Prototype Demonstration of an Integrated Solar Concentrator System and Carbothermal Reactor Using Solar Energy to Extract Oxygen from Regolith

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CaRD Project Goal

- The Carbothermal Reduction Demonstration (CaRD) project was an effort to develop a prototype system to demonstrate the extraction of oxygen from simulated lunar regolith using concentrated solar energy and a carbothermal reaction

- The prototype consisted of a deployable solar concentrator capable of tracking the sun, optical splash plate and shutter, carbothermal reactor, fluid system, gas analysis, and a control system consisting of avionics and software

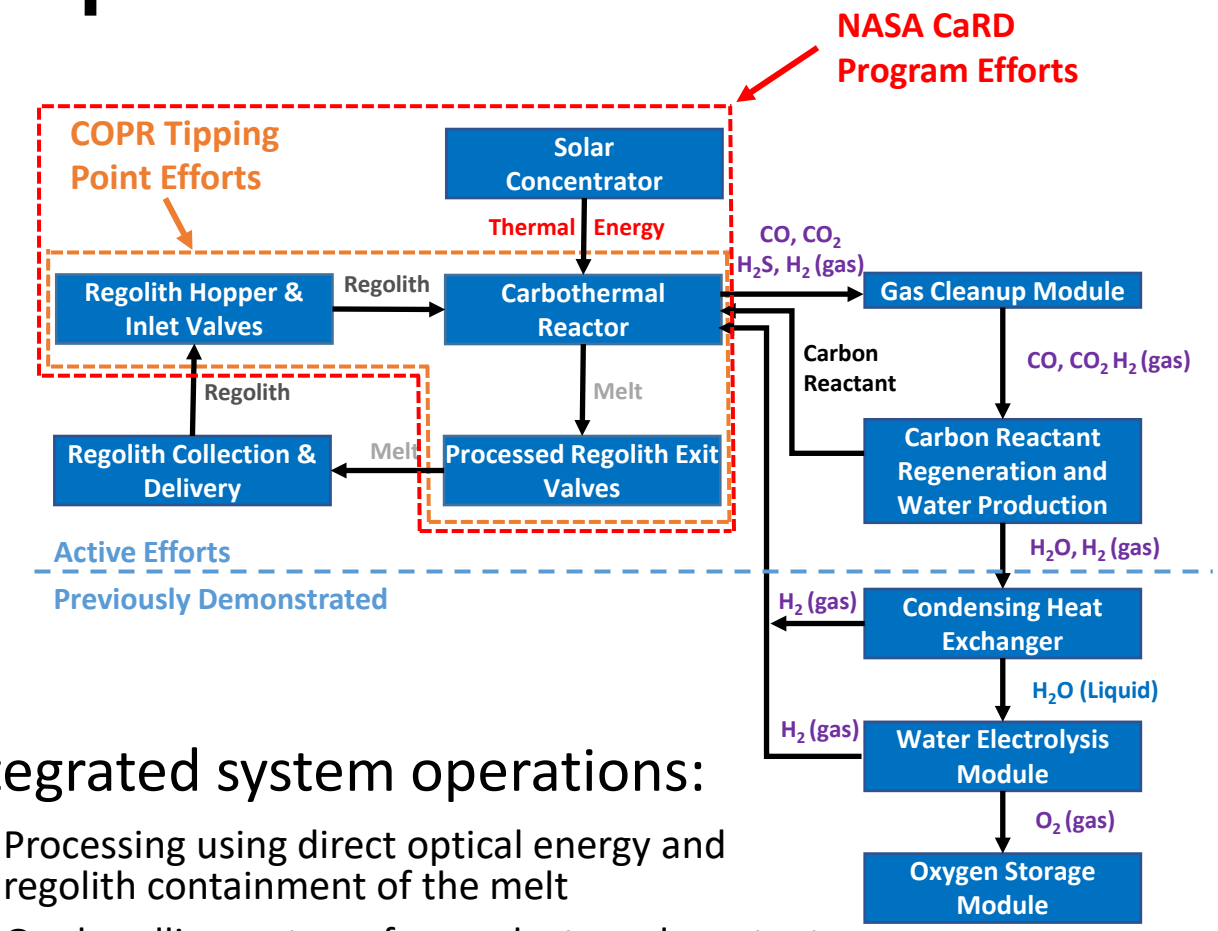
- Carbothermal reactor integrated system was previously demonstrated and matured to TRL 6 in 2024 using NASA JSC TVAC facilities

- Integrated solar testing demonstrates full system integration in a CLPS mission configuration
  - Potential future work to mature the fully integrated system to TRL 6 through additional TVAC testing

Carbothermal Reduction Operations

Direct Solar Testing:

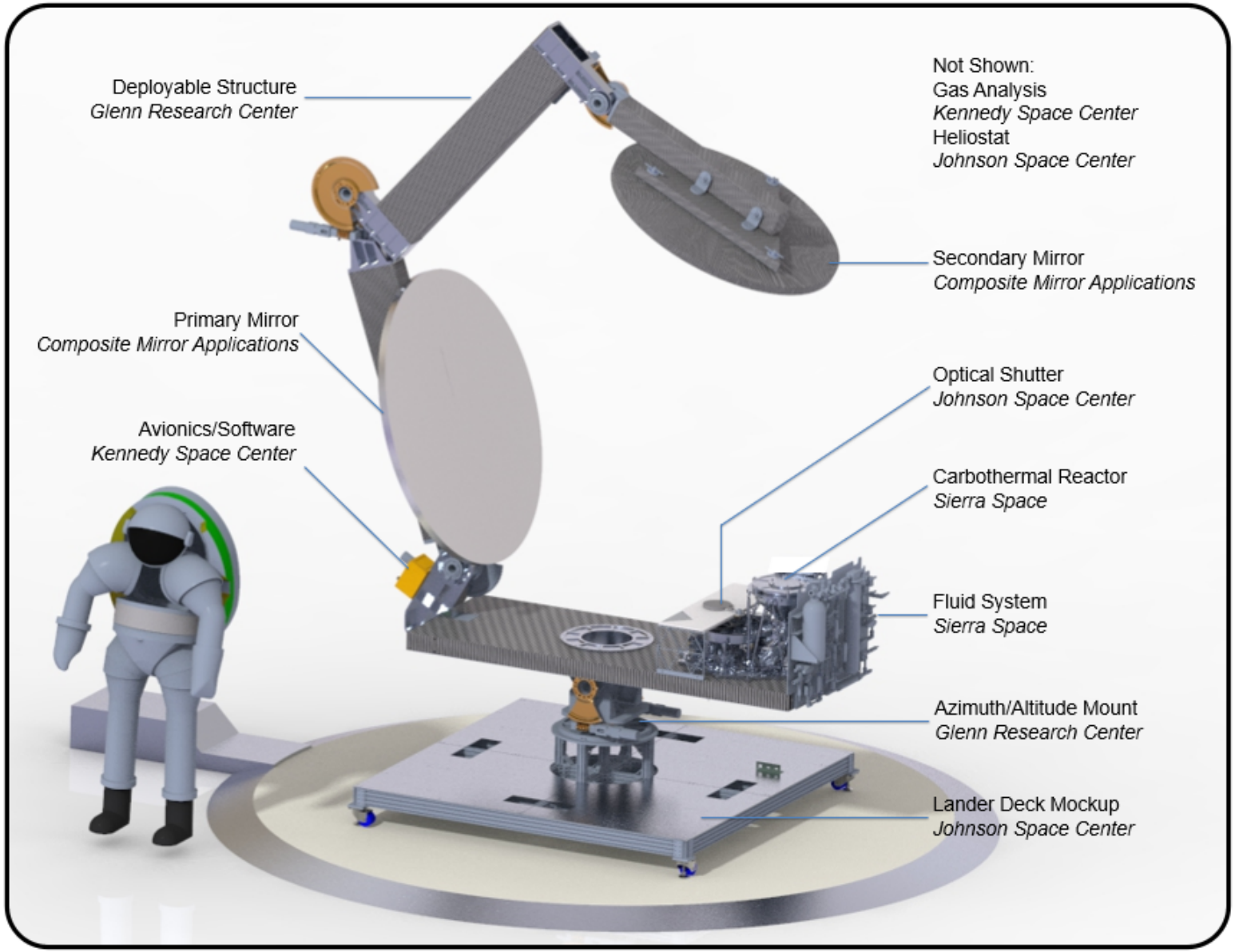
- Crossed Dragone lightweight mirror system deployment
- Direct sun tracking
- Splash plate protection of system from concentrated solar energy
- Carbothermal reduction inside the COPR reactor using direct concentrated solar energy
- Validation of optical protection approaches with solar energy
- Product gas measurements with MSolo



Previously demonstrated automated integrated system operations:

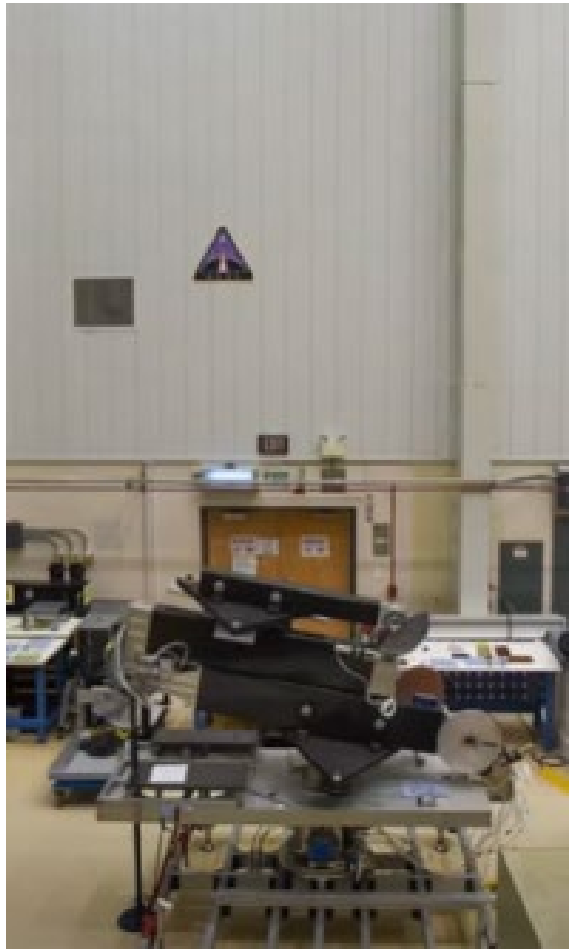
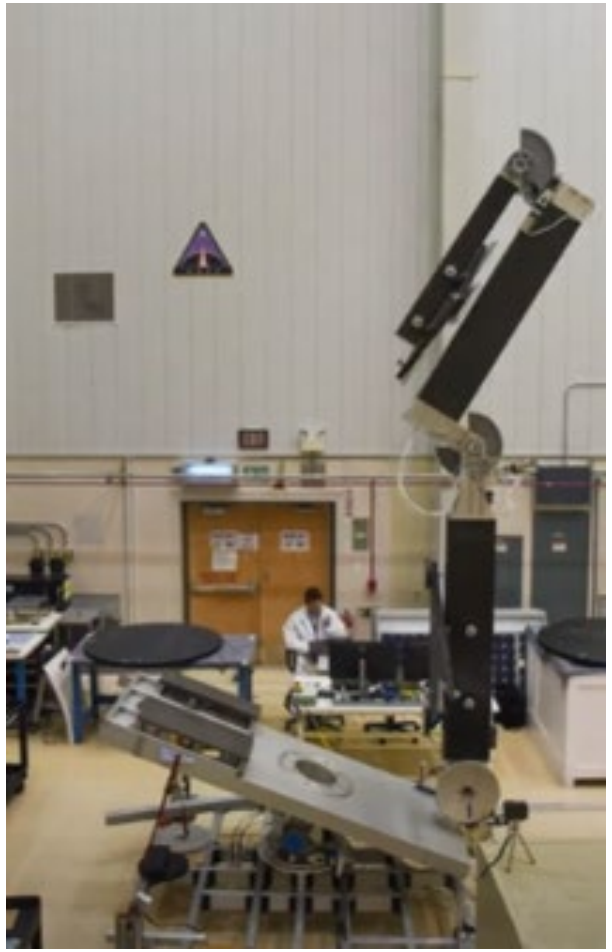
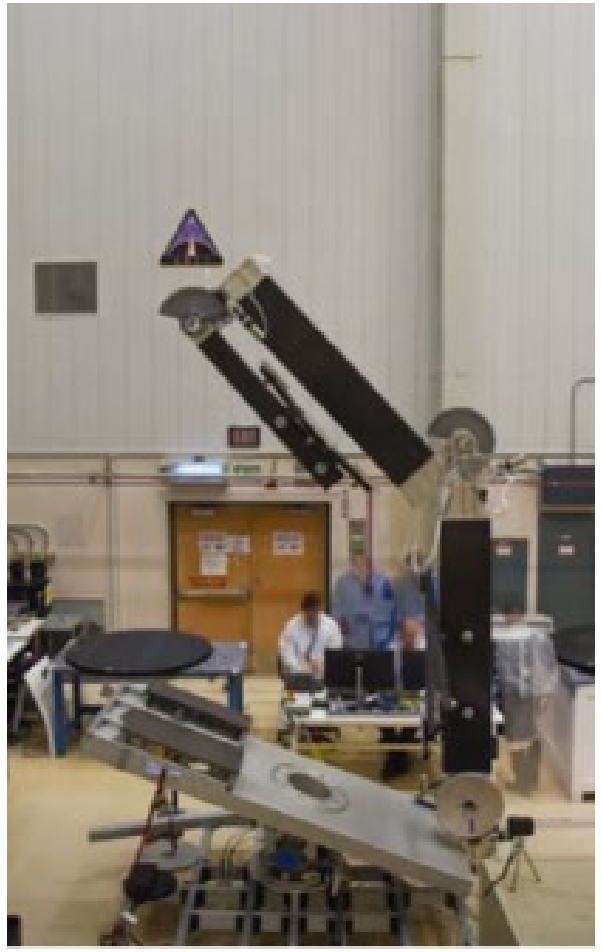
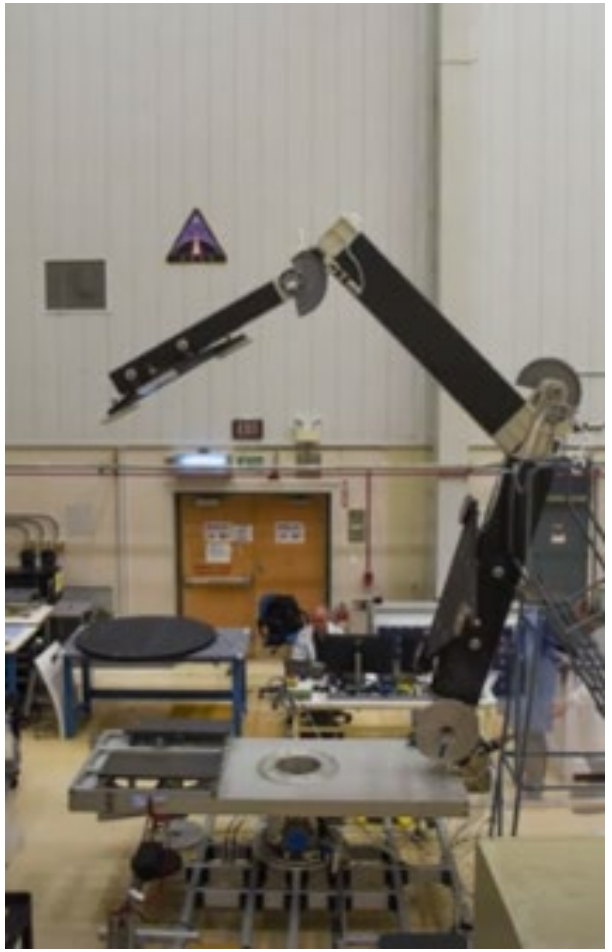
- Ingress of supplied regolith simulant into the system
- Metered flow of regolith simulant
- Handling/transport of the simulant through the reactor
- Protection of the optics providing the concentrated direct solar energy
- Processing using direct optical energy and regolith containment of the melt
- Gas handling systems for products and reactants
- Extraction of processed melts from the reaction zone
- Removal of processed melts from the system

Carbothermal Reduction Demonstration (CaRD) Prototype Overview



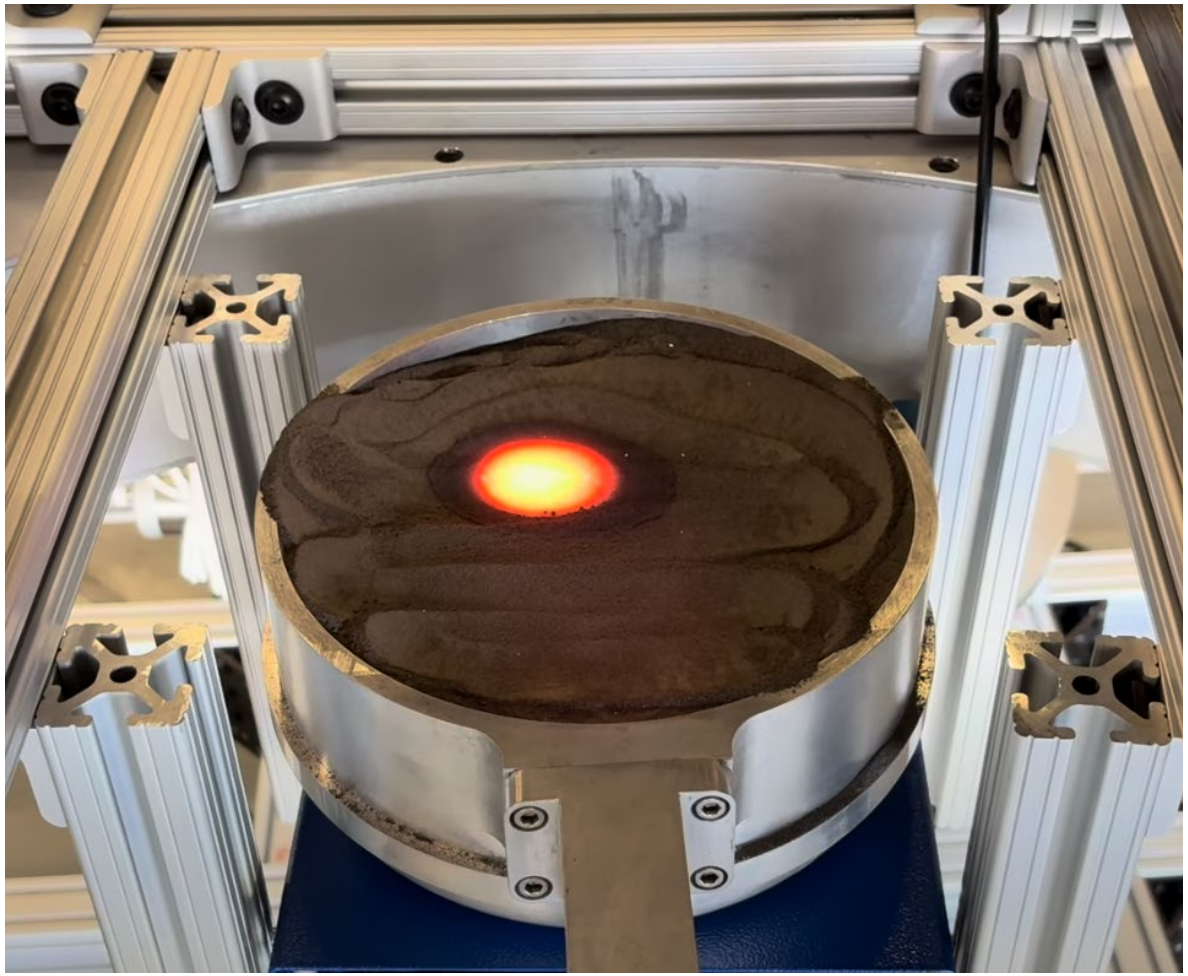
GLENN RESEARCH CENTER
at Lewis Field

Deployable Solar Concentrator

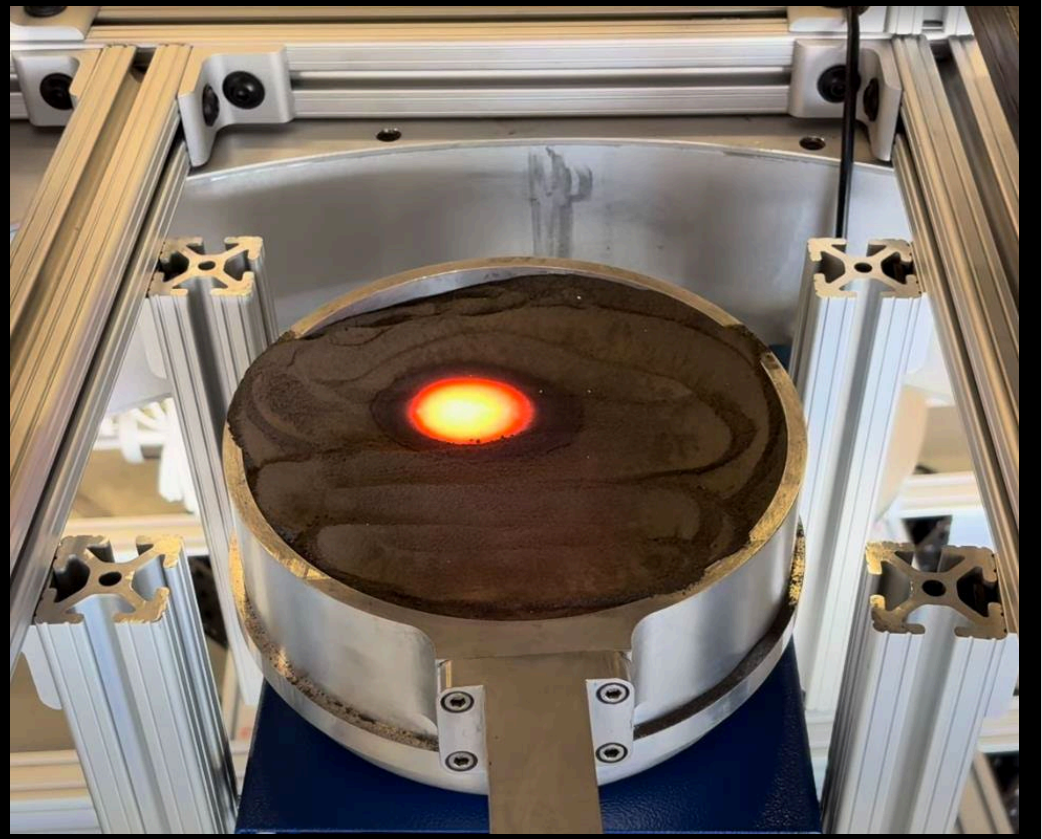
- The deployable solar concentrator mechanisms and structure were developed at Glenn Research Center
- Avionics and Software for the solar concentrator were developed at Kennedy Space Center
- Electrical harnesses for the solar concentrator were developed at Johnson Space Center

Deployable Solar Concentrator Mirrors



- The solar concentrator mirrors were developed by Composite Mirror Applications, LLC
- The primary mirror weighs 46.3 lbs (21 kg), the secondary mirror weighs 30.4 lbs (13.8 kg)
- Clear aperture diameter = 1.6m, Focal point diameter = 36 mm. Geometric concentration ratio = 1975

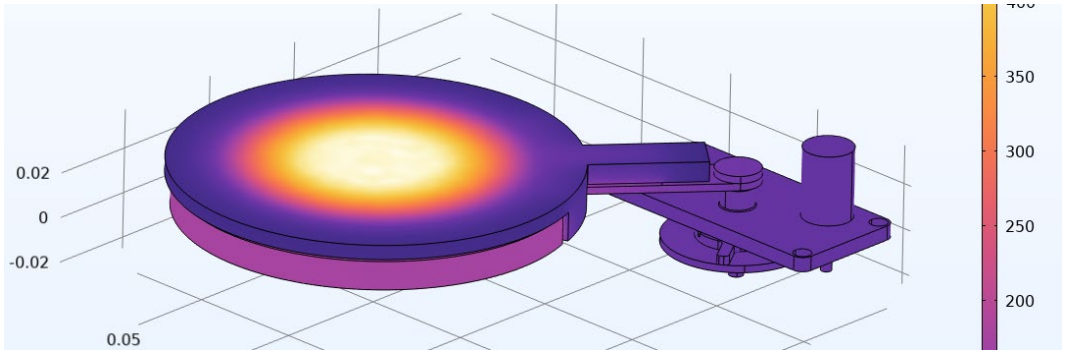
Demonstration of Solar-Carbothermal System



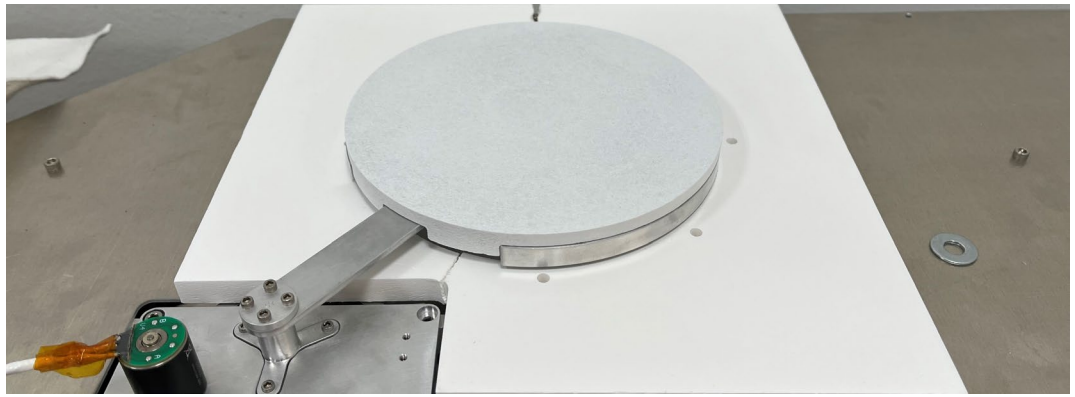
Heliostat and Tracking (Left), Illuminated Solar Concentrator (Middle) and Molten JSC-1A Simulant at Focal Point (Right)

Optical Shutter & Splash Plate

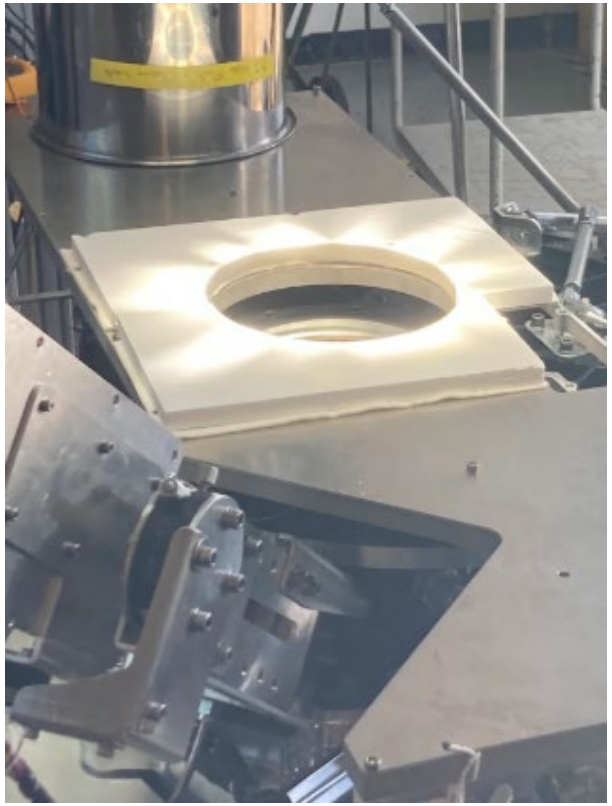
Optical Shutter without LI-900 Installed



Thermal Analysis



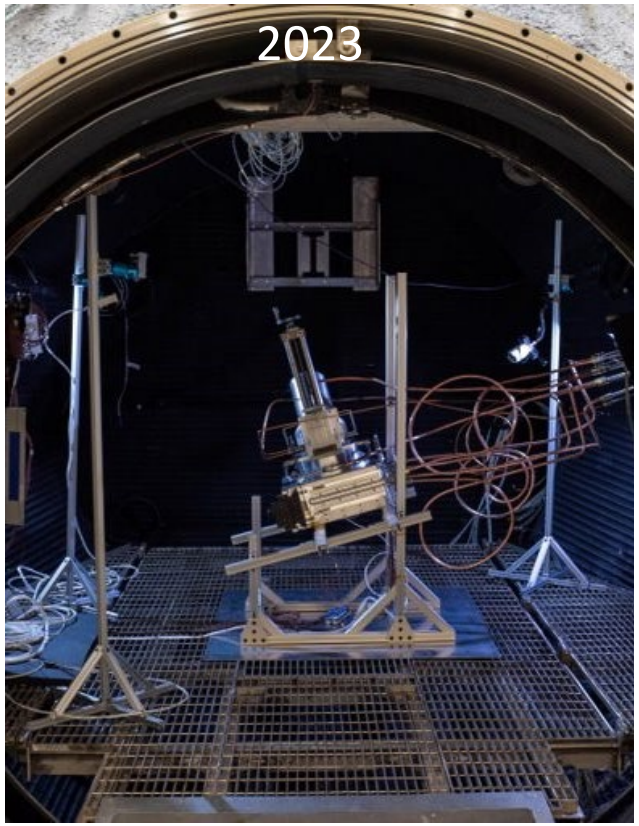
Fractured LI-900

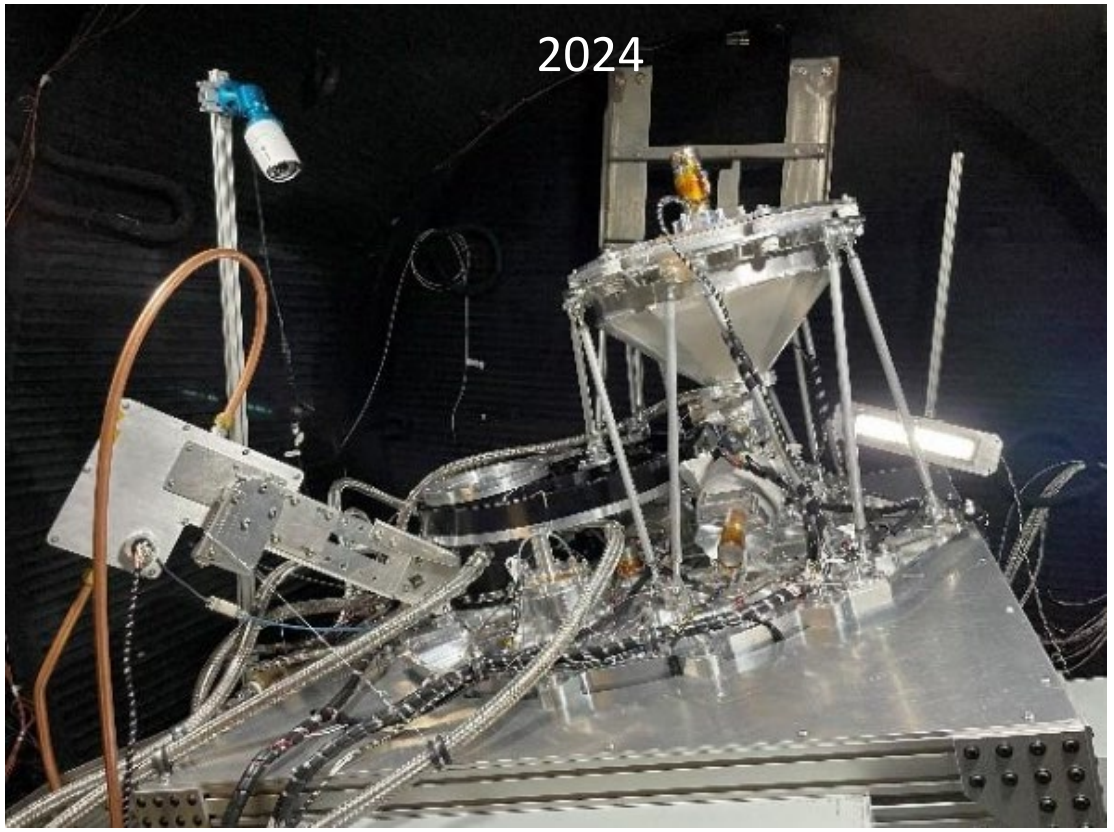


Center Tile of Splash Plate Illuminated with Diffraction Spikes

- The optical shutter and splash plate were developed at Johnson Space Center
- LI-900 (the material used for shuttle tiles) was selected as the direct light interface, but some pieces broke during shipping and the shutter was not fully tested.

Reactor & Fluid System



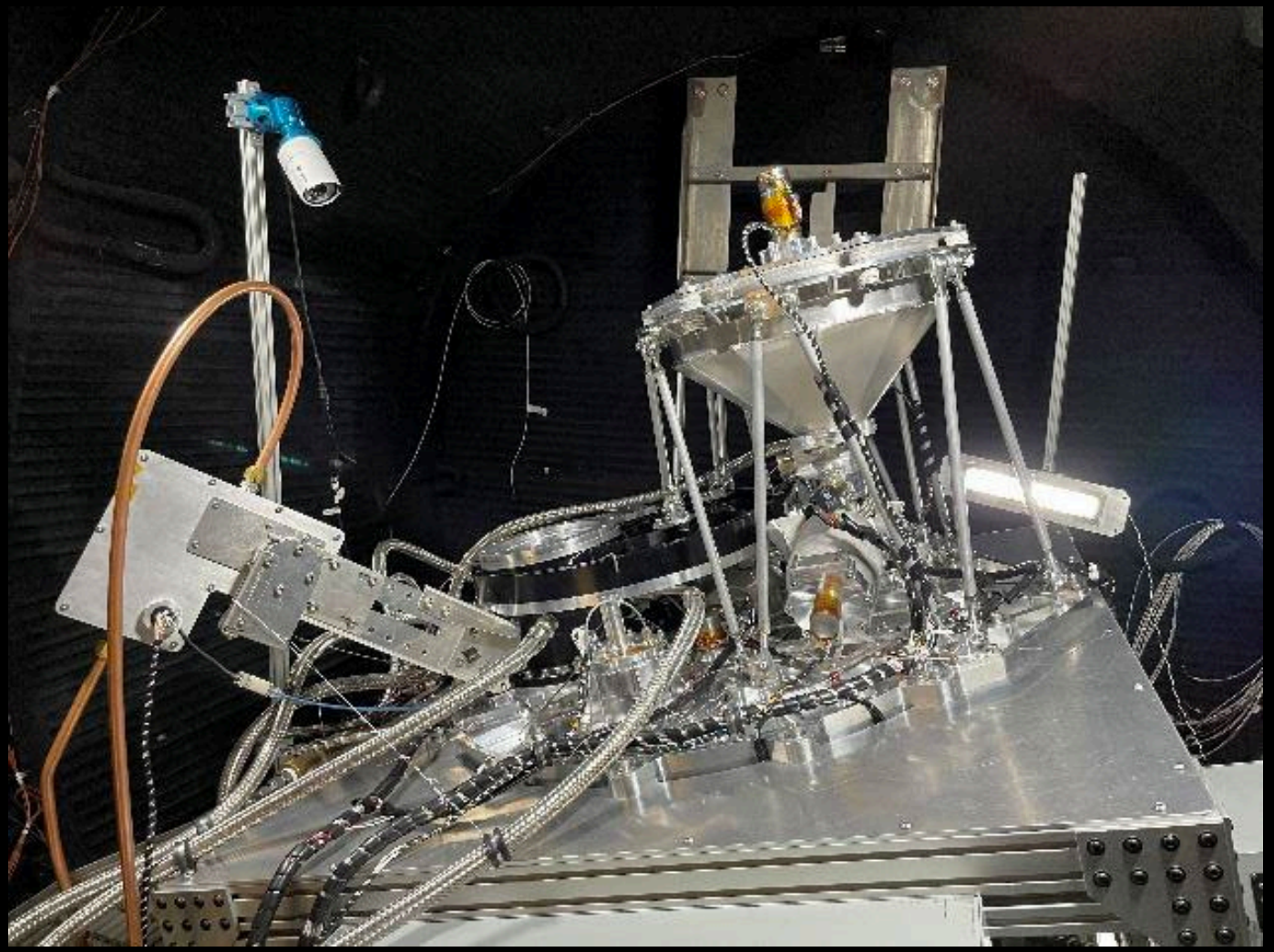


Test Number	grams oxygen extracted/ kWh thermal
CaRD ETU Ambient	13.42
CaRD ETU Vacuum 1	11.53
CaRD ETU Vacuum 2	15.79
CaRD ETU Vacuum 3	10.77

- The CaRD Brassboard/Environmental Test Unit (ETU) was developed by Sierra Space and tested under thermal vacuum in 2023 using a laser placed on the outside of the vacuum chamber.
- The Carbothermal Oxygen Production Reactor (COPR) was developed by Sierra Space as a Tipping Point project and was successfully tested (automated) under thermal vacuum in 2024 using a laser placed on the outside of the vacuum chamber *
- The reactor fluid system was also developed by Sierra Space and funded by the CaRD project. The fluid system was used in conjunction with the reactor during the 2024 thermal vacuum test at JSC

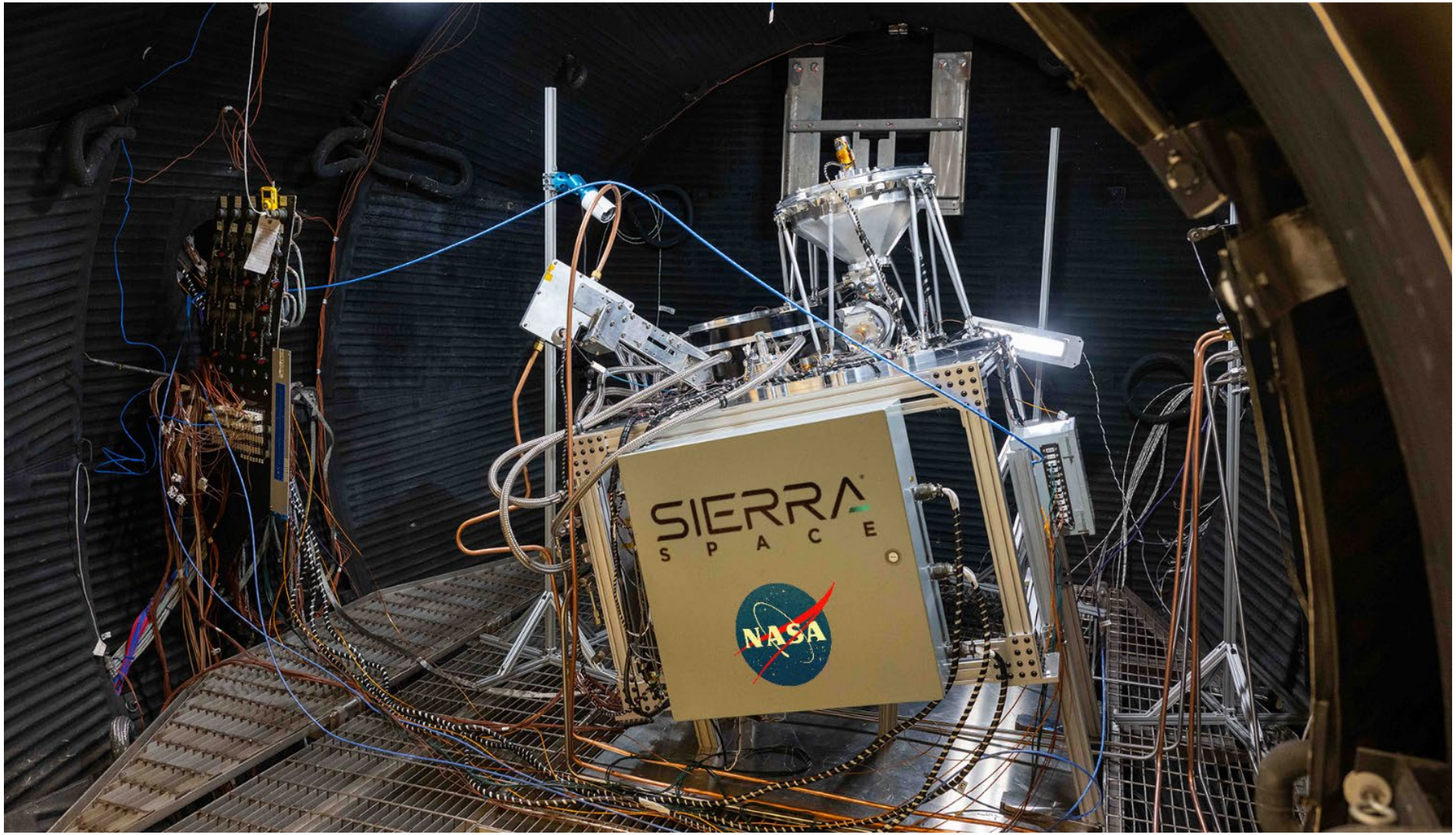
* Haggerty, N. P., White, B. C., Paz, A., O'Connor, D., Azim, N., & Captain, J. (2025, June). Environmental Testing of a Fully Automated Carbothermal Reactor for Lunar Oxygen Production. In *54th International Conference on Environmental Systems (ICES)* (No. ICES-2025-200). International Conference on Environmental Systems.

TRL 6 Demonstration of CaRD



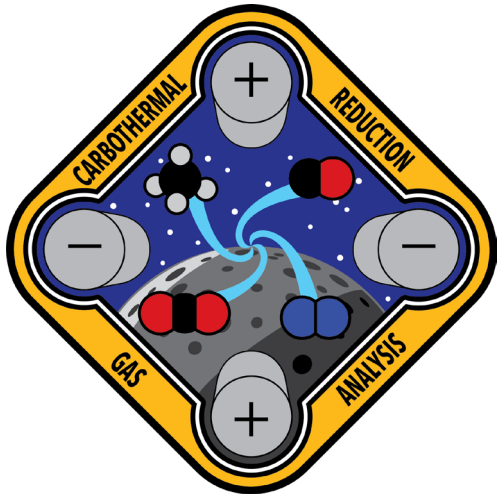
Carbothermal Oxygen Production Reactor (left), Carbothermal Oxygen Production reactor (COPR) Test in 15 ft Dirty TVAC chamber at JSC's Energy Systems Test Area (right)

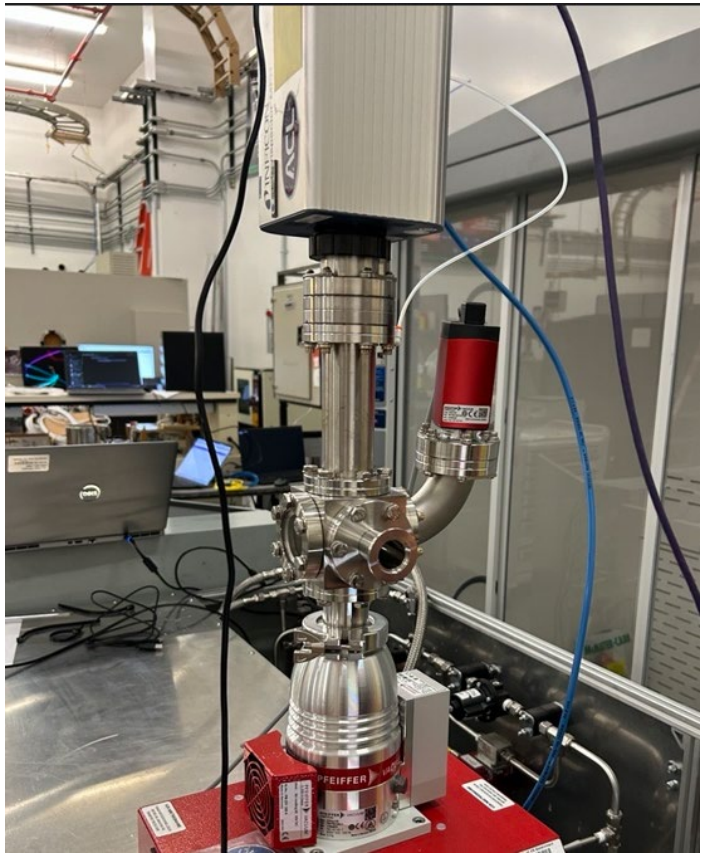
Carbothermal Testing in Lunar Environment



Gas Analysis

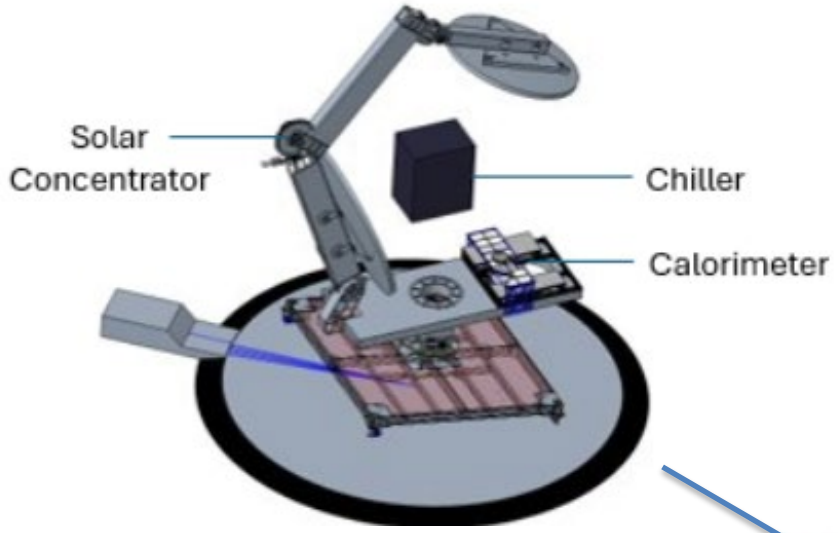
- The gas analysis system used for CaRD was a commercial version the Mass Spectrometer observing lunar operation (MSolo) instrument that recently operated successfully on the Moon during the PRIME-1 mission.
- The gas analysis system was used during the 2023 and 2024 thermal vacuum tests and successfully demonstrated the ability to differentiate between nitrogen and carbon monoxide without the use of a gas chromatograph
- The gas analysis system demonstrated an average relative accuracy to a gas chromatograph of 7.9% +/- 4.3% for CO detection in a relevant gas stream*





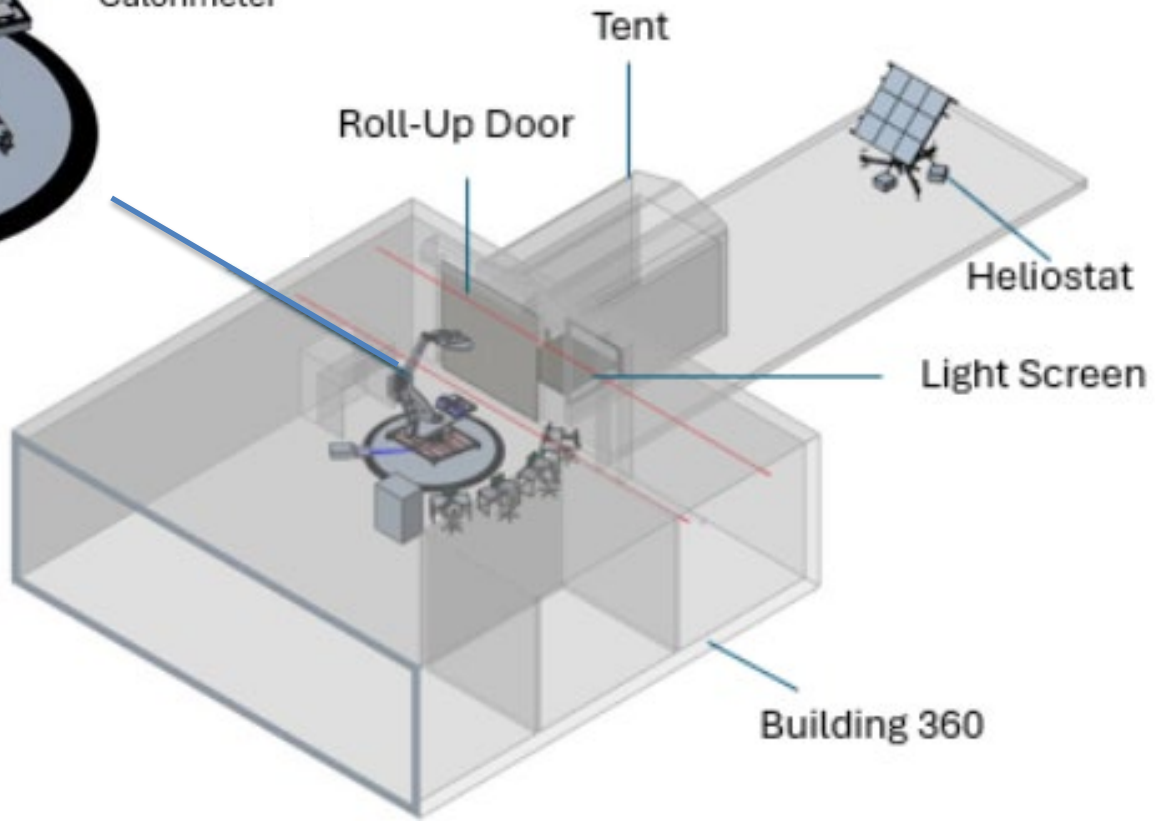
*Gott, R., Olson, J., Azim, N., Aguilar Ayala, R., Captain, J., Haggerty, N., ... & White, B. (2024, July). Carbothermal Reduction Demonstration (CaRD) Gas Analysis Subsystem Development. 2024 International Conference on Environmental Systems.

Integrated Prototype Test Configuration



Calorimeter Illuminated with Light Screen Hole Pattern

Heliostat



Primary Mirror Illuminated with Light Screen Hole Pattern

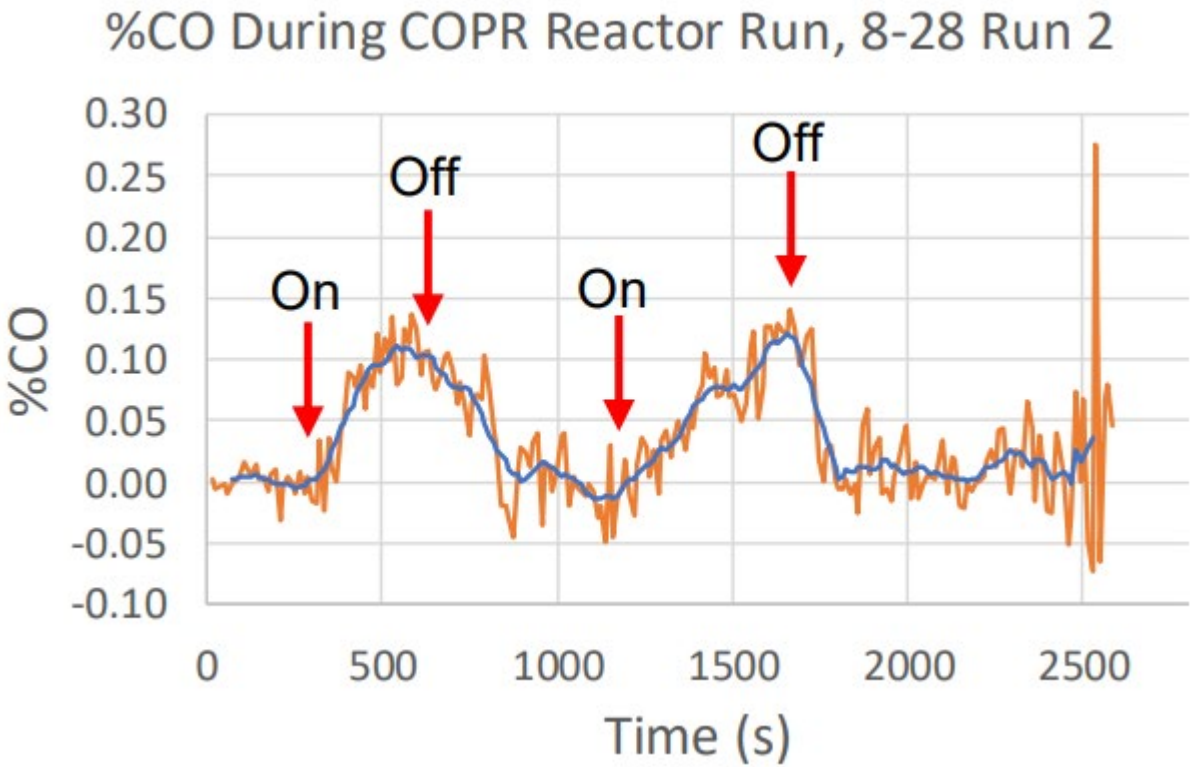
Light Screen

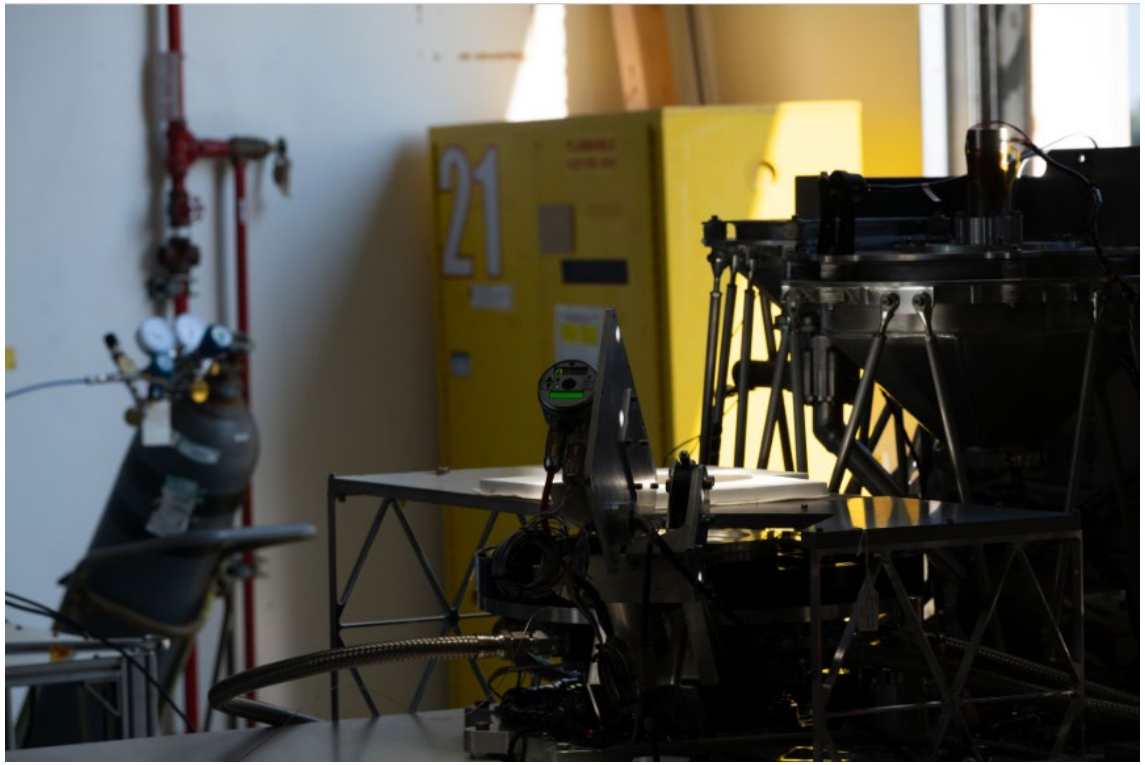
Calorimeter Testing

- Test with no splash plate in place recorded a value of 86.9 Wh at the calorimeter, with 101 Wh or incoming light. This translates to an efficiency of 86% which roughly matches the combined measured reflectivity of the mirrors. Each mirror had a measured reflectance of 92.7% for a combined efficiency of 85.9%
- Test with the splash plate in place only measured the light directed to the focal point and measured 141.4 Wh at the calorimeter with 198.5 Wh of incoming light. This translates to an efficiency of 71.2%

Solar-Carbothermal Testing

- Test in Houston on 8/28/25 extracted 0.195 grams of oxygen in the form of carbon monoxide with 0.38 kilowatt hours of solar energy arriving at the primary mirror of the solar concentrator.
- The light screen was raised when clouds covered the sun and lowered when the sun was clear. The gas analysis system detected a change in CO that corresponded to the light screen configuration and weather conditions.





Results

System	Test Date	Location	Simulant	~Input Solar Flux (W/m^2)	Aperture Area (m^2)	Delivered Power (W)	gO/kWh Input Energy
First-generation	2/4/2010	Mauna Kea, HI	Tephra	989	2.3898	780	0.35
CaRD ETU Brassboard	2/15/2023	Houston, TX	Greenspar 250	laser		1380	N/A
CaRD Prototype	8/26/2025	Houston, TX	Greenspar 250	550	1.889	595	0.29
CaRD Prototype	8/27/2025	Houston, TX	Greenspar 250	675	1.889	730	0.39
CaRD Prototype	8/28/2025	Houston, TX	NUW-LHT-5M	550	1.889	595	0.51
CaRD Prototype	8/28/2025	Houston, TX	NUW-LHT-5M	550	1.889	595	0.28
CaRD Prototype	Prediction	Moon	Regolith	1370	1.889	1561	Unknown
CaRD Prototype	Prediction	Moon	Regolith	1370	1.670	1380	9.53

- The performance of the CaRD solar-carbothermal prototype exceeded the threshold performance established by the first-generation system, despite having poor weather conditions in Houston during the test
- If the CaRD solar concentrator were operating on the moon with no changes, it would deliver 1561 W to the reactor.
- If solar concentrator performance matches laser performance at 1380W, then the CaRD design on the Moon would extract 9.53 grams of oxygen for every kilowatt hour of solar energy arriving at the system. This value can be compared to other methods of oxygen extraction when they are driven by solar power.

Key Program Requirements Achieved

Regolith Handling

- Repeated handling operations with multiple simulants, including agglutinates
- Successful separation and removal of the melt from the regolith bed
- Operations while exceeding worst-case landing site topographies
- Ability to hold and transfer regolith supporting 20+ tests before requiring resupply

Carbothermal Reduction

- Oxygen extraction exceeding KPP goals for thermal energy efficiency (g O_2/kWh) and production yield (g O_2/g regolith)
- Performance of the optical protection system with no issues encountered throughout the test sequence
- Carbon reactant recovery of 99.7% in the processed melt

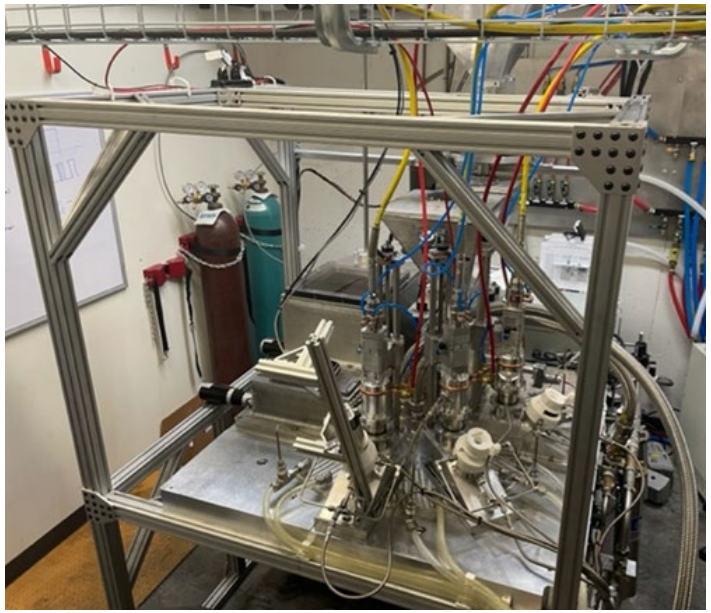
Overall System

- Demonstrated technologies are scalable to a 3.5 tonne/yr O_2 pilot plant
- Operating cycle time and total cycles exceed baseline mission requirements
- System has positive margins and/or demonstrated capability for expected life, vibration, thermal, and pressure requirements of the baseline flight mission

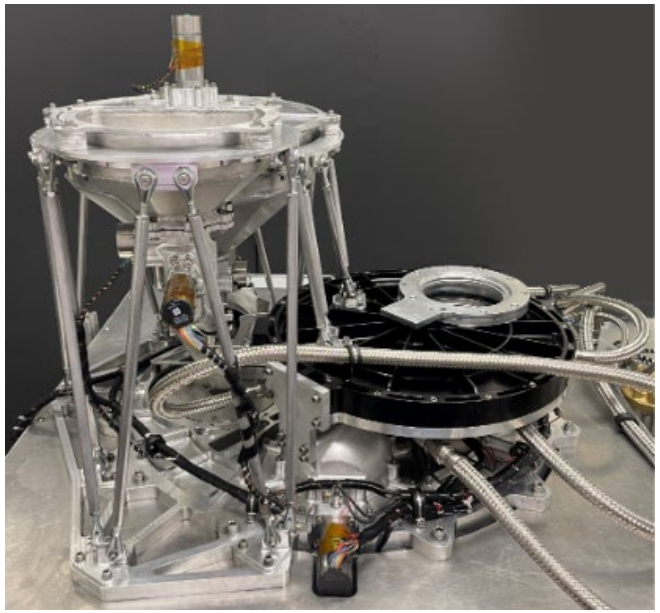
Scalable Flight-Like Architecture

Demonstrating the technologies of a carbothermal oxygen production pilot plant in a system that is sized for a CLPS demonstration payload

- The previous CTOP effort determined what a full-scale carbothermal oxygen plant would look like
- The COPR TP program miniaturized the full-scale technologies into a flight-forward prototype design



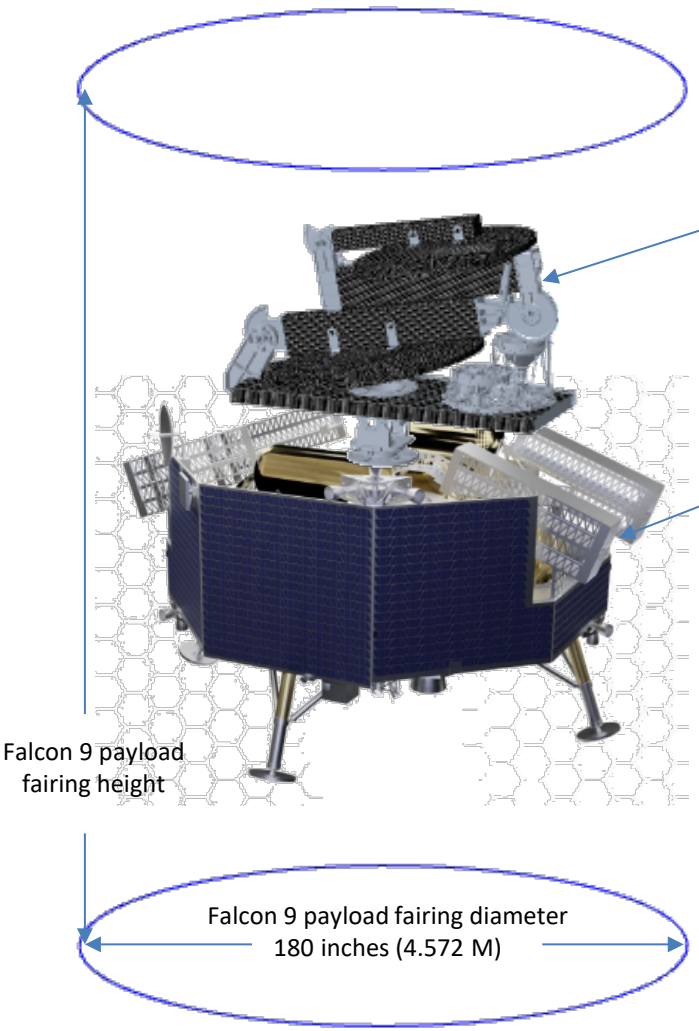
CTOP



COPR TP

A flight demo addresses a strategic knowledge gap by demonstrating the process with actual lunar regolith and solar conditions at 1/6 g

Next Step



CaRD CAD model scaled with Falcon 9 payload volume represented by blue circles

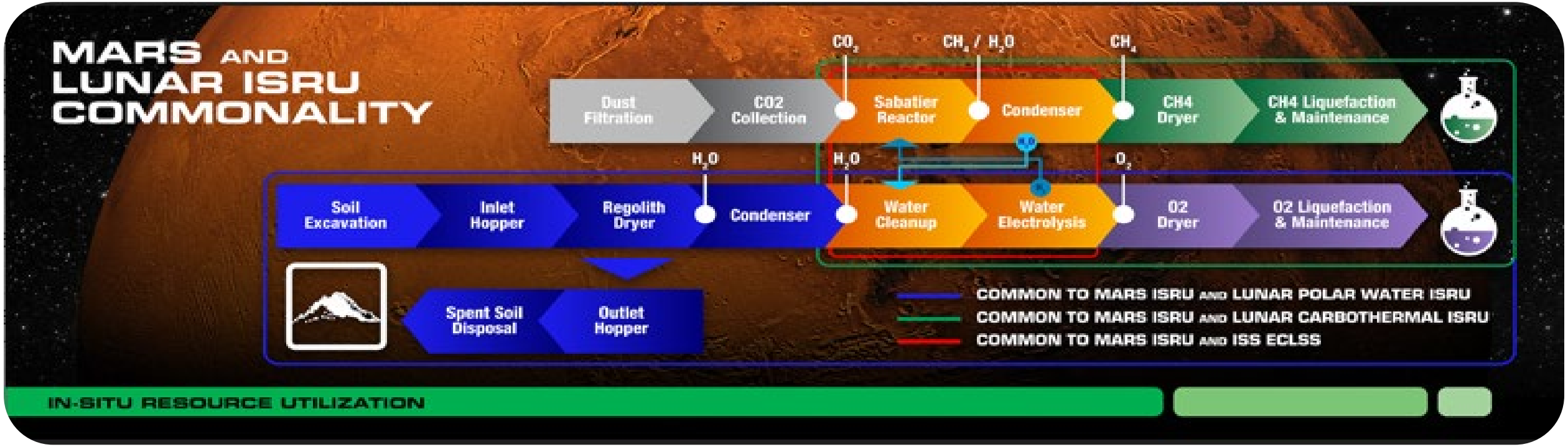
Image of Griffin lander (image credit: Astrobotic) scaled roughly to match Falcon 9 payload volume

Direct concentrated solar on JSC-1A simulant melted within seconds

Direct concentrated solar on Greenspar 250 simulant didn't melt, only slightly sintered.

- A solar-carbothermal flight demo would address a strategic knowledge gap for ISRU. Specifically, the yield of oxygen and associated byproducts from actual lunar regolith.
- A demonstration with real regolith is needed to inform the design of a large-scale system because simulant performance is not reliable. The same test with two different simulants can have very different results.

Future Work



- A carbothermal reduction plant operating on the Moon to make oxygen can significantly reduce the cost of a sustained human presence on the Moon
- Once enough water ice prospecting missions have been completed to start mining water ice at a large scale, hydrogen from water ice can be fed into a carbothermal reduction plant to make liquid methane, which is much easier to store than liquid hydrogen
- A carbothermal reduction plant on the Moon would test most of the technologies that are needed to produce liquid oxygen and liquid methane propellants on Mars.