Testing of Solid Oxide Electrolysis System and Balance of Plant for H_2/O_2 Production from Lunar Water

Source: Kornuta et al. (2017)

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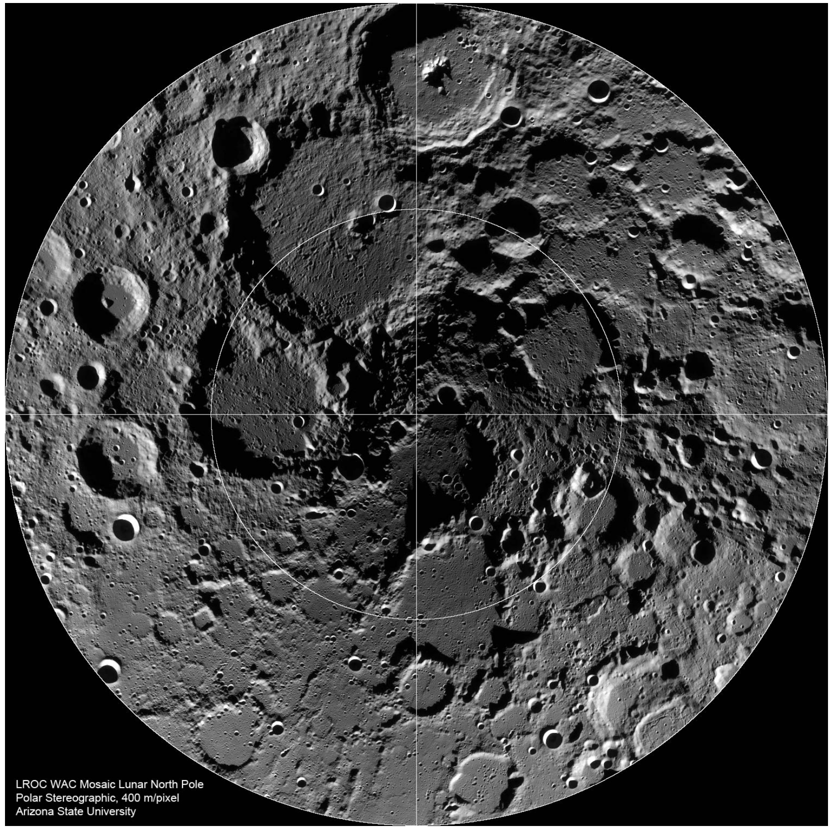
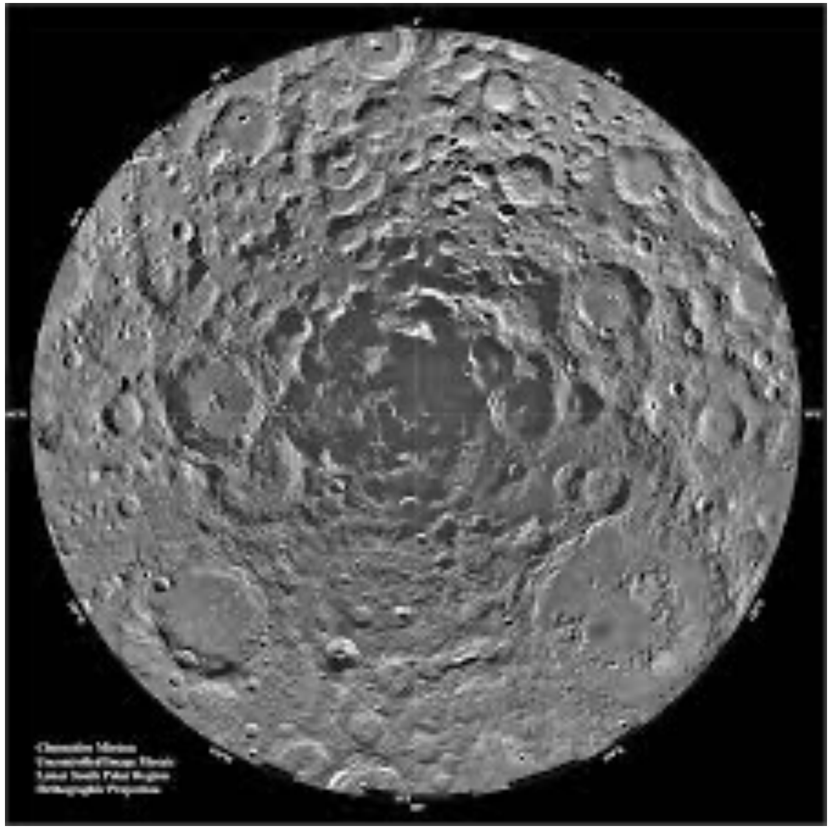
Introduction





- Discovery and mapping of water at lunar poles expands possibilities for a cislunar economy.
- Electrolysis of lunar water to produce hydrogen in-situ is a key technology needed to further ISRU and expand the scope of space resources.

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Background

- Lunar water is generally found in permanently shadowed regions (PSRs), with lack of sunlight and temperatures <100 K.
- This poses unique challenges for equipment reliability, maintainability, and availability.
- Electrolysis has particularly large energy costs, and therefore demands energy efficiency.

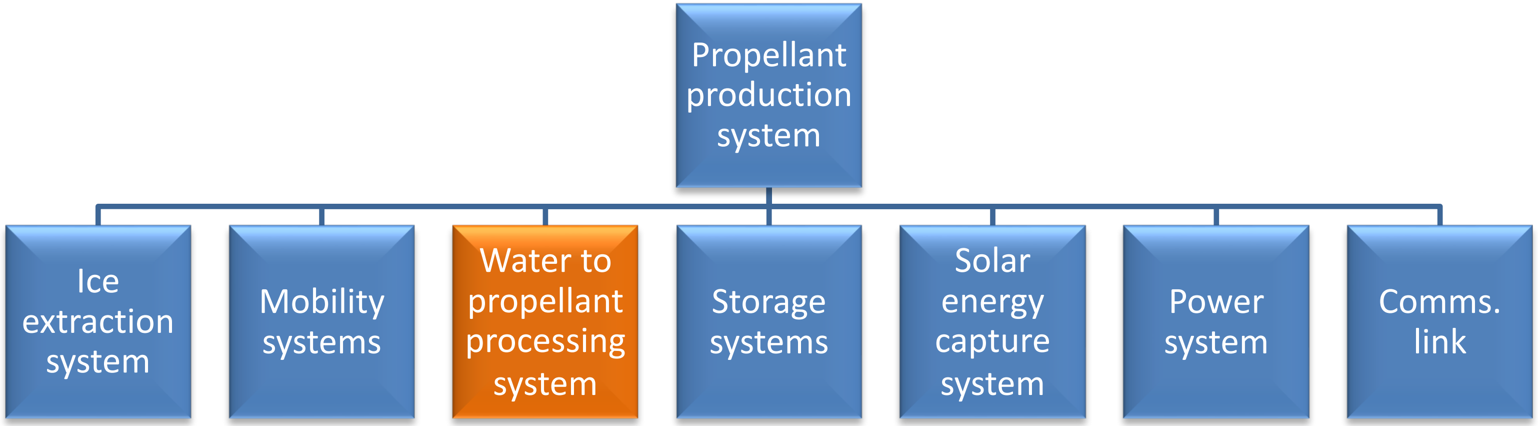
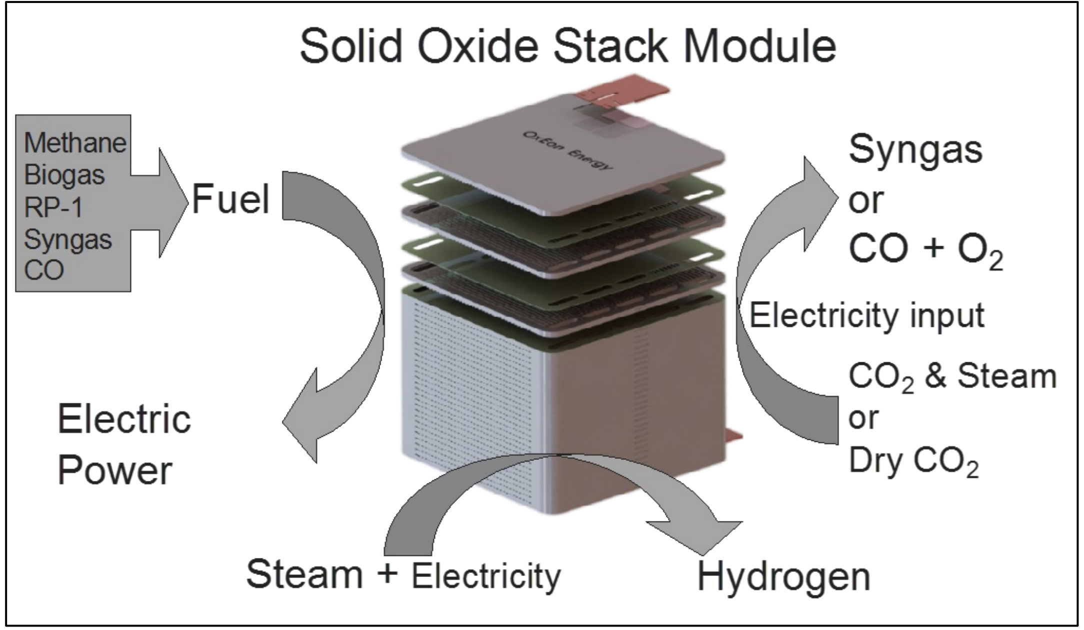


Image provided by: ULA

Solid Oxide Electrolysis

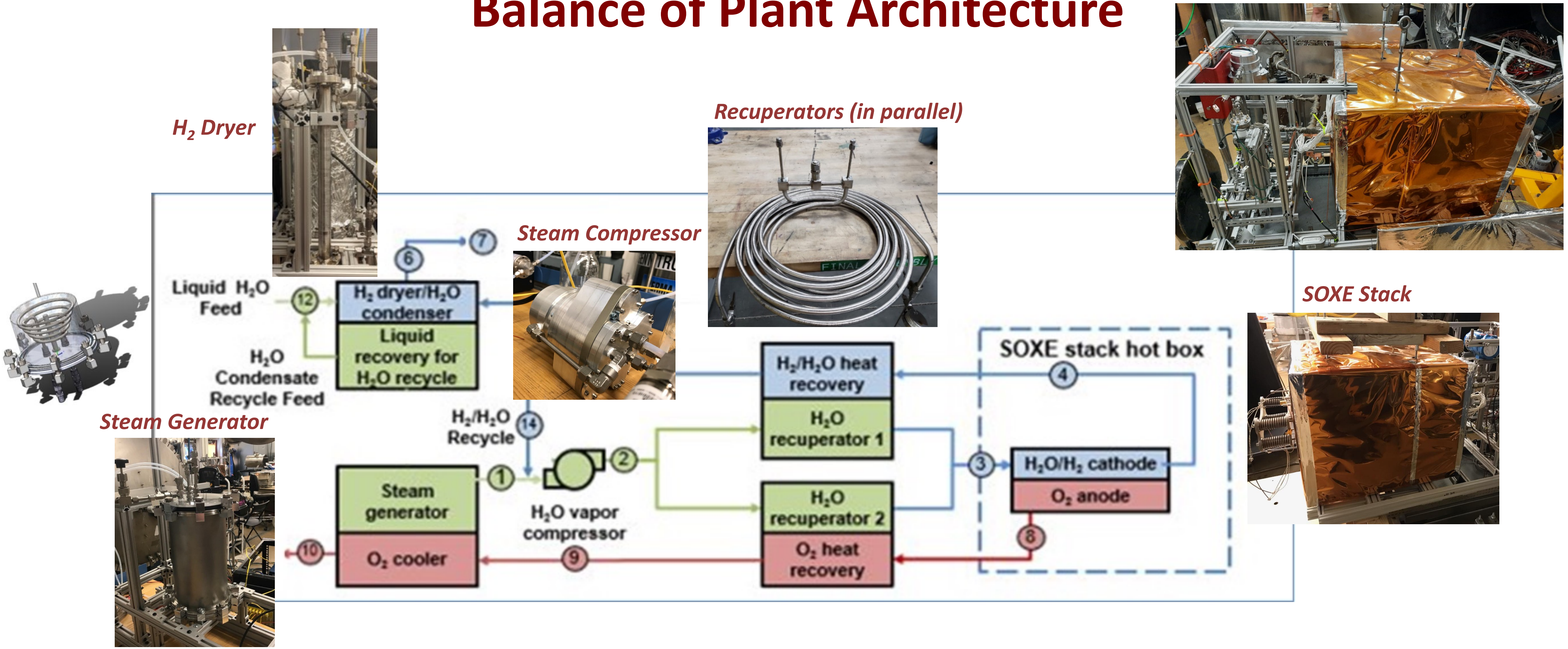
- Solid oxide electrolysis (SOXE) operates on steam at $T > 600°C$
  - Lowers required thermal neutral voltage (due to no internal phase change)
  - Lowers open circuit voltage (due to high T, i.e., lower Gibbs free energy of H_2O splitting)
  - High current density and lower kWh_{elec}/kg_{H2} than lower-T PEM and alkaline electrolysis.



- OxEon Energy and Mines, in a NASA Tipping Points project, are developing and demonstrating a SOXE stack with a thermally integrated balance of plant (BOP) to separate chilled water into H_2 and O_2 products.

- Key performance parameters:
  - H_2 production: ≥ 1.8 kg_{H2}/day
  - O_2 product pressure: ≥ 2 bar
  - System specific power: 46 kWh_{elec}/kg_{H2}

Balance of Plant Architecture



- High-T electrolysis requires optimal BOP to minimize undesirable energy costs due to electrical heating.
- BOP includes multiple heat exchangers to recover heat and recover excess H_2O from the SOXE stack.

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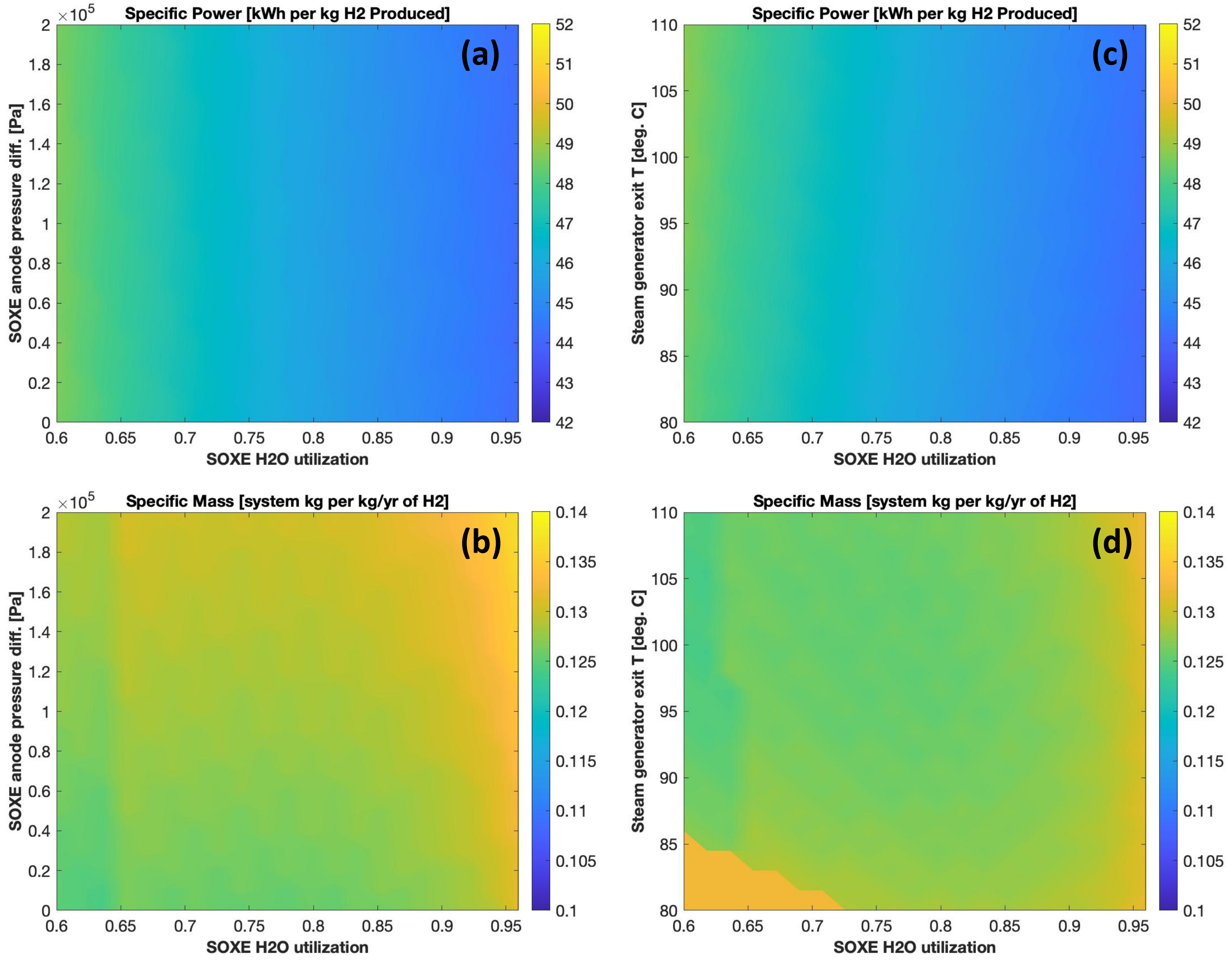
Optimization and Modeling

- System modeling effort to:
  1) optimize stack mechanical components, cells, and thermal integration, using specific power and specific mass as performance measurements,
  2) design the integrated lab-scale stack and BOP components for a preferred, optimal configuration.
- Parametric studies to compare different configurations and optimize control parameters:
  – ε_{H2O}: SOXE stack steam utilization
  – P_{rat}: compressor pressure ratio,
  – T_{vap}: steam vaporization temperature
  – ΔP_a: SOXE anode pressure differential



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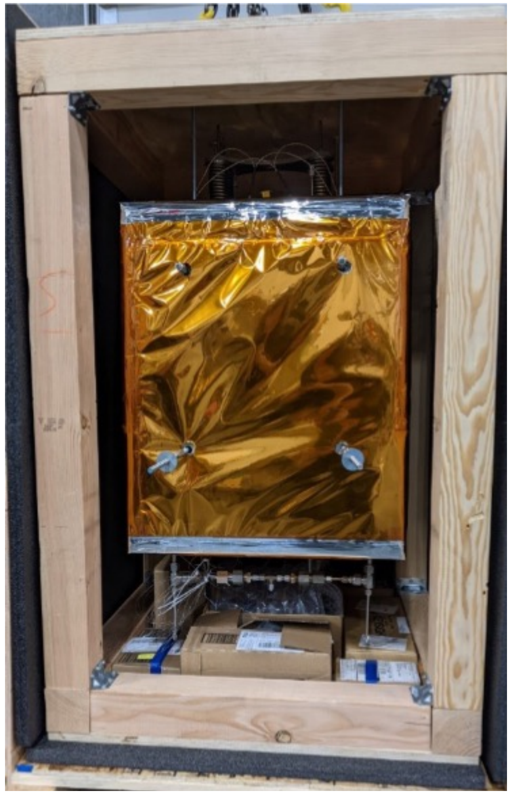
Testing (Stack and Recuperators)



- High-*T* SOXE stack and exhaust recuperators are designed and tested under thermo-neutral operating conditions (*T* = 800°C, *P* up to 2 bar, $\varepsilon_{H2O} \leq 0.95$)
- Fabrication and seals designed to operate without leaks in vacuum.
- Hotbox with multi-layer insulation designed to keep heat losses under 250 W.

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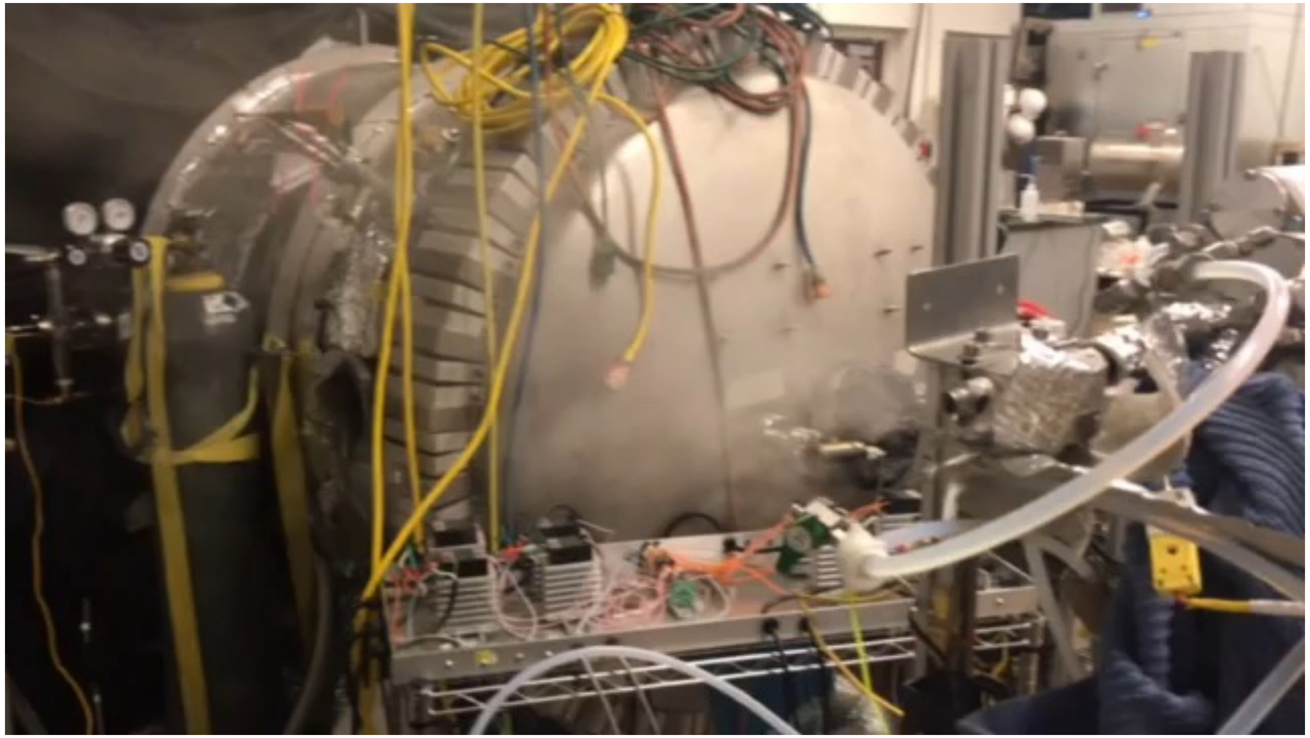
Balance of Plant Testing (Steam Compressor and Generator)

- Steam generator designed and fabricated at Mines requires electric heater to keep T_{vap} > 90°C
  - 2nd largest electric load (up to 8.2 kWh_{elec}/kg_{H2}) after SOXE stack
- Oil-free scroll compressor built by Air Squared for operation at compressor inlet > 100°C for $P_{rat} \leq 4.0$
  - At low P_{rat} loads < 2.0 kWh_{elec}/kg_{H2}
- Control loops control compressor speed, liquid flow rates, and T_{vap} to support steady steam flow to SOXE stack and recuperators.



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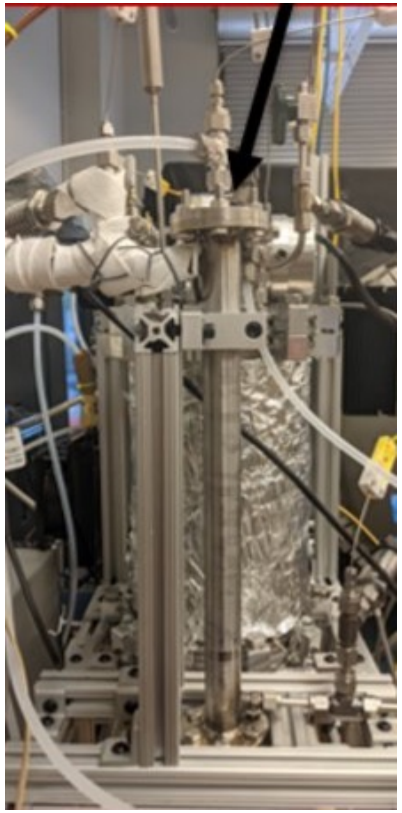
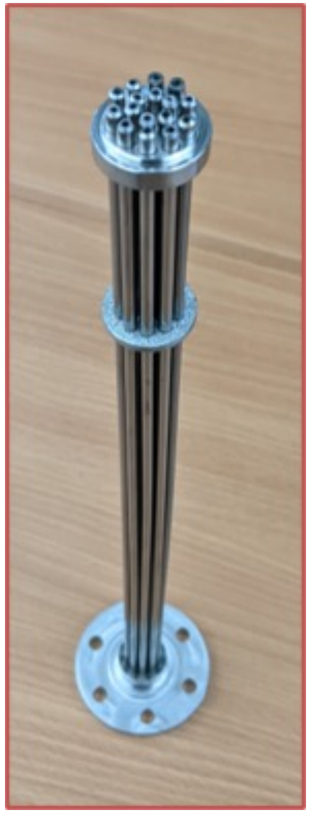
BOP design and testing -- H_2 dryer

- Model-based design led to fabrication of a unique shell and tube heat exchanger with condensate separation for cooling and drying of H_2 exhaust from SOXE cathode.
- A small fraction of H_2 is recycled back to compressor inlet to keep the SOXE cathode in chemically reduced at high *T*.
- Excess liquid water through the internal tubes cools the H_2 and avoids pinch point due to condensation for excess H_2O recovery.
  - Most liquid H_2O is recycled back to the supply reservoir.





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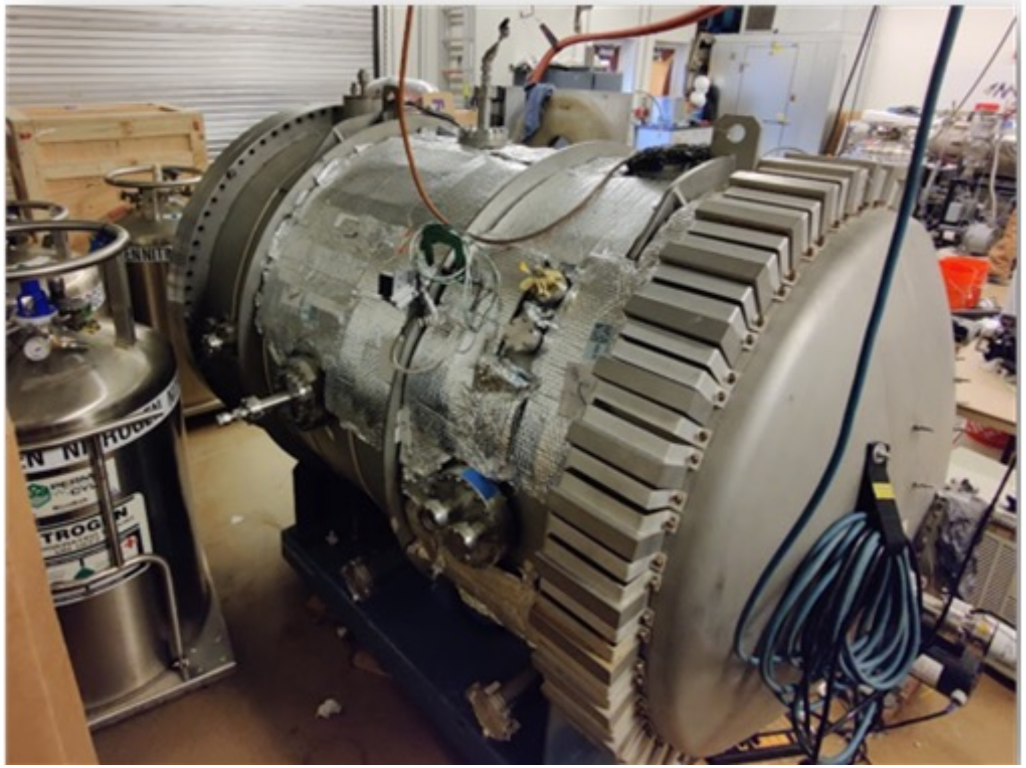
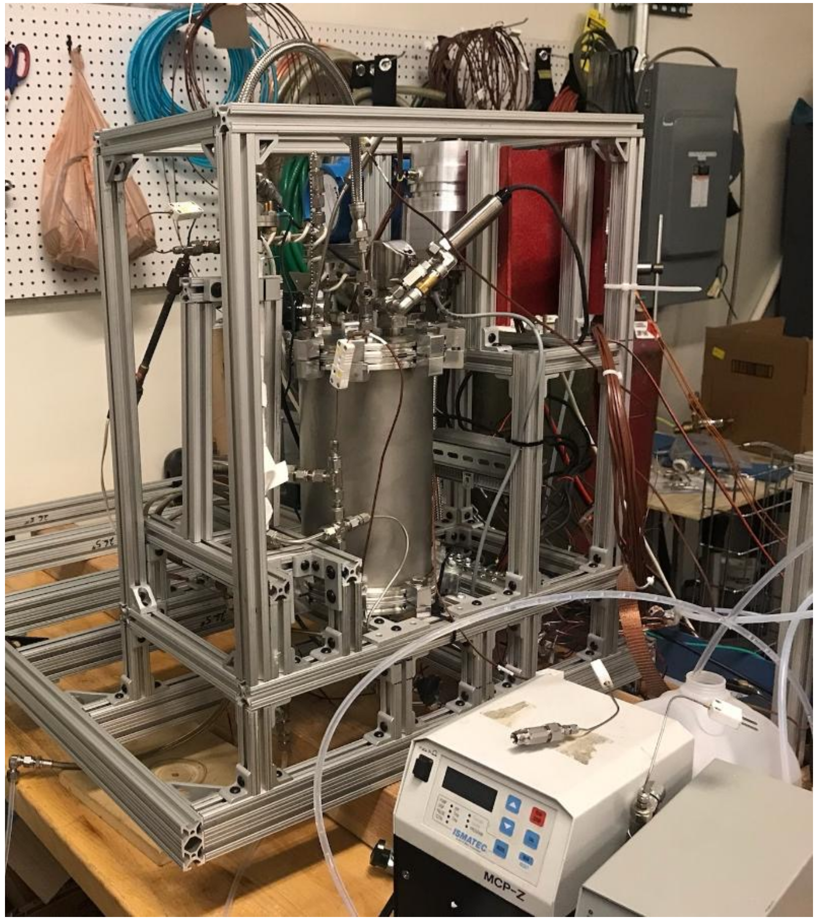
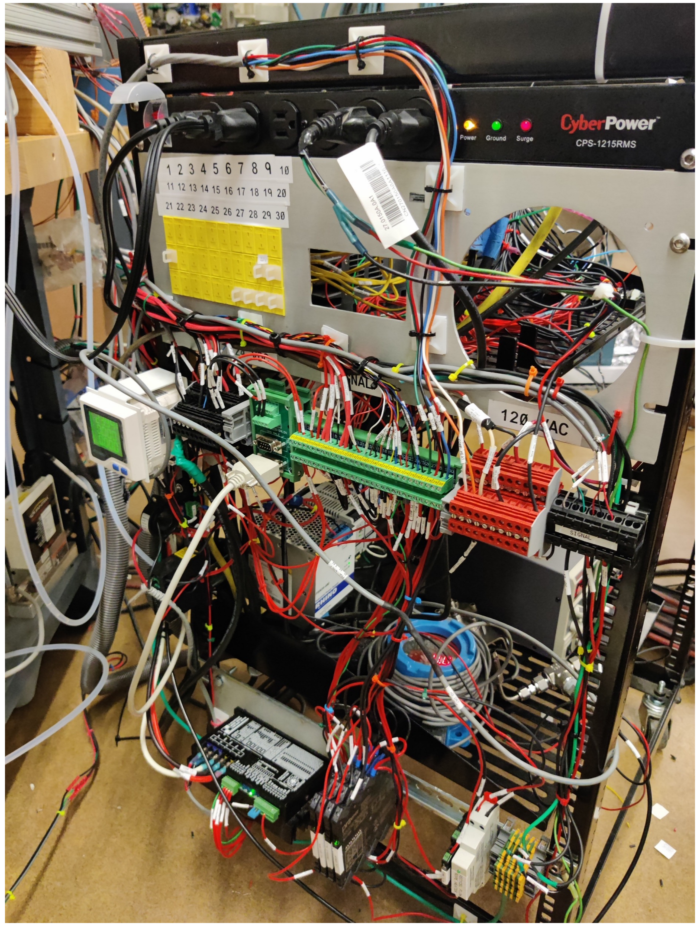
Vacuum Chamber

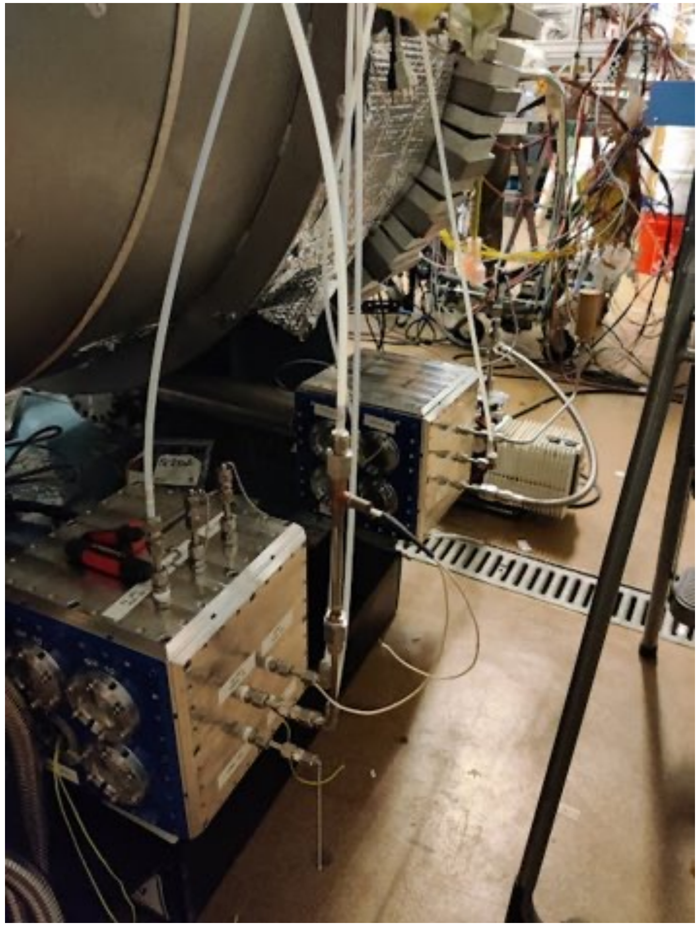


- Large cryovac chamber is needed to test system in TRL-6 relevant lunar-like environment.

Balance of Plant Integration

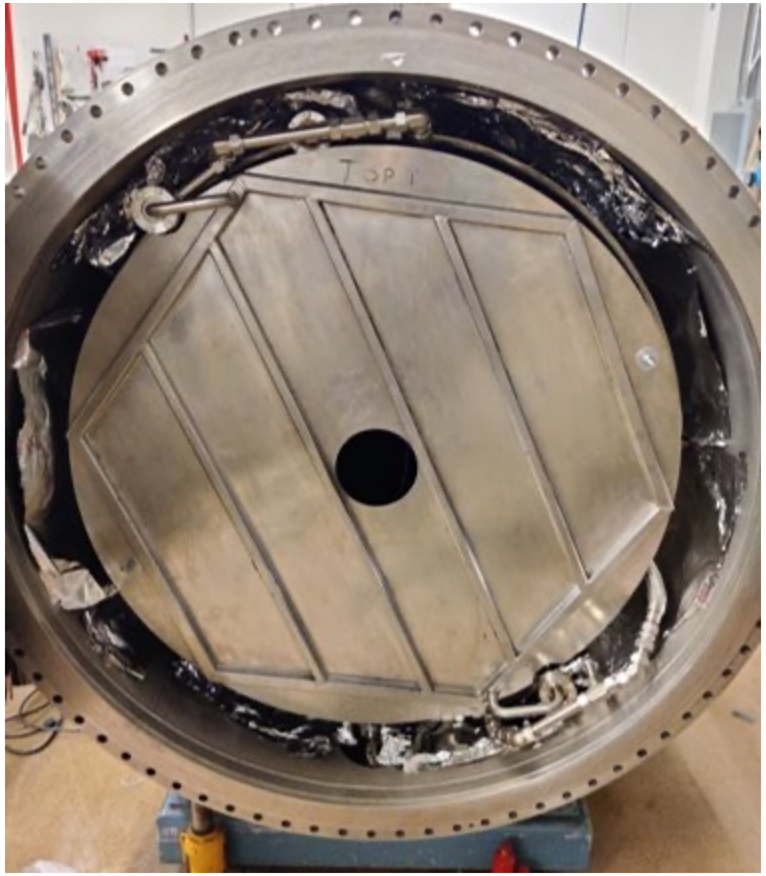


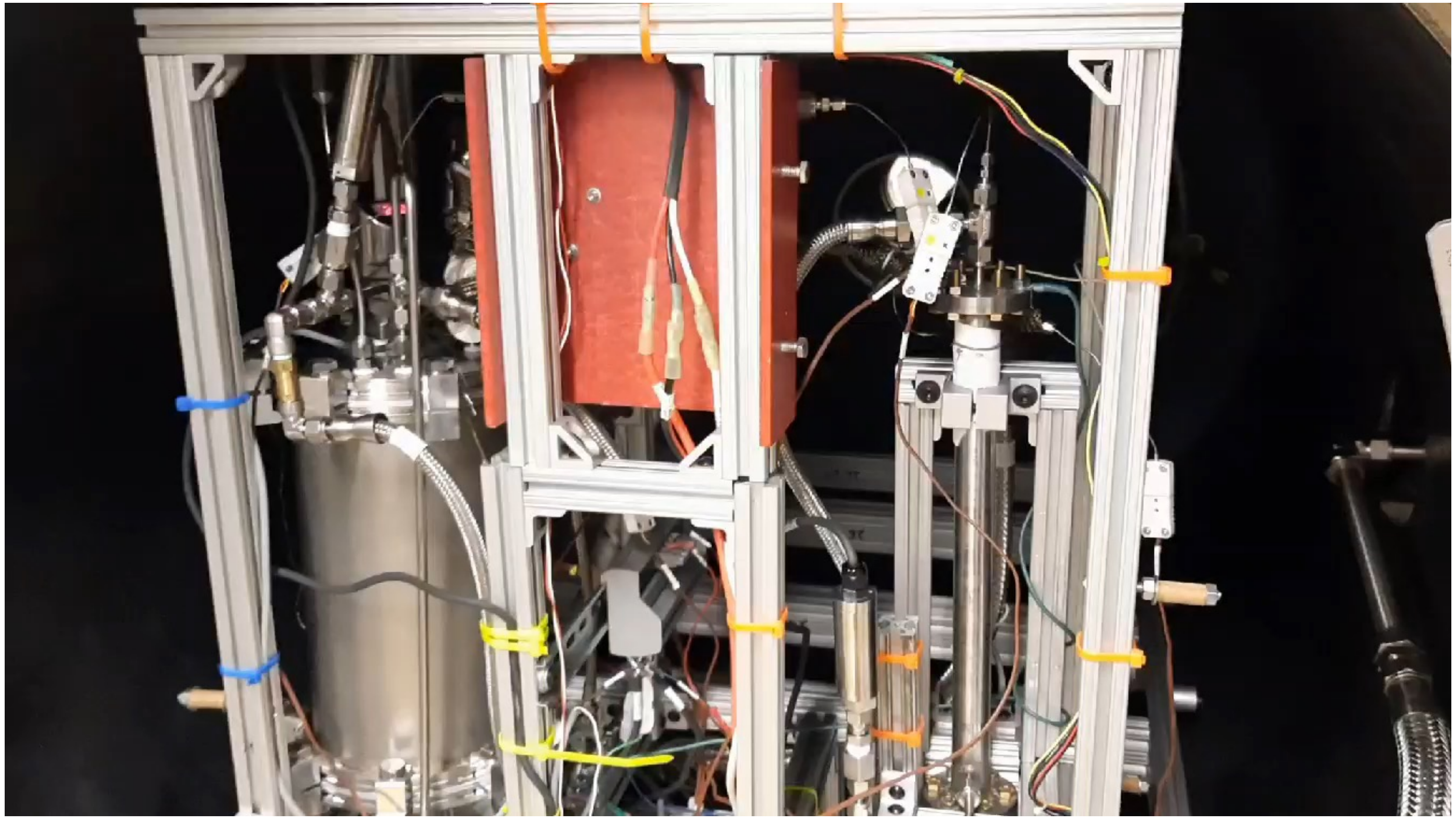




- BOP components were tested individually and integrated together over 2021.
- Fluid, power, thermocouple, and signal feedthroughs were integrated into vacuum chamber.
- Control software and data acquisition hardware were integrated into balance of plant and vacuum chamber.

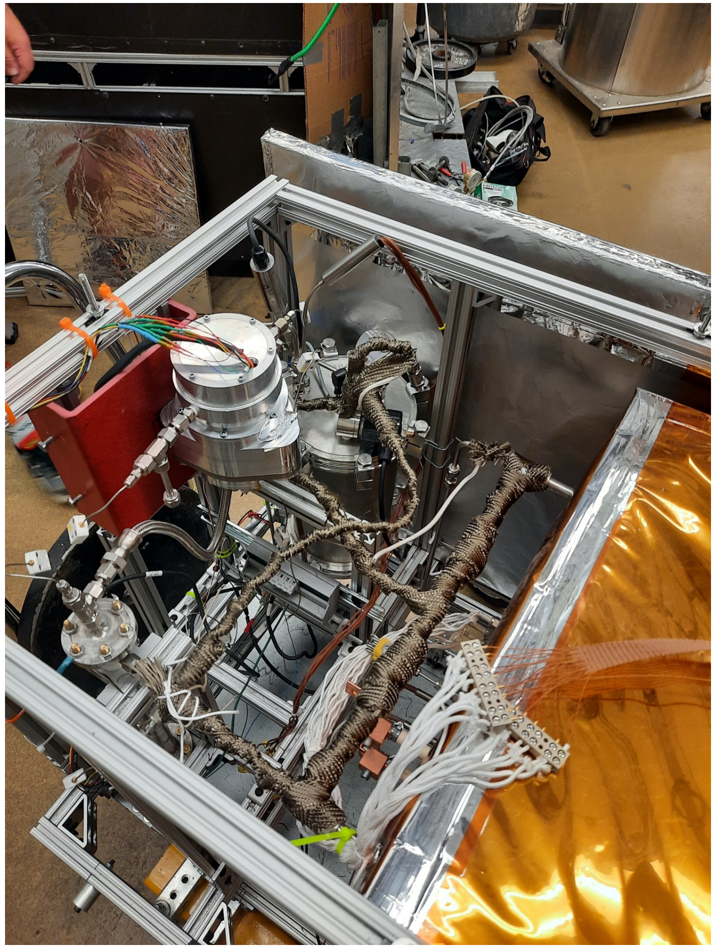
Vacuum Testing of Balance of Plant

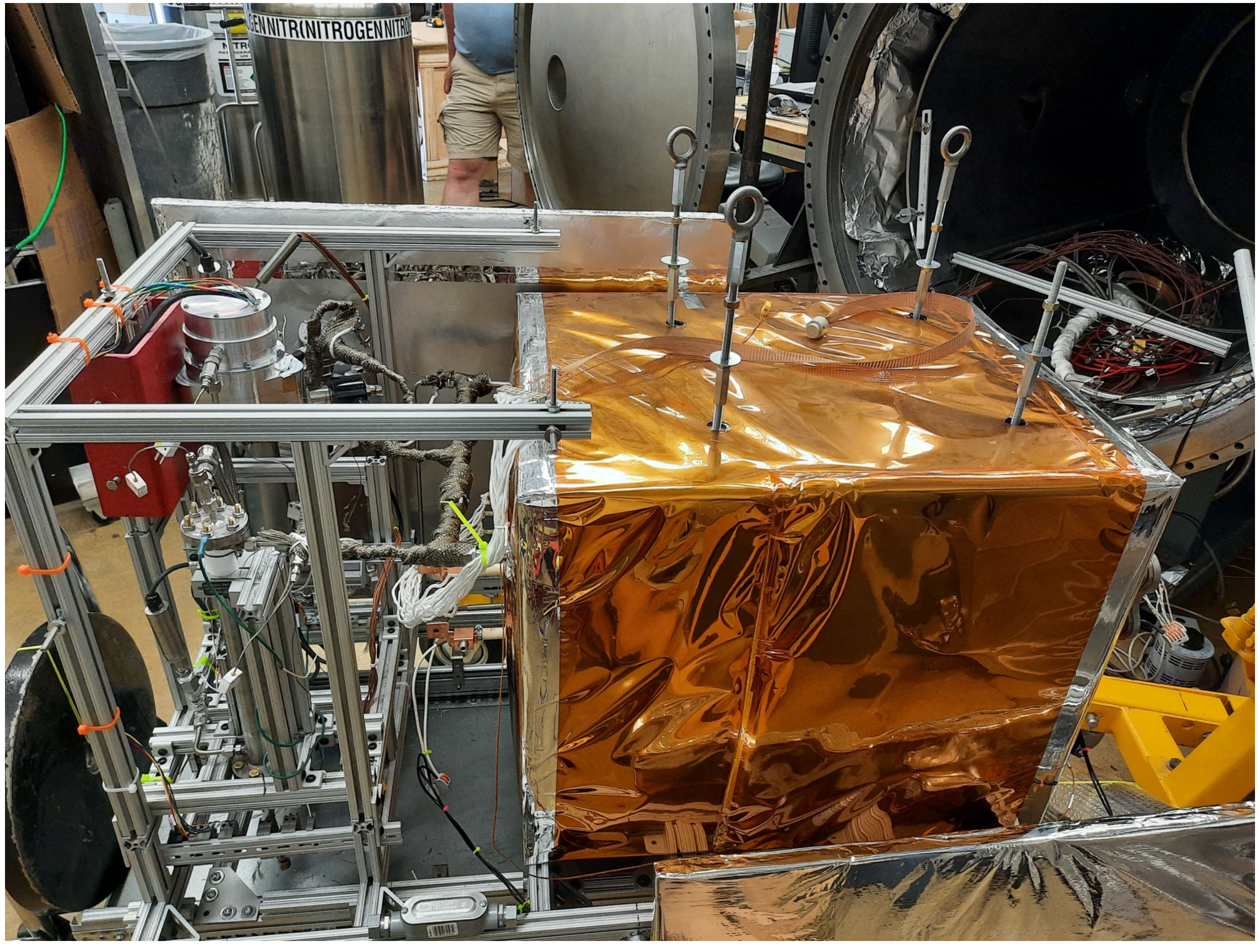




- BOP was run in vacuum continuously (without electrolysis stack) for 12 hours.
- System functioned smoothly, with no major component malfunctions or faults.

Integration of Stack and Balance-of-Plant

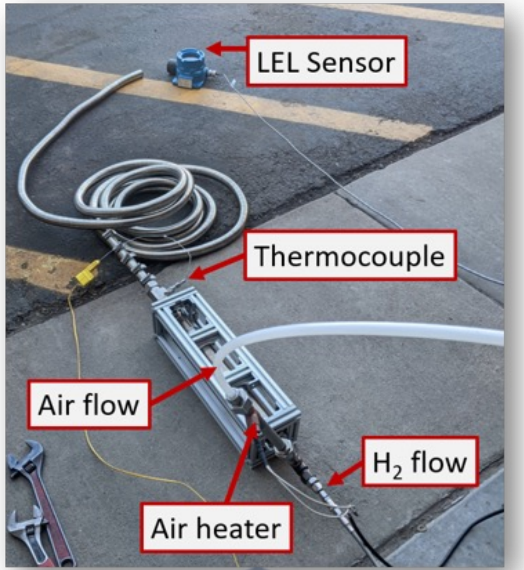




- The BOP and stack are currently fully integrated with control software between stack and BOP.
- Power, signal, and thermocouple feedthroughs for stack integrated into vacuum chamber.

Safety and Test Readiness

- Safety is a top priority during this integrated test.
- Catalytic combustor placed high above vacuum chamber along with high-temperature duct to take exhaust out of the lab.
- TRR documents reviewed, finalized, and signed off on by team.



Combustor (for burning off H_2)

TRR Documents (HazOps, Test Procedure, TRR Checklist)

Job Primary Hazard Summary

What hazards may employees encounter in execution of this work?

Y	N	Hazard	Description	Y	N	Hazard	Description
		Pressure	Compressed cylinder handling	x		Electrical	208V
x		Temperature	Max operating temp of 800 C		x	Mechanical	
x		Flammable	H2 being produced by stack	x		Oxygen Gas	NFPA- **H** 3, **F** 0, **R** 0, **S** OX
	x	Reactive		x		Nitrogen Gas	NFPA- **H** 0, **F** 0, **R** 0, **S** - Nitrogen leak can cause asphyxiation
x		Toxic	Potential for H2, N2 buildup	x		Hydrogen Gas	NFPA- **H** 3, **F** 4, **R** 0, **S** -
x		Burn	Liquid N2				

Job Specific PPE Requirements

What PPE do employees need to complete this work safely?

This portion of the HazOp Assessment is for supervisory planning purposes to determine PPE that must be worn/used to perform this work. PPE requirements should be verified with the Safety Department.

Y	N		Y	N		Y	N	
	x	Hardhat		x	Safety Glasses with Side Shields		x	Safety Toed Boots
	x	FRC Coveralls		x	Goggles		x	Metatarsal Guard Boots
	x	Additional FRC C						
	x	Chemical Protecti Clothing						
	x	Fall Protection Eq						
	x	Air Purifying Resp						
	x	Air Supplied Resp						
	x	SCBA						

Integrated Testing Procedure with Stack

- Mines highlight
- OxEon highlight
- Test time estimate
- Outstanding task/issue

Test Readiness Review

Program	Tipping Point
PI/PM	Joe/Jessica
Test Name	Integrated System Test
Target Start Date	6/6/22
Reviewers	Mines/OxEon

Are all test materials in house?

Process Area	Material
Start Up	Start Up Gas (N2/H2 Mix)
	Start Up Gas (N2)
	Gaseous N2 (Hotbox purge)
	Distilled H2O

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Continuing Work

- We are currently underway with our full integrated test of the SOXE electrolysis stack and the BOP.
- Key performance parameters will be measured and monitored for the next several days.
- We aim to advance this technology to TRL 6 in the next few weeks and so doing, further the state of the art of ISRU and space resources writ large.

Key Performance Parameters

Parameter	Units	State of the Art (SOA)	Threshold Value	Project Goal	Current Value To Date	Current Value: Technical Basis of Estimate	Expected Exit Value	Exit Value: Technical Basis of Estimate
Integrated breadboard system H_2 production rate	kg/day	Scalable	1.5	1.8	2.2	Substantiated	1.8	OxEon SOXE stack testing adjusted for planned BOP
Oxygen product pressure	bar	Study	1	2	1	Verified	2+	MOXIE qual, analysis, anecdotal data
System Specific Power	kWh/kg H_2	51	50	46	34	Substantiated	48	System trade-study optimization task with SOXE stack data

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