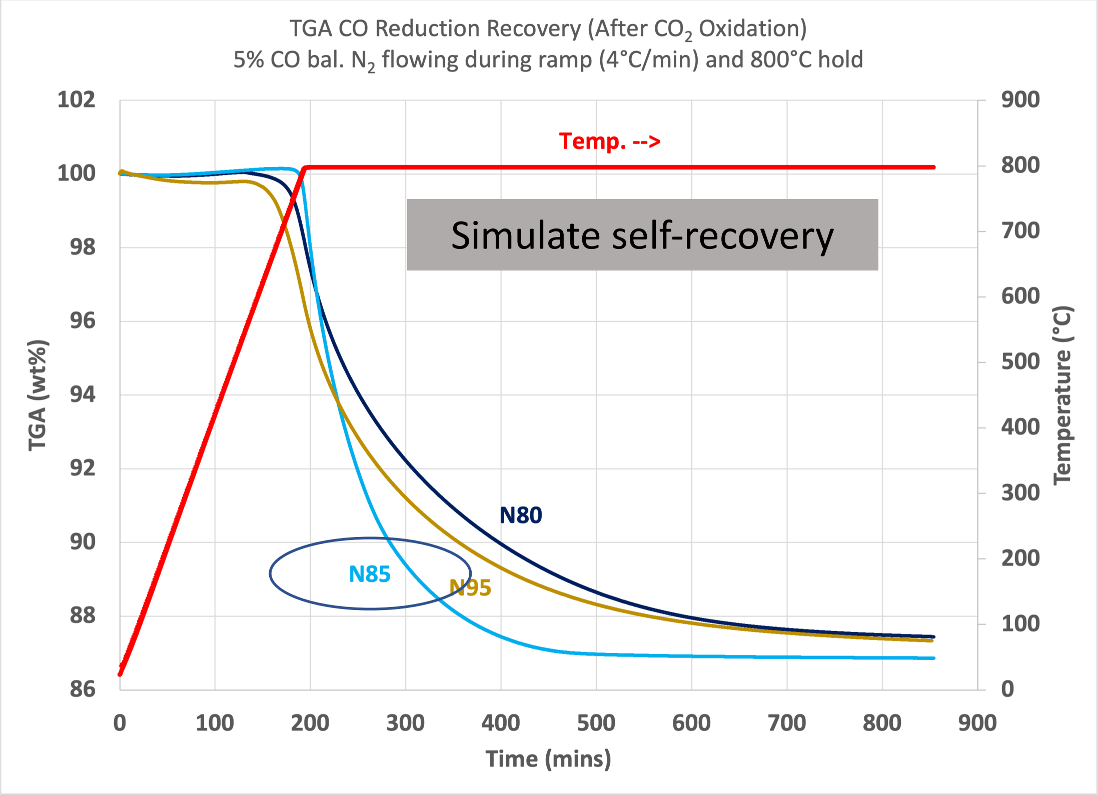
After oxidation in CO_2 the same samples were re-reduced in either H_2 or CO

- Selected a composition that reduces quickly and completely

H_2 Reduction



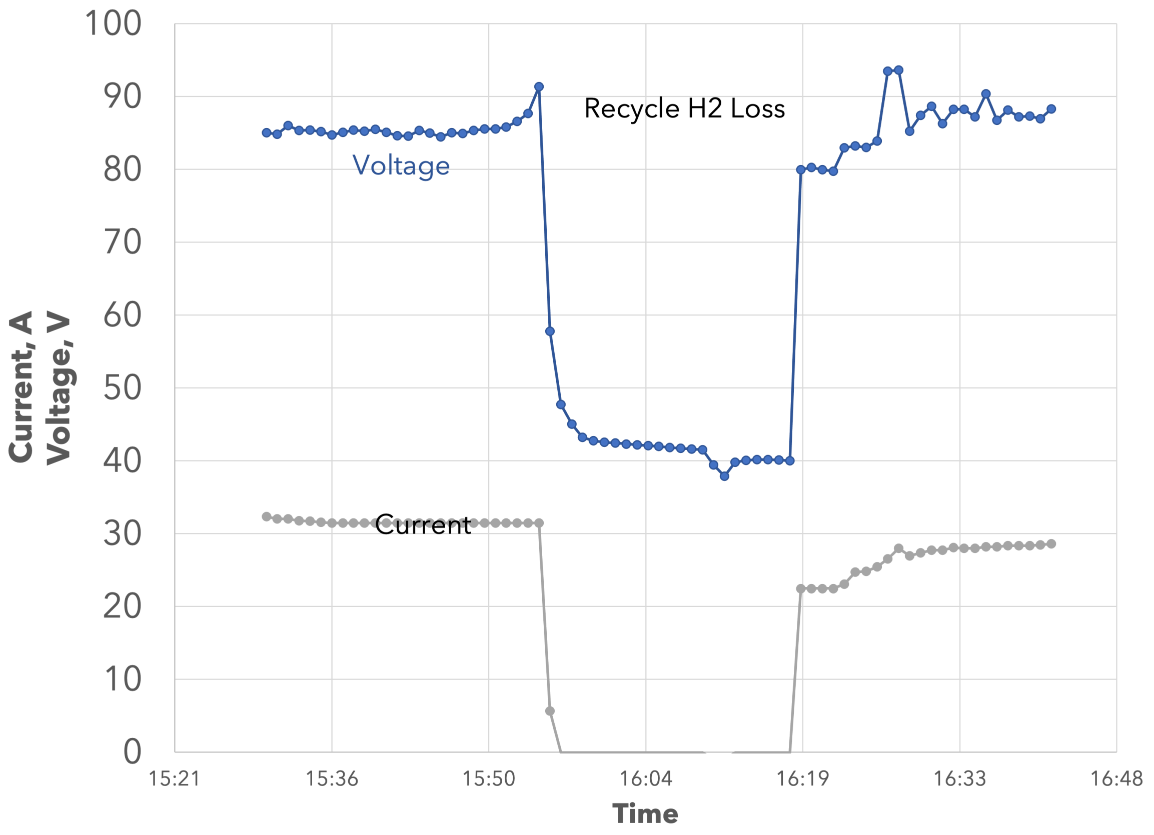
CO Reduction



Cathode Demonstration: Redox Cycle and Coking Limit

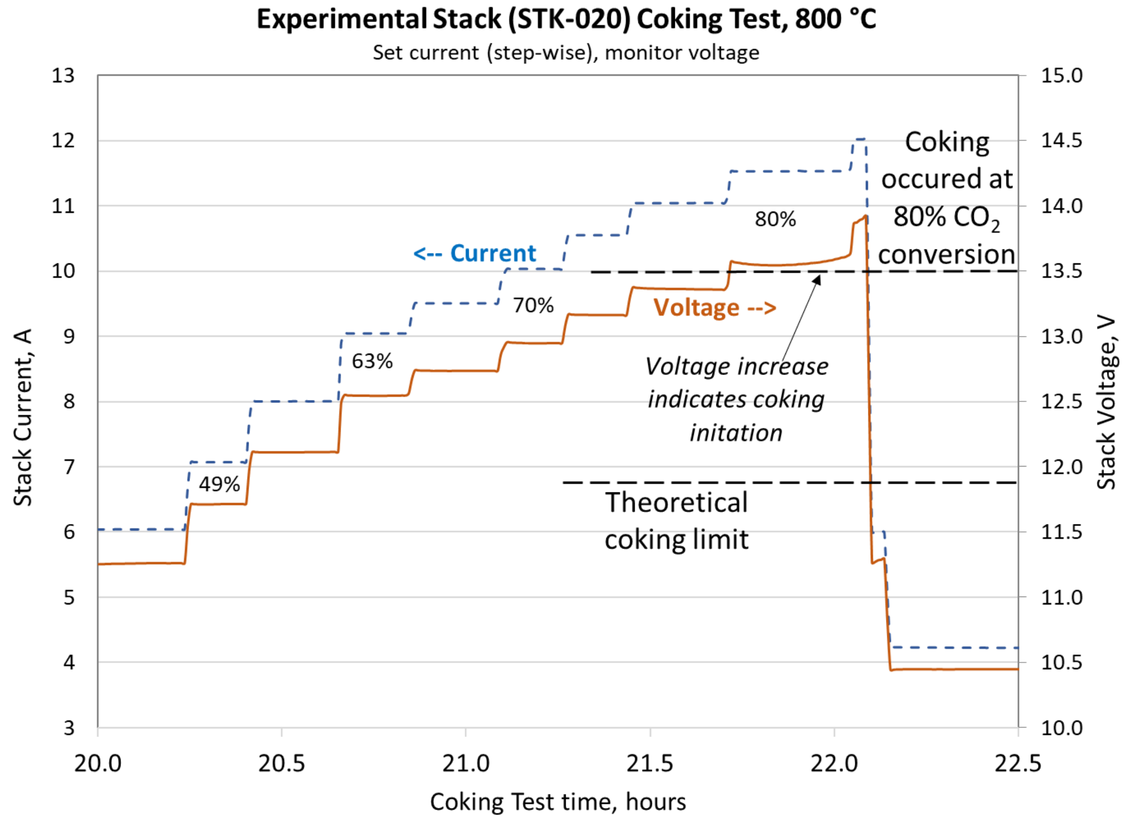
Redox Cycle with Lunar Demonstration

- Power supply problem resulted in no H_2 in stack feed
- Stack performance recovery observed when H_2 recycle re-established



Coking limit evaluation with dry CO_2

- Stacks with new cathode material able to operate above theoretical coking limit
- Demonstrated Mars demonstration system during JPL Mars chamber test



Post-MOXIE Scale-up ISRU Accomplishments

- 33x device scale-up
  - Human exploration mission-scale stacks
- Lunar and Martian demonstration systems
  - Relevant condition testing
  - Flexibility in feed composition from dry-CO_2 and steam alone, to any mix of H_2O/CO_2
- Cathode material development
  - Redox tolerance for recycle elimination
  - Coking resistance observed
- Demonstration of additional functionality
  - Electrochemical compression of O_2 product
  - High steam utilization for H_2 product drying

Beyond Current Potential

Thank you

jjh@oxeonenergy.com

OxEon Energy, LLC
257 Riverbend Way
North Salt Lake, UT 84054

Info@OxEonEnergy.com
+1-801-677-3000
OxEonEnergy.com

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