Solid Oxide Cell Technology for Propellant and Power Production

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SPACE RESOURCES ROUNDTABLE

COLORADO SCHOOL OF MINES

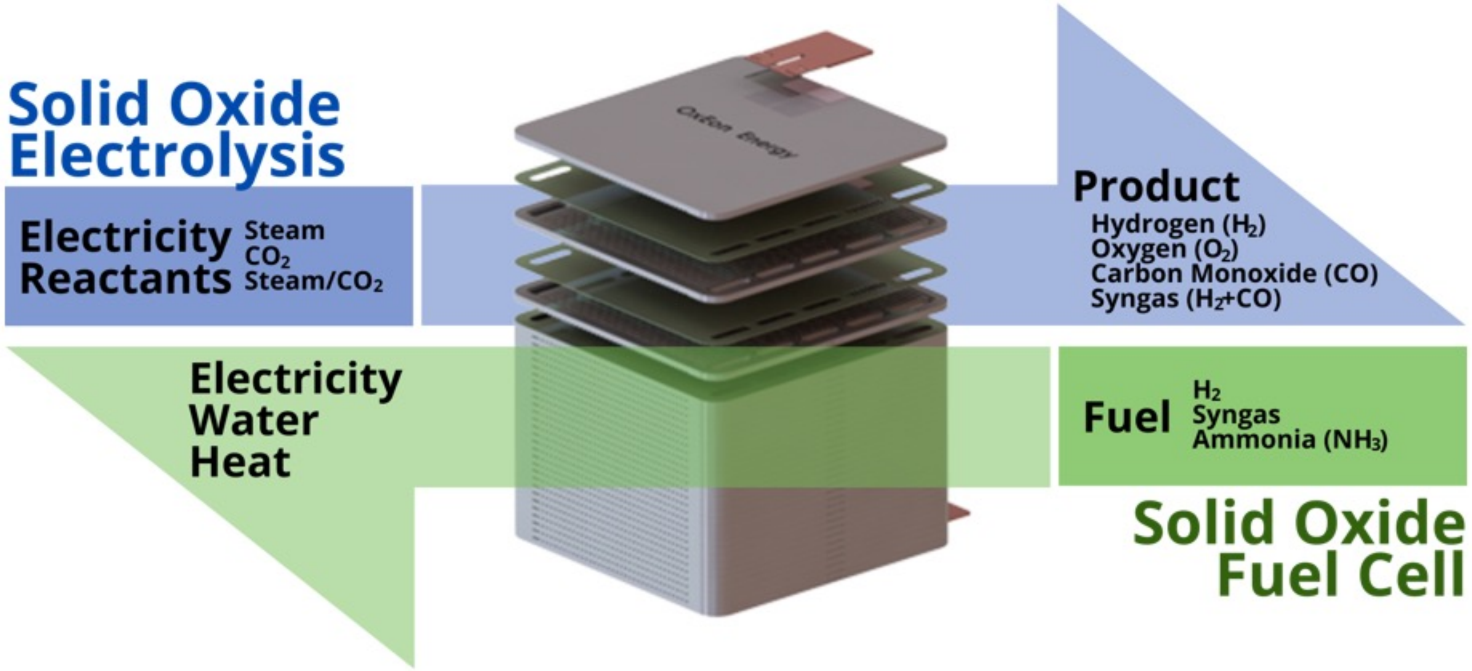
OxEon energy

Beyond Current Potential

Solid Oxide Cell Technology

Electrolyzers (SOEC) and Fuel Cells (SOFC)

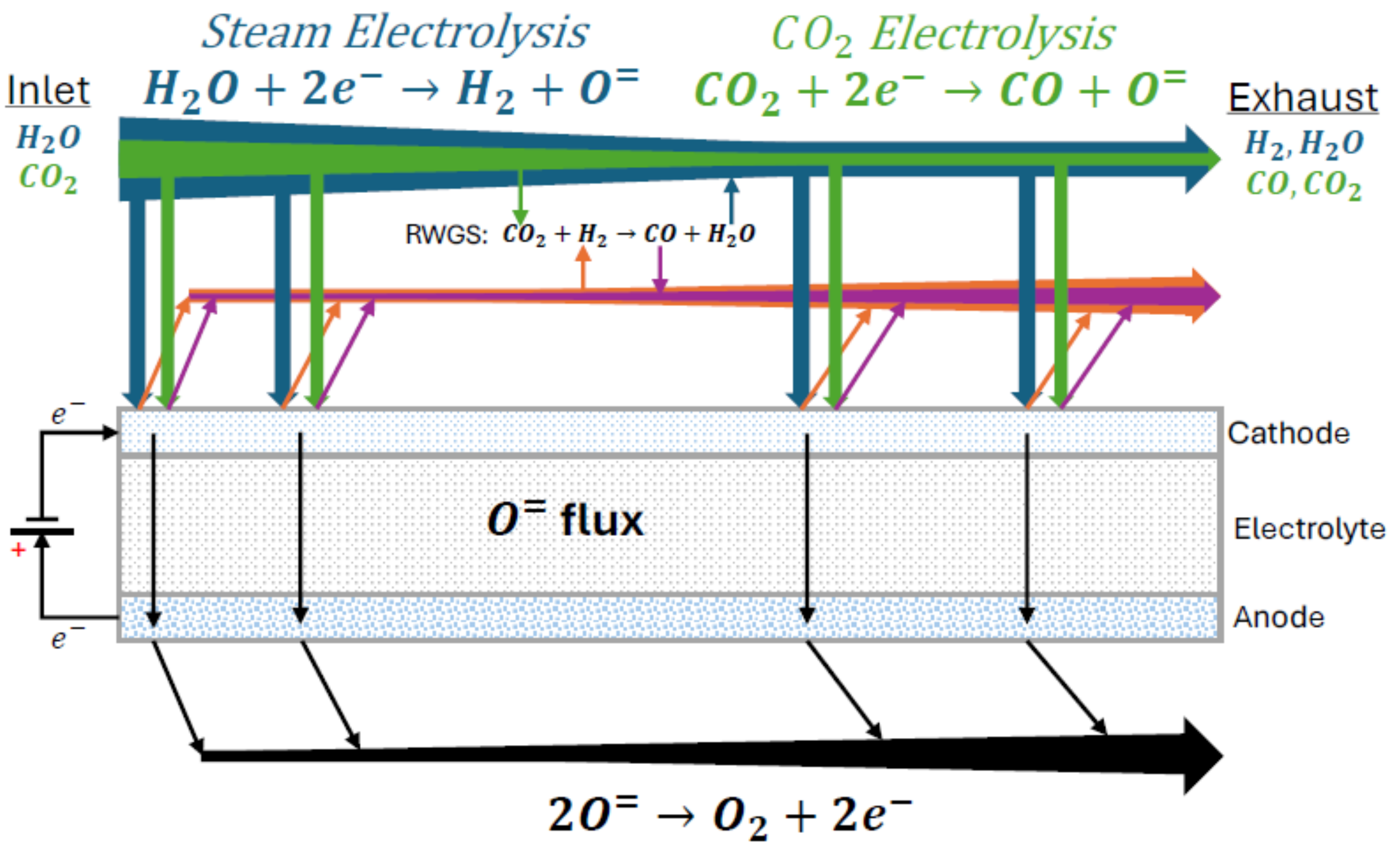
- A solid oxide cell (SOC) consists of a ceramic electrolyte between a porous anode and porous cathode
    - Solid ceramic electrolyte allows oxygen ions to conduct from the cathode to the anode
- SOCs operate at high temperatures (750-850 ^{o}C)
- Accepts diverse inputs – CO_2 and Steam in SOEC mode and CH_4, H_2, and NH_3 in SOFC mode
- Can operate reversibly to generate propellants when power is available and then convert those propellants into electricity



Solid Oxide Cell Technology

Electrolysis for space propellant production

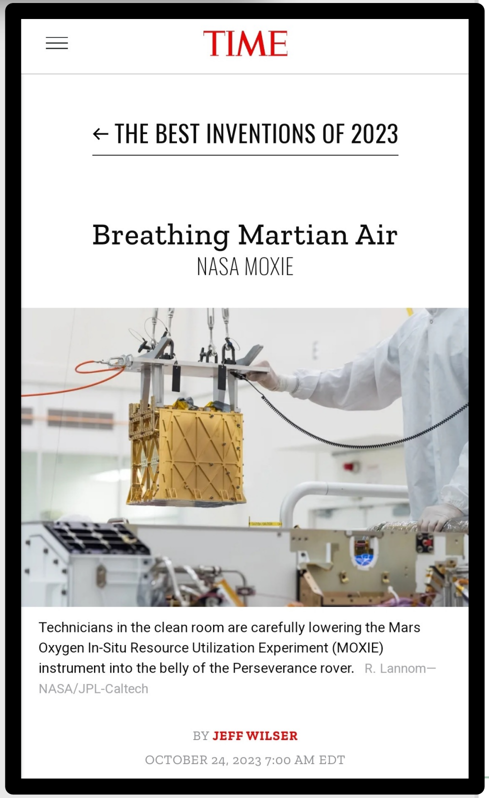
- In SOEC mode, electricity splits steam or CO_2 to form O_2
- O_2 can be collected as a high purity stream for use as a propellant
- Presence of water in Lunar PSRs and CO_2 in Mars atmosphere provide inputs for SOEC
- In-situ resource utilization (ISRU) of these resources for propellant production would decrease launch mass, make new opportunities available
- Mars OXygen ISRU Experiment (MOXIE)



Solid Oxide for ISRU Propellant Production

NASA funded flight program
- First space ISRU demonstration
- Produced O_2 from Mars Atmosphere
- 16 operational cycles completed on Mars
- Operations have spanned the climactic extremes of the Mars' year

MOXIE team
- MIT: Science Team Lead
- JPL: System integration & Qual
- OxEon: SOEC development and production


TIME

← THE BEST INVENTIONS OF 2023

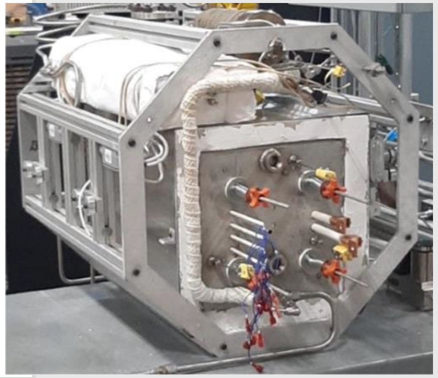
Breathing Martian Air
NASA MOXIE

Technicians in the clean room are carefully lowering the Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE) instrument into the belly of the Perseverance rover. R. Lannom—NASA/JPL-Caltech

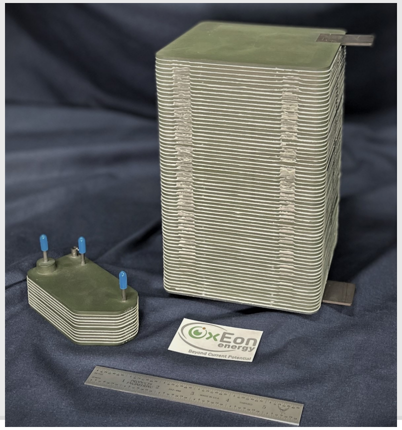
BY JEFF WILSER
OCTOBER 24, 2023 7:00 AM EDT

Scale-up of SOC device
- 5x increase in cell area
- 7x increase in cells per stack

Lunar ISRU: production of propellant H_2 and O_2 from Lunar PSR ice
Mars ISRU: production of propellant O_2 and CH_4 from Mars CO_2 and H_2O



Testing for TRL 5



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

Solid Oxide for Propellant and Power Production

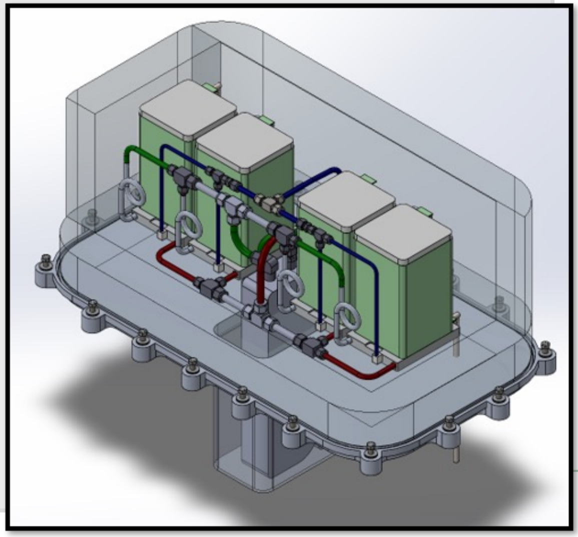
MOMS
MARS OXYGEN AND METHANE SYSTEM

MOMS

- Target production of 1-3 kg/hr O_2 and associated CH_4 from H_2O and CO_2
- High purity (>99.6%) O_2 at 1-4 bar_a
- Overall CO_2 to CH_4 60-80%

Testing of new materials

- Coking resistance
- Long term stability (5,000-10,000 hour stack test)
- Contaminant exposure



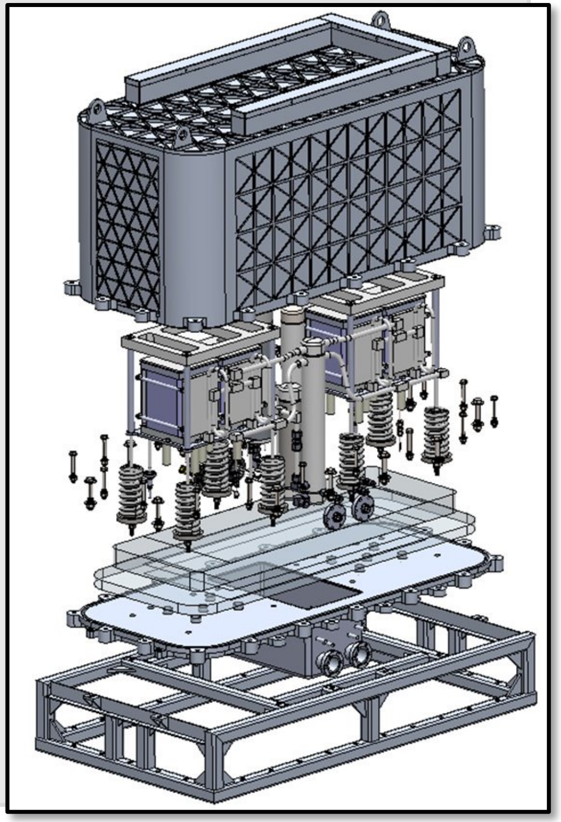
SOOPER
Sustained On Orbit Propellant Enabled Ruggedized SOFC

SOOPER

- Evaluate TRL of SOFC power system for Mars applications
- Develop 2-kW_e peak SOFC system hardware
- Operation of SOFC system with methane and O_2 to produce power

TRL Testing

- Commissioning in three orientations
- TVAC testing through 9-hour ConOps profile
- Shock/ Vibration



NASA SBIR SOC Materials Improvements

Successful NASA SBIR Phase II to develop a redox tolerant fuel electrode followed by Sequential Phase II to focus on oxygen electrode & electrolyte materials for improved stability and reduction of overall stack resistance.

Fuel Electrode

- Developed redox tolerant cathode
- Increased performance and stability with simplified cell processing
- Demonstrated coking resistance
- Dry CO_2 conversion as high as 75% and CO_2-H_2O conversion up to 85%

Oxygen Electrode

- Developed segregation resistant electrode
- Improved long-term performance via catalyst
- Improved barrier layer
- Reduced ohmic and polarization losses

Electrolyte

- Optimized processing for high yield
- Improved phase stability
- Improved ionic conductivity
- Enhanced sealing compatibility

Fuel Electrode Development

Goal: Redox Tolerant Cathode

⚠️ Traditional SOEC Challenge

✗ Ni-based cathodes oxidize to NiO upon air/oxygen exposure

✗ Oxidation causes irreversible microstructural damage

✗ Requires continuous supply of reducing gas (H_2) even at startup

✗ System complexity & cost increase significantly

✗ Limits deployment flexibility and reliability

✓ OxEon Redox Tolerant Solution

✓ Completely tolerates partial AND full redox cycling

✓ Full redox = complete oxidation of Ni to NiO, then re-reduction using reducing gas produced by the stack

✓ Performance recovery in minutes using H_2 from steam electrolysis

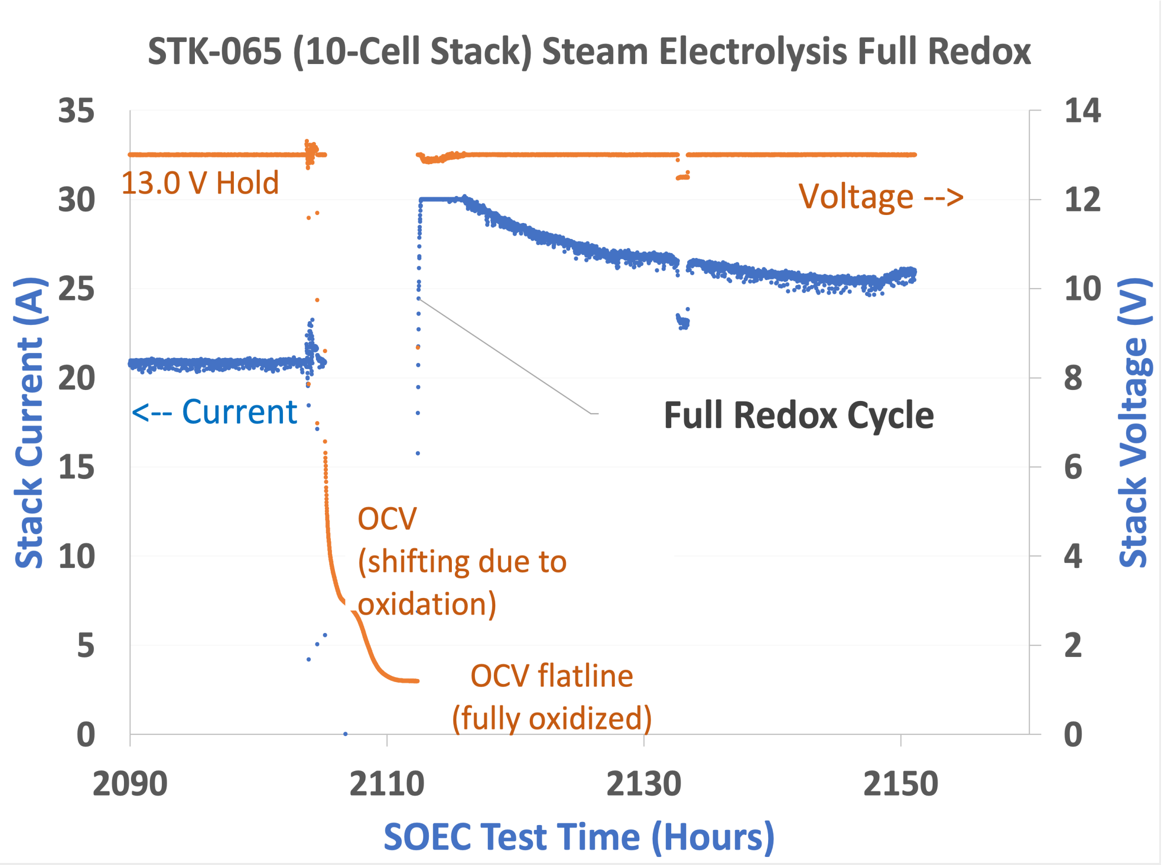
✓ Eliminates need for external reducing gas supply and/or recycle

✓ Also robust for dry CO_2 and steam + CO_2 electrolysis — Coking formation resistant up to 75% CO_2 conversion and 85% CO_2-H_2O conversion to date

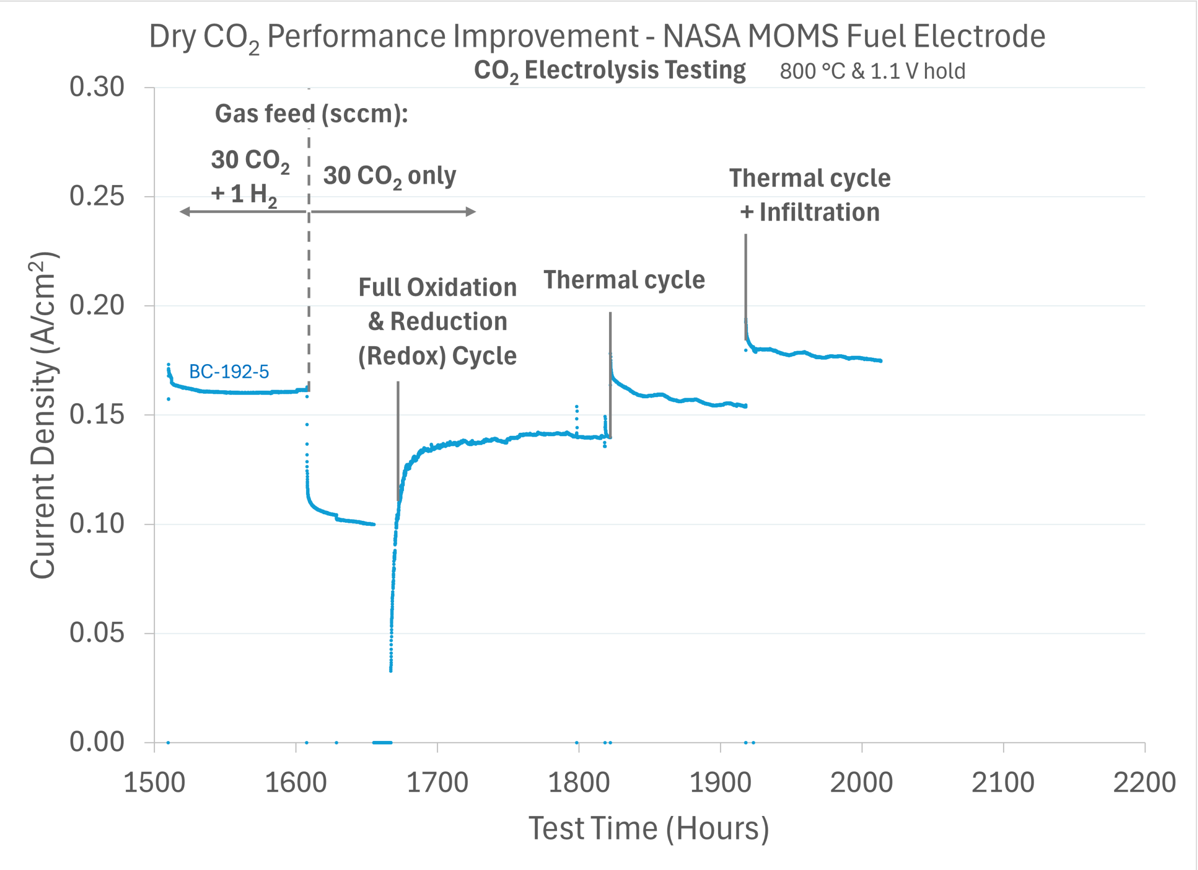
Fuel Electrode Development

Oxidation & redox cycle capabilities

Demonstration of complete oxidation & redox cycle with steam electrolysis followed by stack recovery once current reapplied.



Demonstration of complete oxidation & redox cycle with CO_2 electrolysis followed by stack recovery once current reapplied. Complete thermal cycle with and without infiltration also shown.

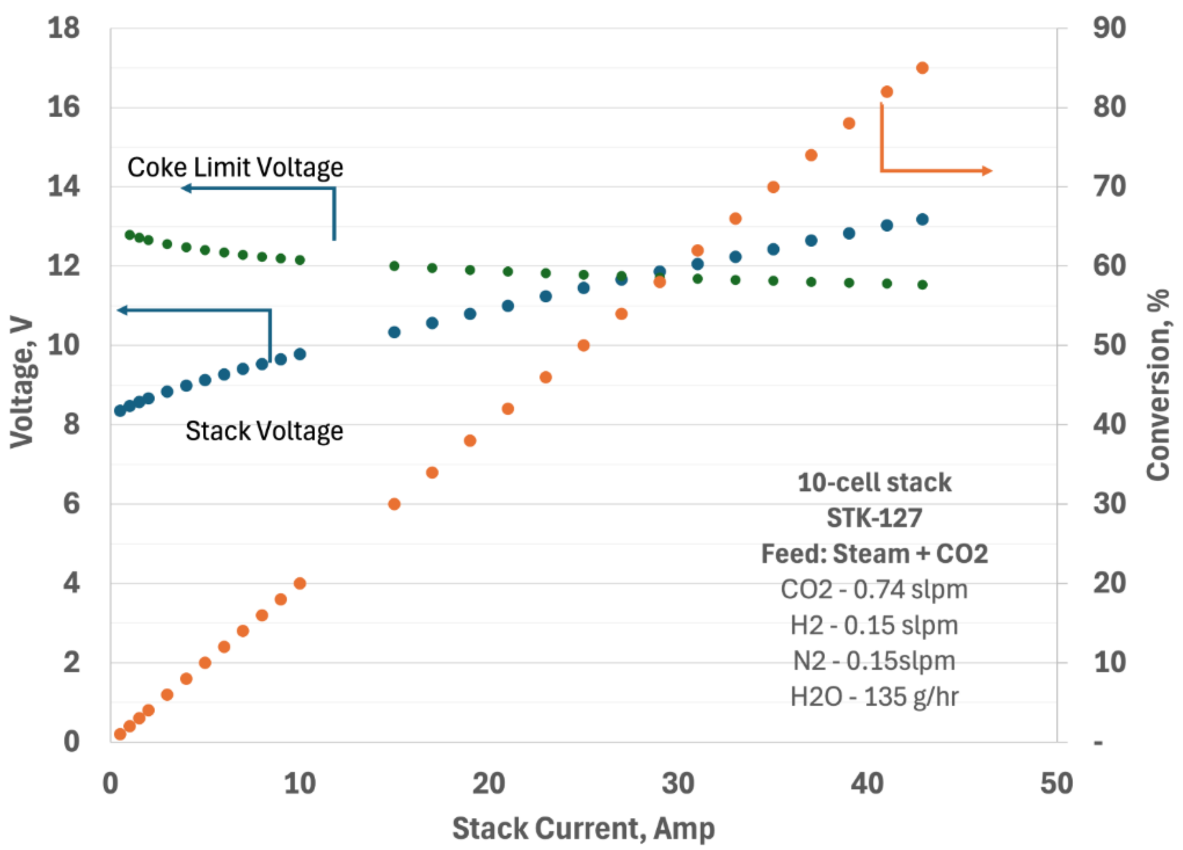


Redox tolerant cathode | NASA SBIR II | Thermal cycling

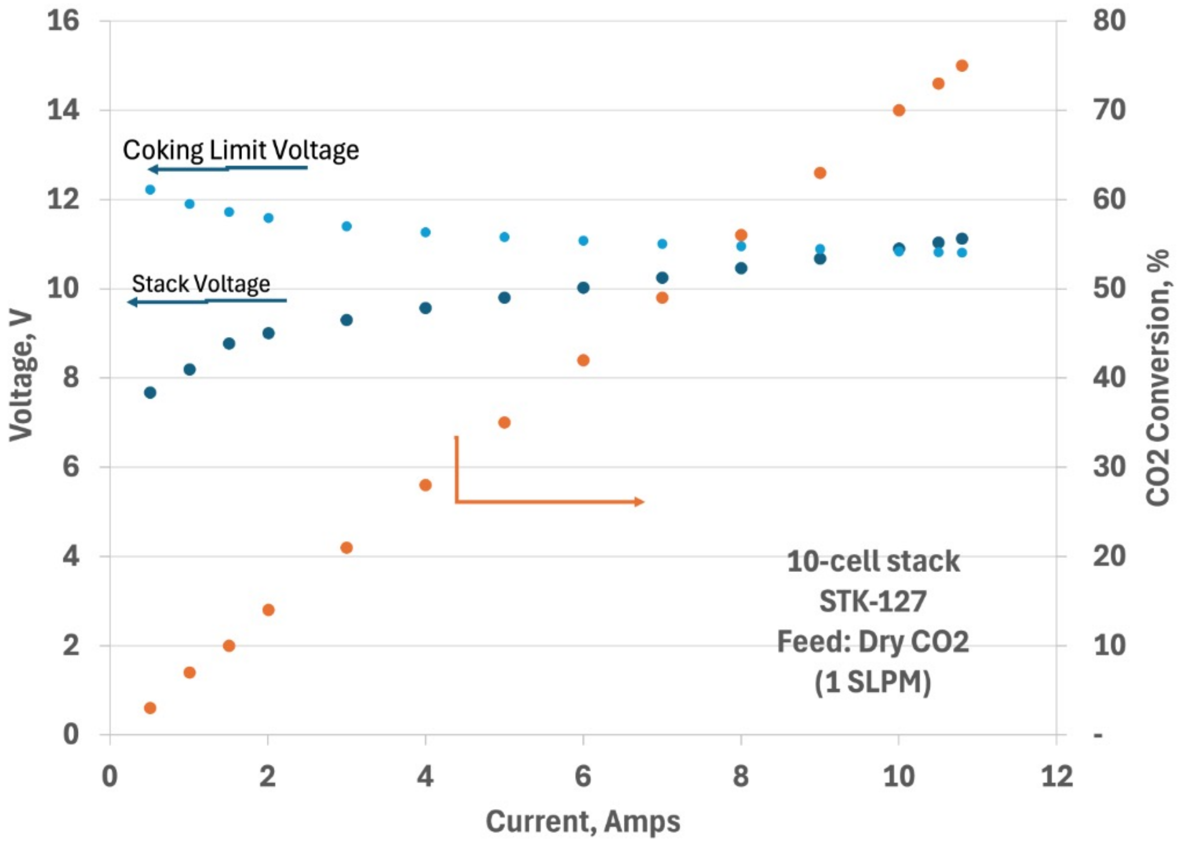
Fuel Electrode Development

Coking resistance testing

Coelectrolysis of CO_2-H_2O demonstrated 85% conversion at 0.2 V/cell above the coking potential without any indication of carbon formation



Dry CO_2 electrolysis demonstrated 75% conversion at a voltage above the coking potential without any indication of carbon formation

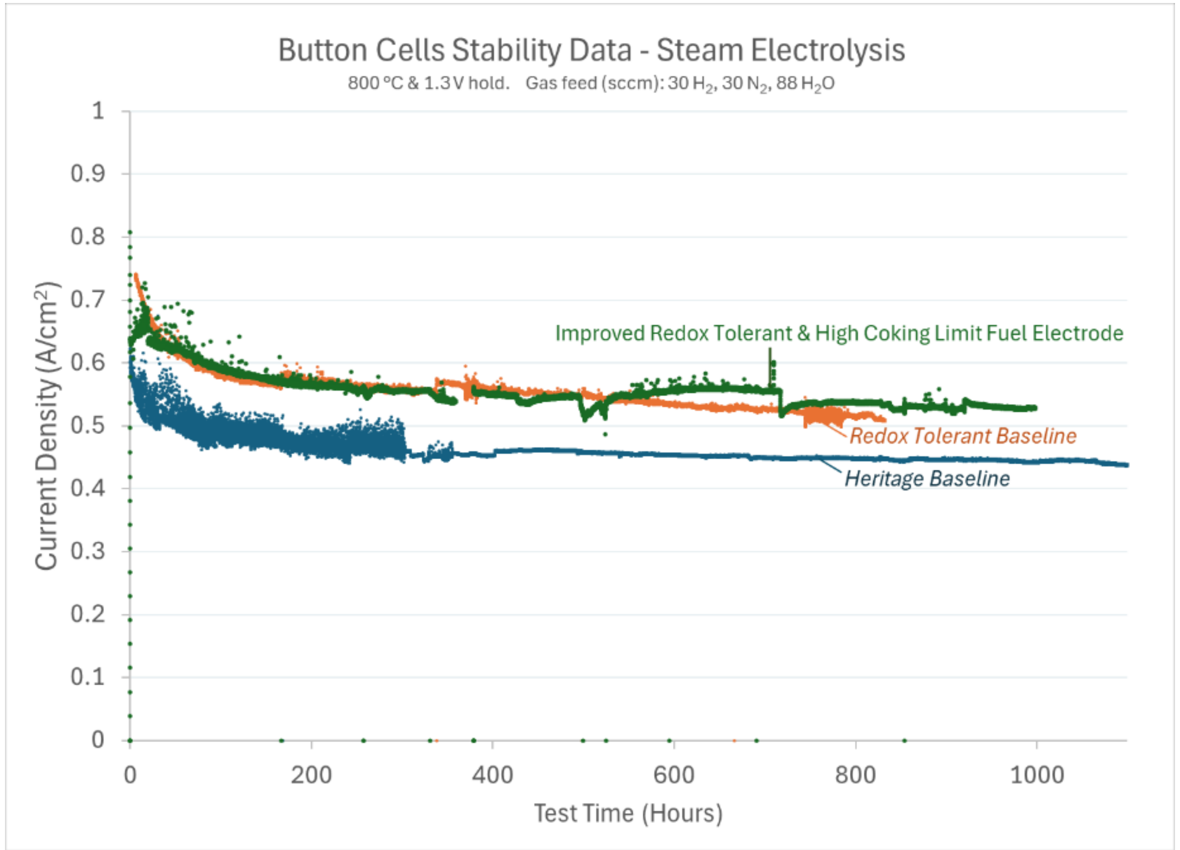


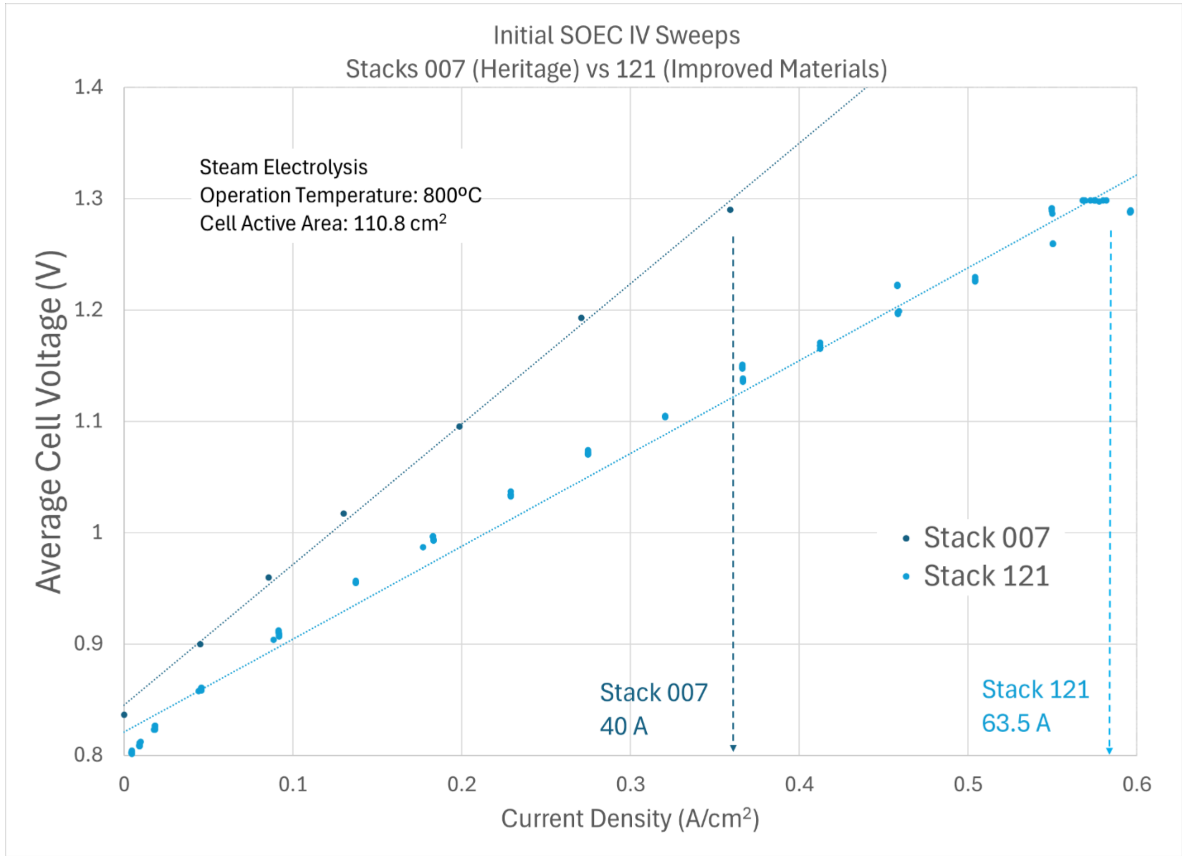
Fuel Electrode | Coking resistant stack | Dry-CO_2 operation | Coelectrolysis of CO_2-H_2O

Oxygen Electrode and Electrolyte Development

Improved performance and stability

NASA SBIR Phase II Sequential allowed changes to the electrolyte and oxygen electrode barrier to address low phase stability and stack performance. The resulting materials have been incorporated into button cells and full stacks that demonstrate improvement to long-term stack performance and stability.





Long term testing

5,000-10,000 hour continuous stack operation

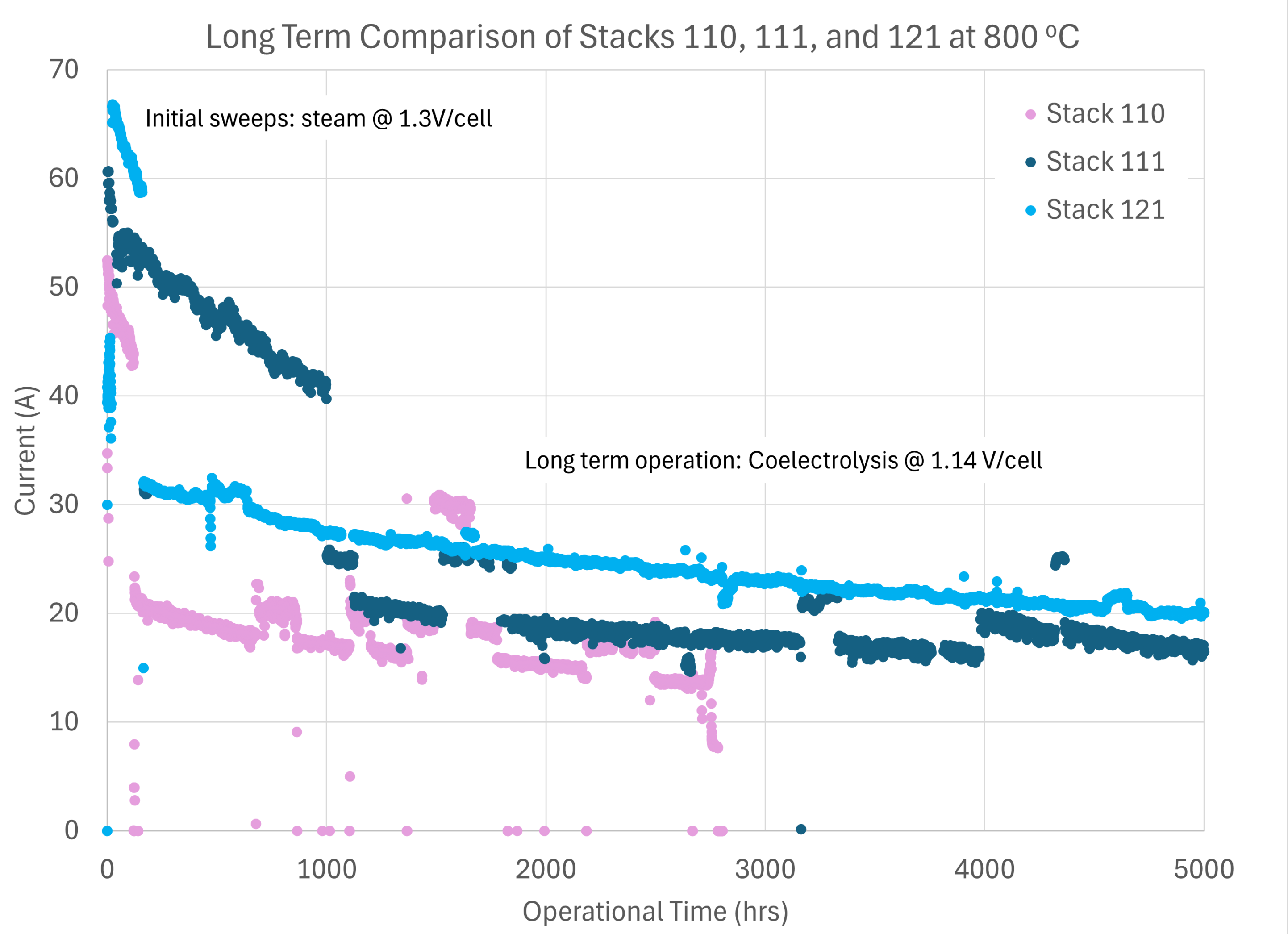
Long term testing results

Initial sweep in steam electrolysis mode to establish baseline performance

- Heritage baseline sweep up to thermal neutral voltage (1.3 V/cell) produces 40 A stack current
- Early Phase II stacks hit 55 A on initial sweep (37% more than heritage)
- Latest Phase II stacks hit 68 A on initial sweep (70% more than heritage)

Long term operation in coelectrolysis mode with CO_2-H_2O

- Operation at 1.14 V/cell maintained for all stacks to allow for comparison in long-term stability and degradation rate



Year 1 Accomplishments

MOMS: Mars Oxygen Methane System

Short term performance and coke resistance testing

>80% conversion at 0.2 V/cell above coking potential in co-electrolysis operation demonstrated with 2, 10-cell stacks without indication of coking event. Both stacks achieved nearly 75% dry CO_2 conversion without coke formation.

Long term stack testing

Baseline and improved materials stack each testing for >5000 hours, with improved stack currently being operated for an additional 1000 hours at target hardware demonstration conditions.

Materials Development

- Improved electrolyte processing and yield
- Improved air electrode stability with infiltrated catalyst treatment
- Developed a single print & fire fuel electrode that retains redox tolerance and high coking resistance limit

Preliminary Design Review

Hardware demonstration system preliminary design review occurred with program requirements used to size system to meet KPP targets for oxygen production, pressure, and overall system CO_2 conversion.

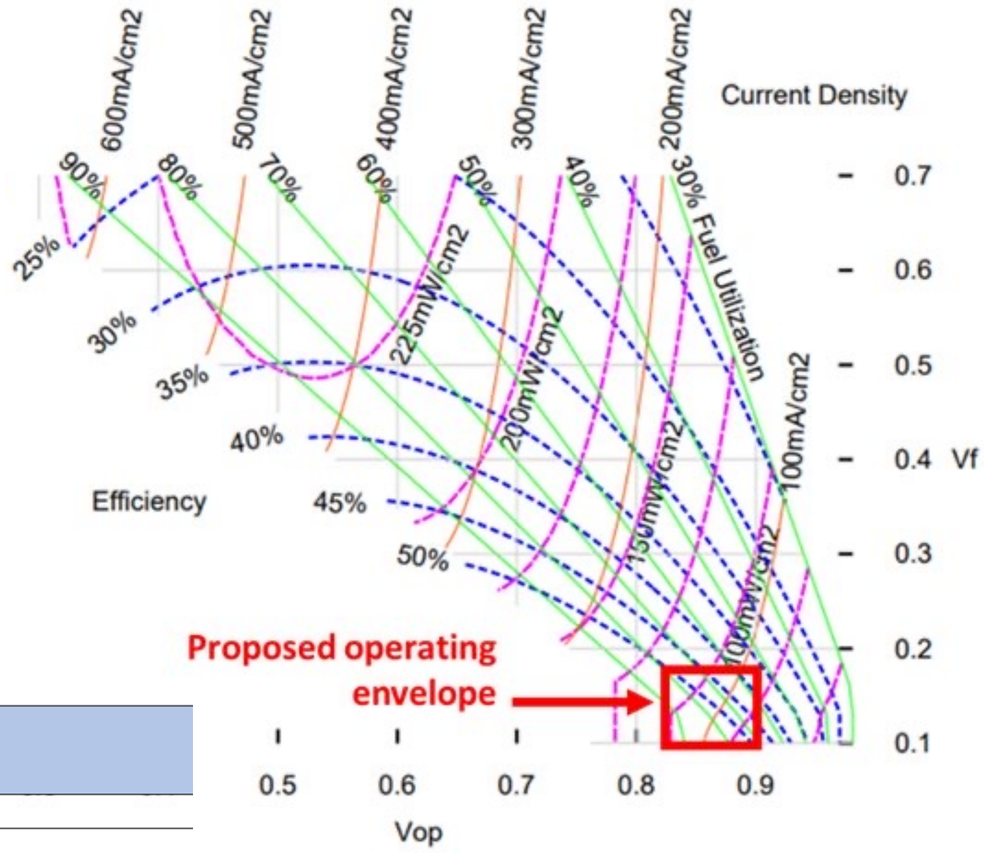
SOOPER

Sustained On Orbit Propellant Enable Ruggedized Solid Oxide Fuel Cell (SOOPER SOFC)

System Requirement to operate with

methane | oxygen

- Typical SOFC operation uses 6-10 stoichs excess air for cooling
- Potential operating envelope identified using stack model simulations
- 10-cell SOFC stack testing with methane reformate syngas as fuel and high purity oxygen as oxidant to demonstrate concept



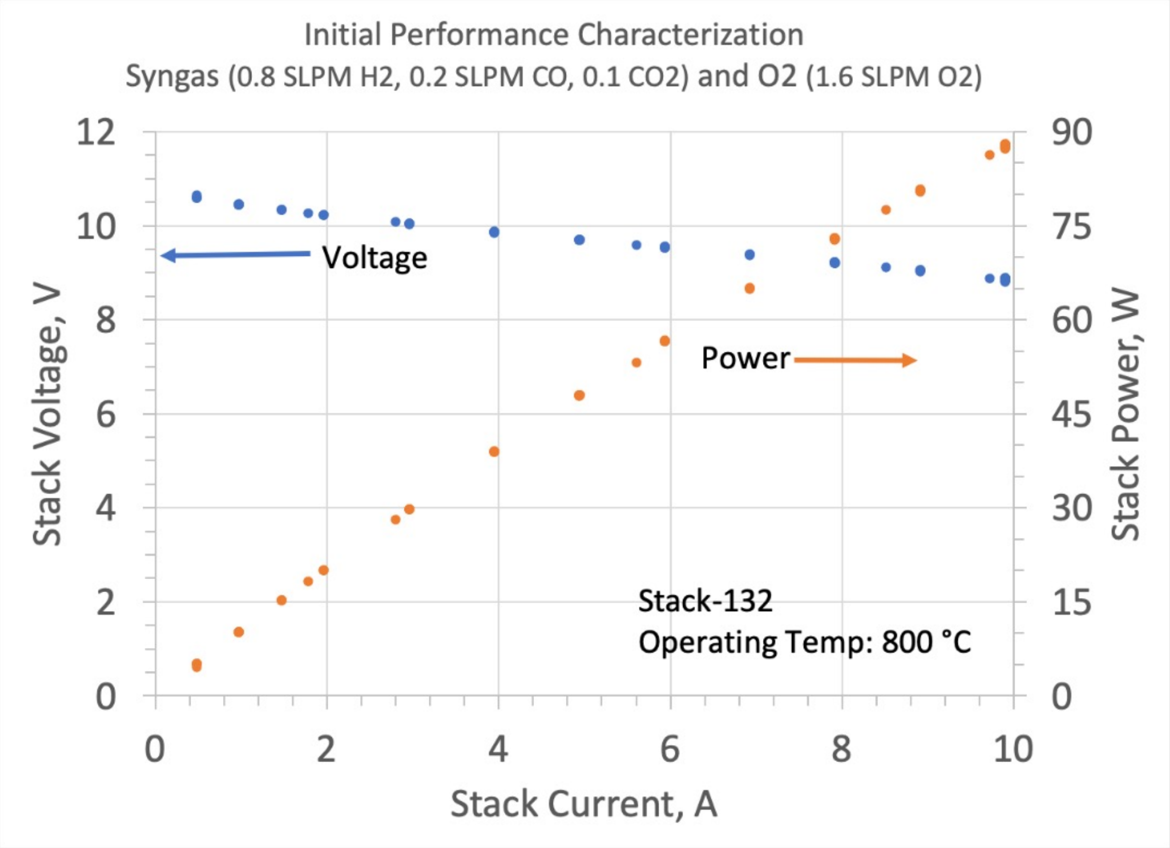
Test Objective (Milestone, customer requirement, etc)	
1	The purpose of the test is to run in SOFC mode using sygnas as fuel and O2 as oxidant
2	Target: 70-90% fuel utilization (H2 and CO in syngas)
3	Low current density operation to control stack temperature (MAX STACK TEMP 850 C), anticipate stack current will will be ~10-12 Amps
4	Determine stack baseline performance (ASR)
5	Target: 70-90% O2 utilization
6	Evaluate in-stack TC readings against O2 inlet TC readings during heat-up

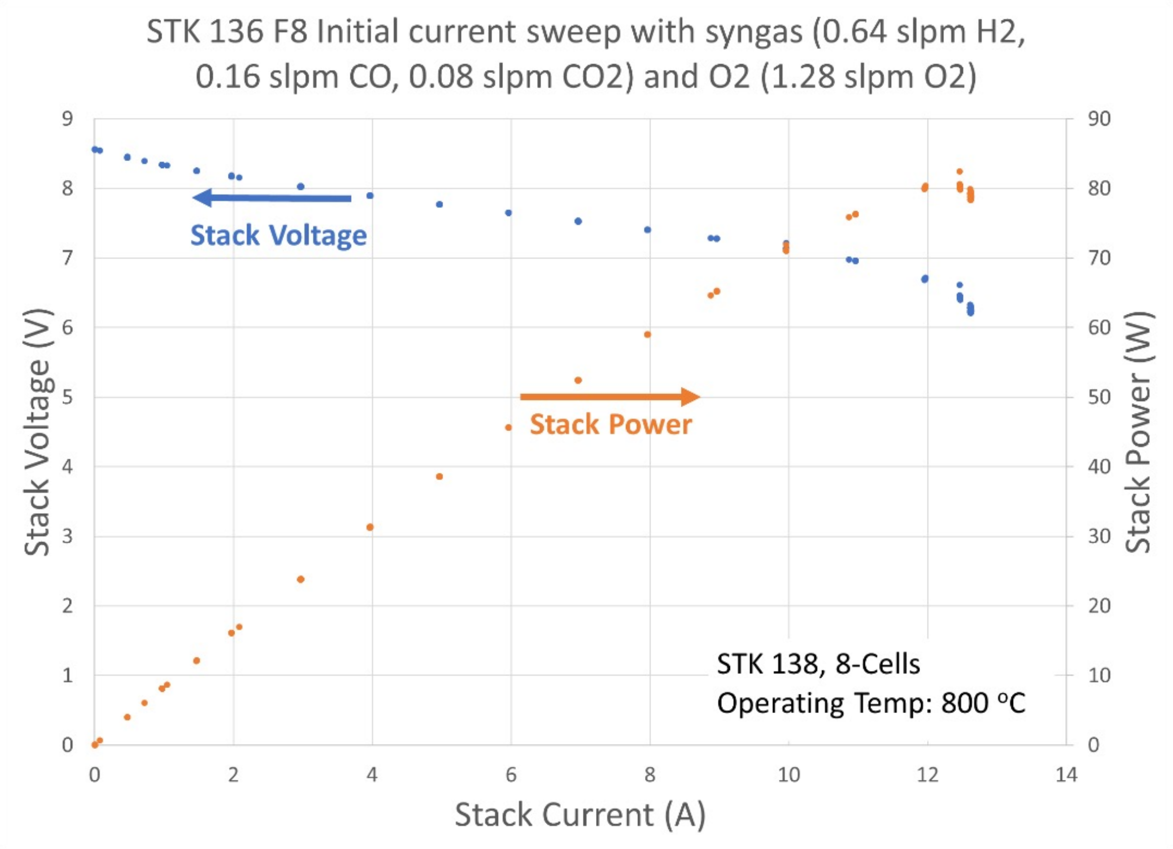
SOFC

Concept demonstration / stack testing

System Requirement for power output > 2.0 kW_e

- Power sweeps support system with 4, 50-cell stacks will be able to meet power generation requirement



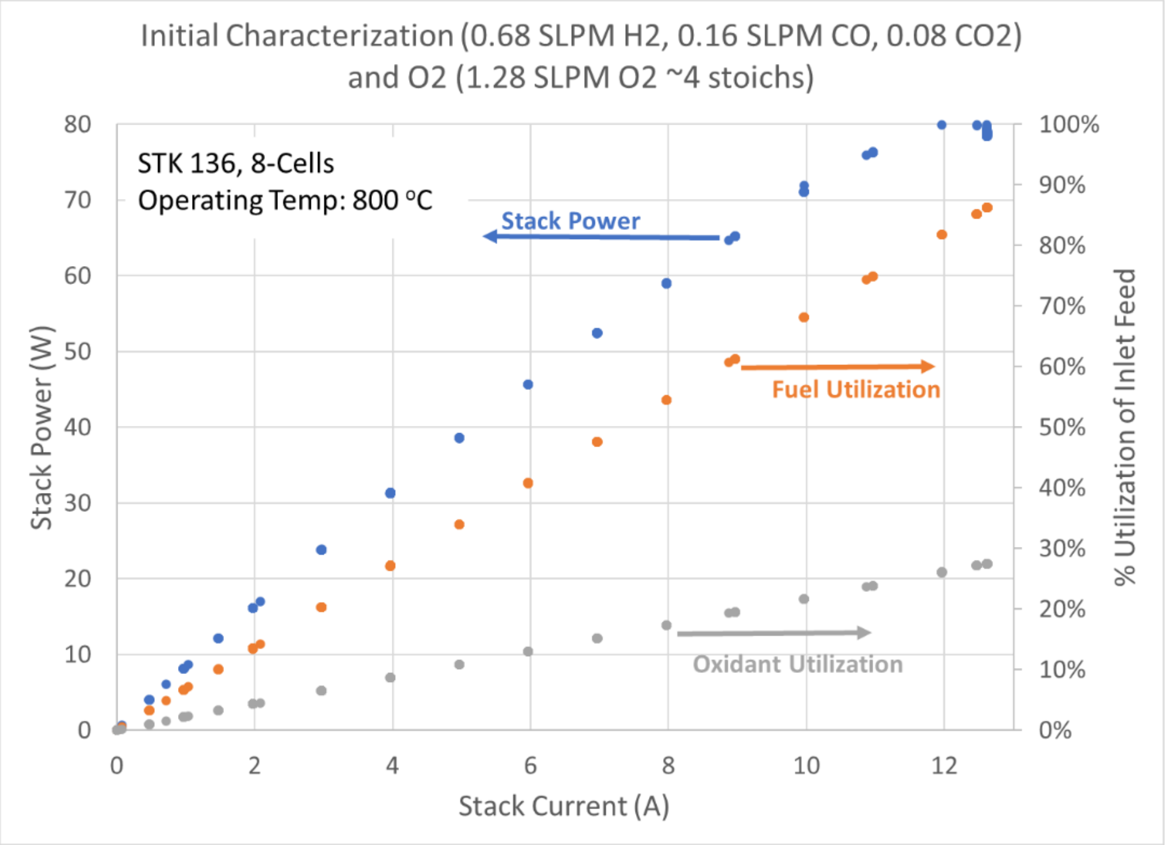


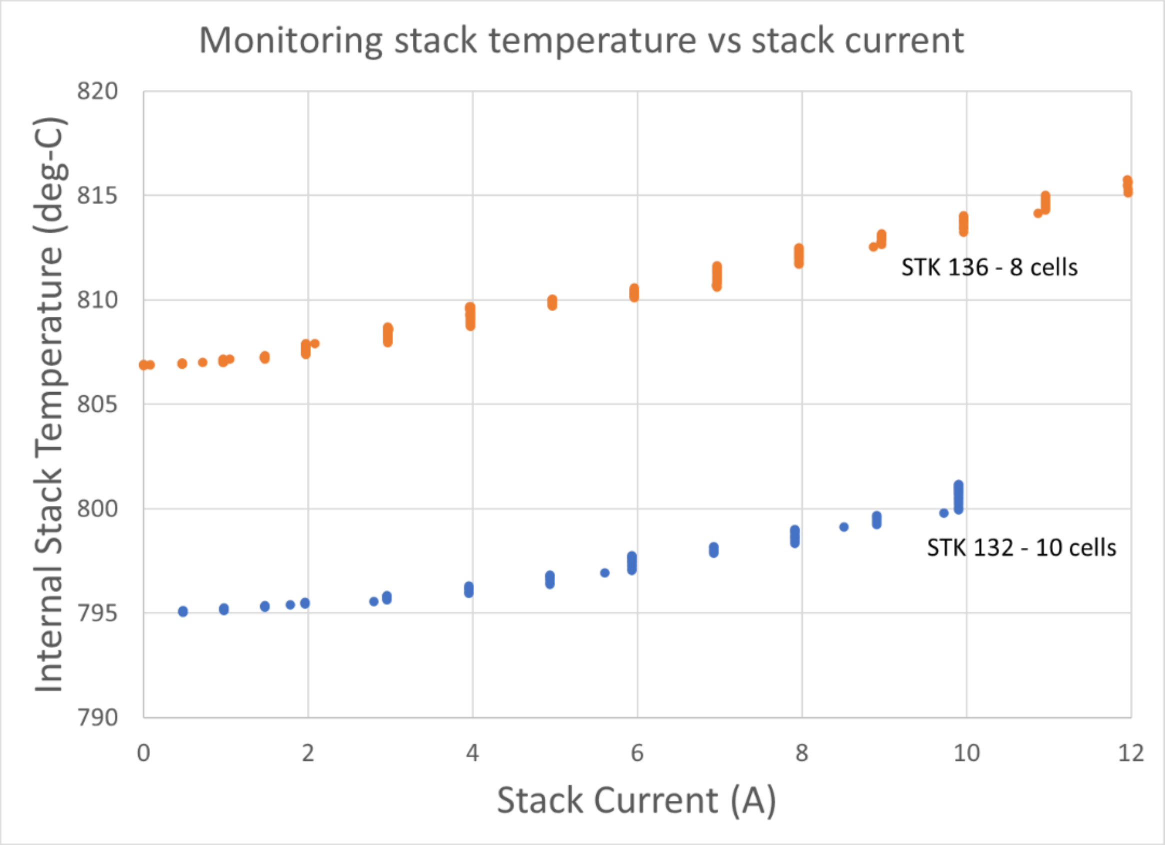
SOFC

Concept demonstration / stack testing

System Requirement for operating with O_2 and syngas (CH_4 reformate)

- Stack current limited in this operating mode (sans cooling air) to prevent excessive dT across stack



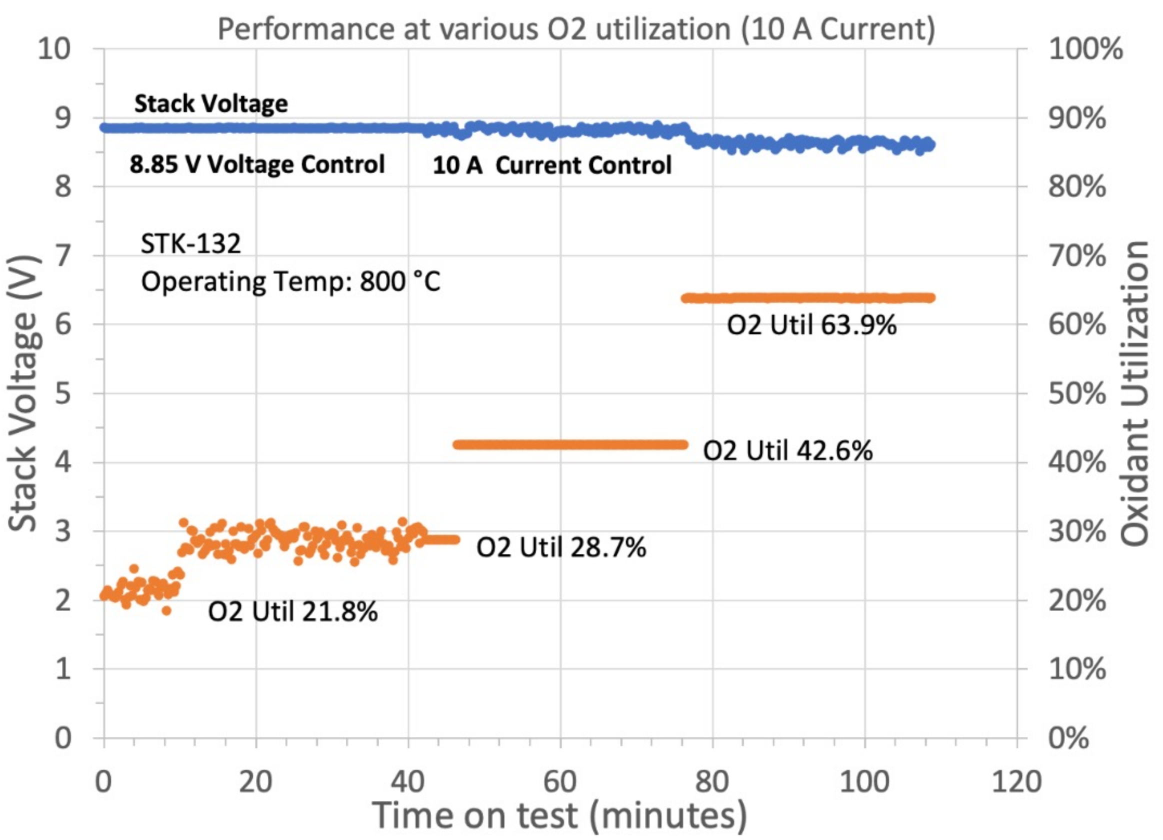


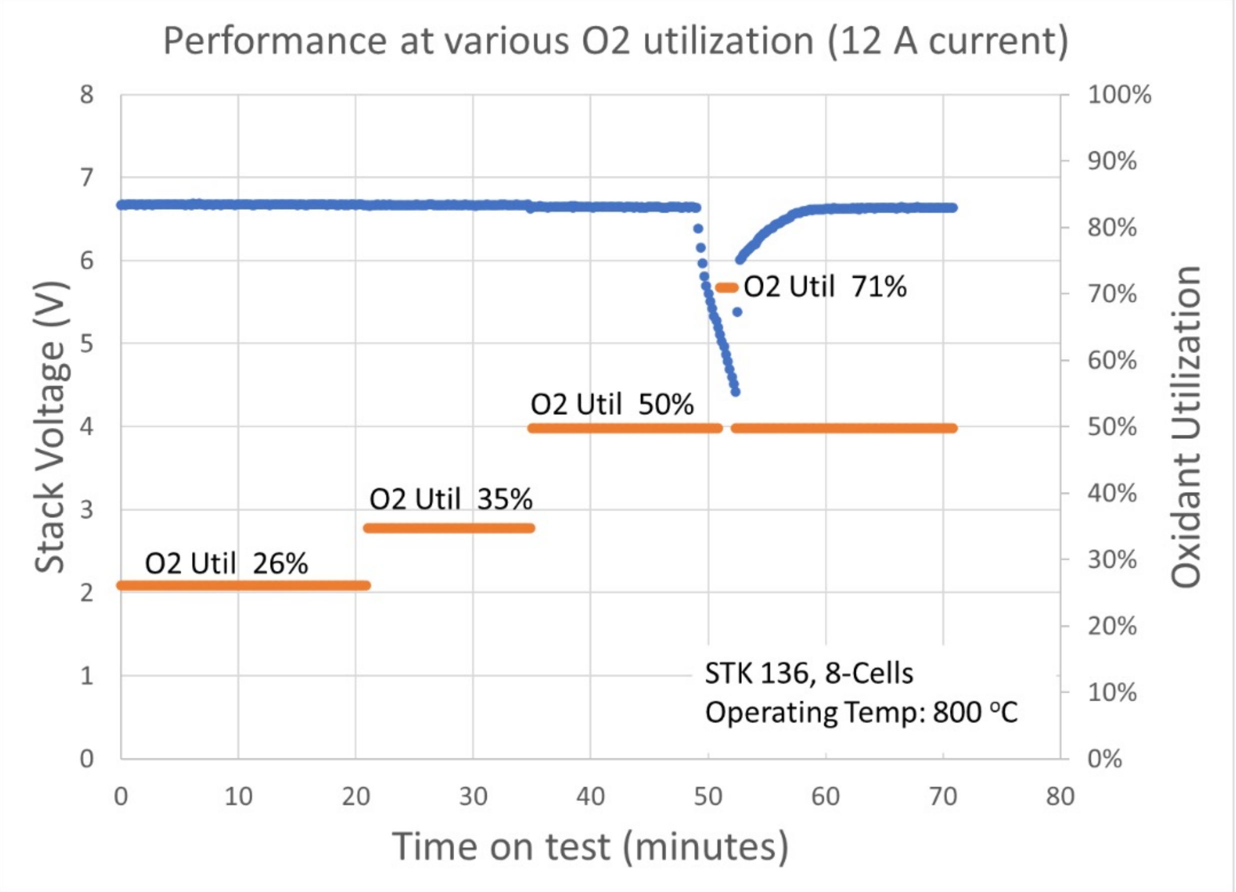
SOFC

Concept demonstration / stack testing

System Requirement for operating with O_2 and syngas (CH_4 reformate)

- O_2 feed manifolding identified as area for improvement to allow for higher O_2 utilization by stack





System Development

SOOPER SOFC

Stack concept testing

Successful operation in SOFC mode with oxygen and methane reformate, demonstrating syngas utilization up to 90% and oxygen utilization up to 60%. A 4, 50-cell stack system will meet program power requirement for > 2 kW_e.

Oxygen feed manifolding

Manifolding design development for the oxygen is underway to ensure electrical isolation from the stack and ensuring a low leak rate for high stack utilization.

Reformer development

A reformer test article, which will be thermally integrated in the SOFC enclosure, was successfully operated to demonstrate methane reformation into a syngas feed compatible with the stacks. Feed ratios, operating temperature, and GHSV were evaluated for system optimization.

Stack thermal enclosure

Design for the thermal enclosure for the SOFC stacks will enable maintaining a nominal pressure (~7psi) on the stacks during testing in TVAC chamber.

Demonstrated SOC Capabilities

Redox Tolerance

Complete tolerance of partial and full redox cycling with rapid performance recovery using self-generated H_2 or CO. No external reducing gas required.

Thermal Cycling

Demonstrated 70 thermal cycles with a button cell and 5 thermal cycles with a full-size stack (RT ↔ 800°C) without observed performance loss and degradation. Enables grid-responsive operation.

Improved Performance

Initial current-voltage stack sweeps show 50% increase in current density indicating a 50% increase in H_2 production potential per stack device.

CO_2 Robustness

Fuel electrode operates stably in dry CO_2 and CO_2 + steam feeds at very high conversion (>70%) with no indication of coking. Critical for space and other industrial processes.

System Integration

Successful integration of SOEC with methanation reactor to produce O_2 and CH_4 propellants and methane reformer with SOFC for thermal benefits provides path for future rSOC sytsems.

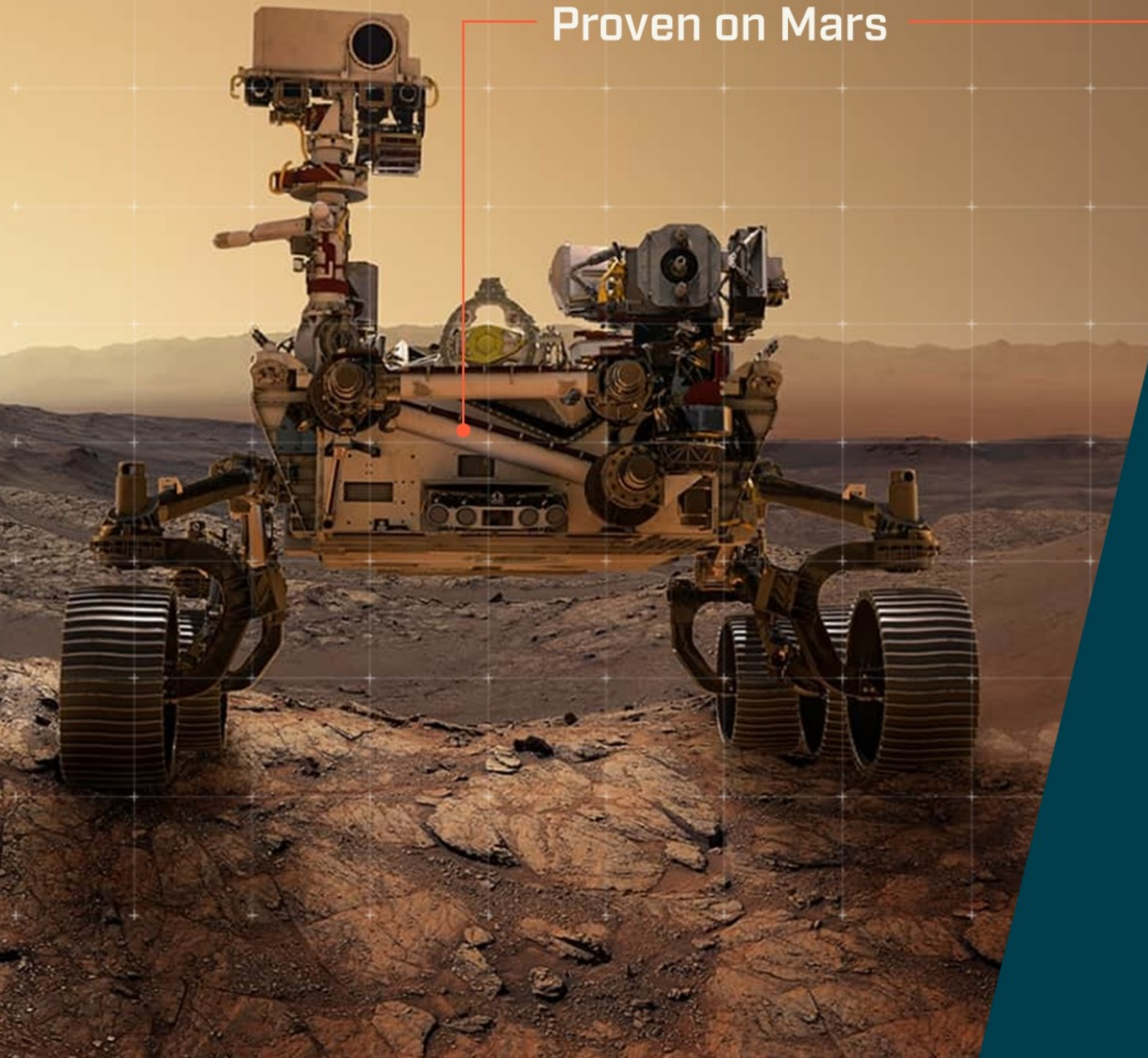
Long-Term Stability

5,000–10,000 hour full-size stack tests underway to monitor degradation rates and validate materials for commercial deployment.

Clean Fuels Anywhere

Proven on Mars

For Solutions on Earth



OxEon energy

Beyond Current Potential

Thank you

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