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Prototype Demonstration of Solar Carbothermal System to Extract Oxygen from Regolith

In-Situ Resource Utilization and Mining

ASCEND™

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In-Situ Resource Utilization (ISRU)



- **Current cost to the lunar surface is \$1.2M/kg based on at least one rate published by CLPS provider**
- **If a single lunar launch requires 10,000 kg (10 Tonnes) of oxygen, that will be \$12B worth of oxygen burned per lunar launch at current cost.**
- **If the future cost to the lunar surface is reduced to \$0.1M/kg, a single launch that burns 10 Tonnes of oxygen would cost \$1B.**
- **Every kilogram of propellant produced from lunar resources is one less kilogram of mass that must be landed on the lunar surface.**
- **A full-scale oxygen production plant on the Moon should be able to produce several times its own landed mass in propellant, potentially saving billions of dollars over the course of a sustained campaign.**

From the FY27 Budget Request for NASA:

Space Technology (–\$297 million). The Budget prioritizes early-stage research and development for technologies required for future lunar missions as well as advancements to support a competitive space industry, including **commercial programs to produce rocket fuel on the Moon** and to develop small radioisotope nuclear power systems.

2009: LRO/LCROSS provided definitive proof of water in Cabeus crater and reported a concentration of 5.6% +/- 2.9% water by mass (-84.675, 311.275)

2025: PRIME-1 landed near Mons Mouton region but was not able to drill into the surface

2026: [Chang'e - 7](#) (-88.8, 123.4)

2027: [VIPER](#) previously selected Nobile landing site

2027: [ProSPA](#) (-84.5, 31.5)

2028: [LUPEX](#) (location TBD)

- Lunar Water ISRU Measurement Study ([LWIMS](#)) recommended that a water prospecting campaign is needed before we can start mining water ice at a useful scale.
- At this time, we only have one data point on the concentration of lunar water ice in a single location
- Using water as propellant implies the use of liquid hydrogen, but the liquefaction of hydrogen in-situ is difficult using existing technology
- The majority of the mass of propellant is oxygen. If the goal is to produce oxygen, it may be easier to extract oxygen from regolith than from lunar water because regolith is more accessible.

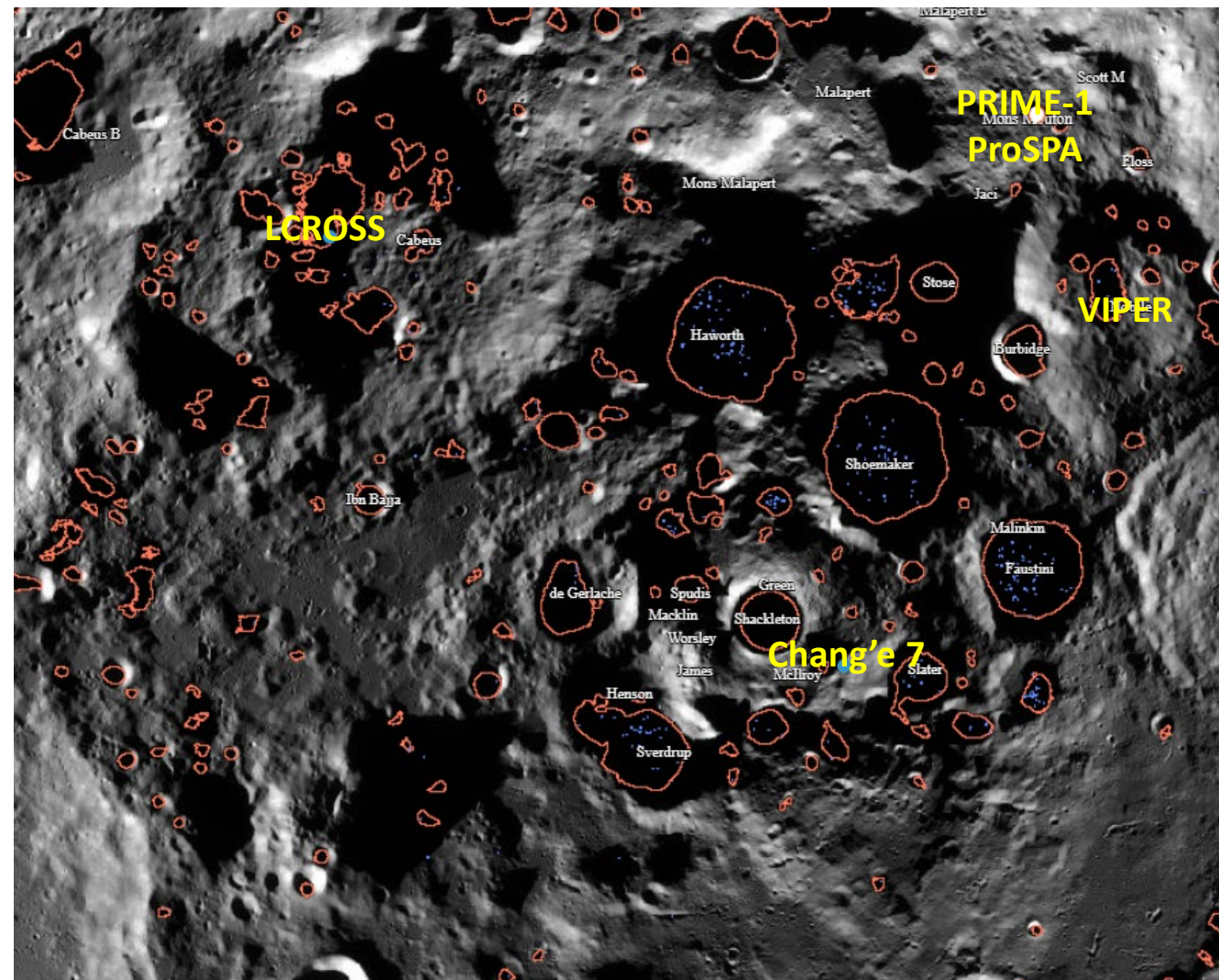
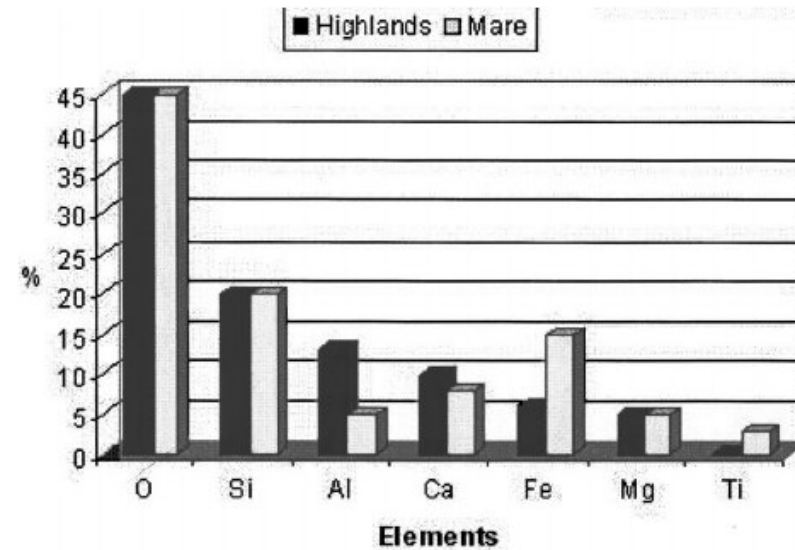


Image Credit: ACT Lunar/LROC Quickmap

Oxygen From Regolith

- Lunar regolith is ~45% oxygen by mass
- There are at least 20 ways to extract oxygen from lunar material*
- Only two methods (hydrogen reduction and carbothermal reduction) have been demonstrated at a relevant scale *without human intervention*. Automation remains a challenge for most oxygen from regolith methods.
- Hydrogen reduction only works well in areas that have a high iron oxide content.
- The data we have indicates that the regolith at the lunar poles is chemically closer to highlands than mare.
- Hydrogen does not reduce silicon oxides.
- Carbon can reduce silicon oxides at ~1600 C.
- The carbothermal reduction process is well known and has been used for decades to produce steel and silicon terrestrially.



Ruess, F., Schaenzlin, J., & Benaroya, H. (2006). Structural design of a lunar habitat. *Journal of Aerospace Engineering*, 19(3), 133-157.

Sample	SiO ₂	Al ₂ O ₃	TiO ₂	FeO	MgO	CaO	Na ₂ O	K ₂ O	MnO
Lunar: 10019	41.1	13.7	8.25	15.7	7.86	11.9	0.93	0.14	0.22
Lunar: 10022	43	13	7	16	8	12	0.54	0.12	0.23
Lunar: 70161	40.34	11.6	8.99	17.01	9.79	10.98	0.32	0.08	0.23
Lunar: 64501	53.63	12.77	3.47	13.37	3.57	9.2	0.73	1	0.2
Lunar: 14053	48	12	1.5	16	8.4	12	0.38	0.14	0.29

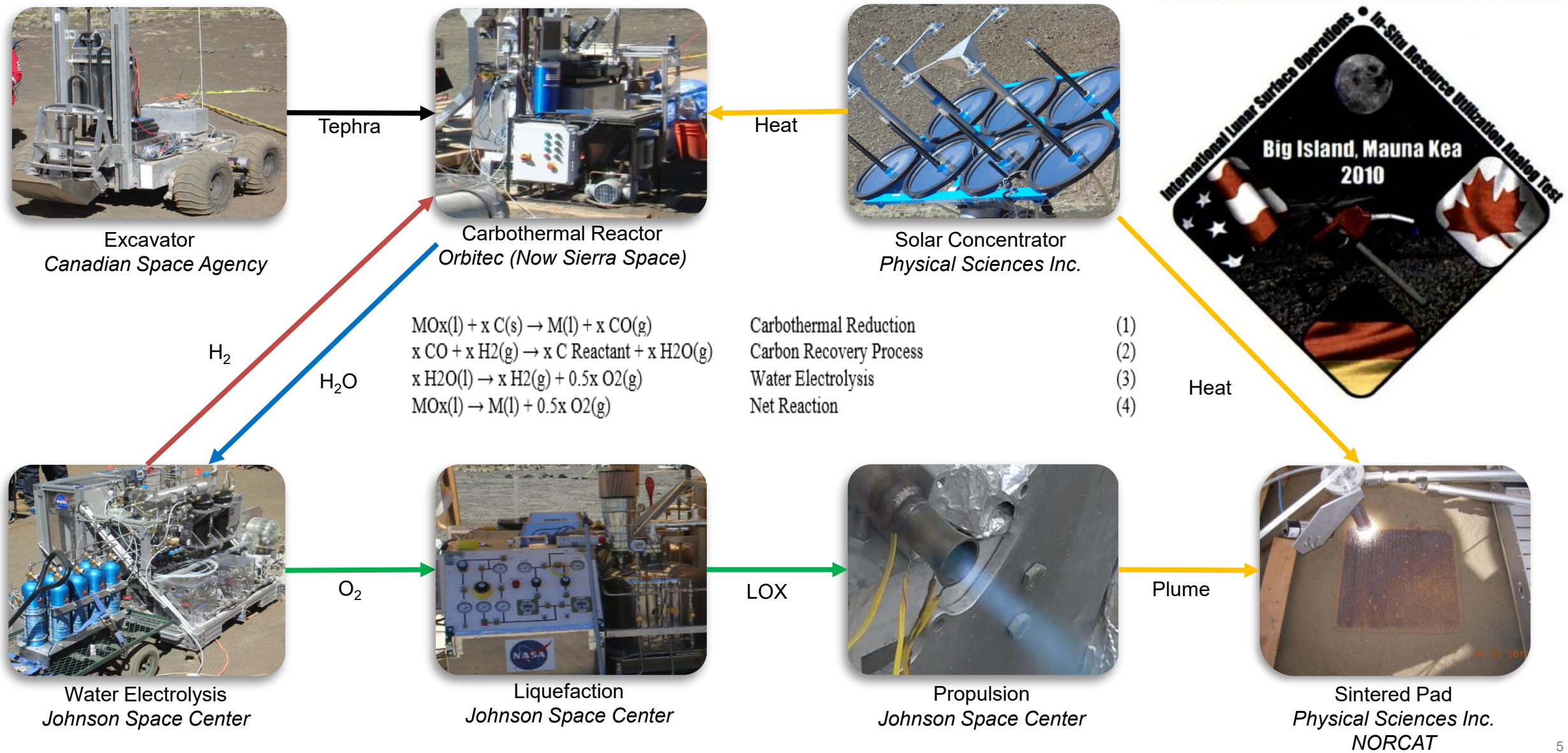
Examples of Lunar Regolith Chemical Composition

[Loftus, D. J., Tranfield, E. M., Rask, J. C., & McCrossin, C. \(2008\). The chemical reactivity of lunar dust relevant to human exploration of the Moon.](#)

*Taylor, L. A., & Carrier III, W. D. (1992). Production of oxygen on the moon: which processes are best and why. *AIAA journal*, 30(12), 2858-2863.

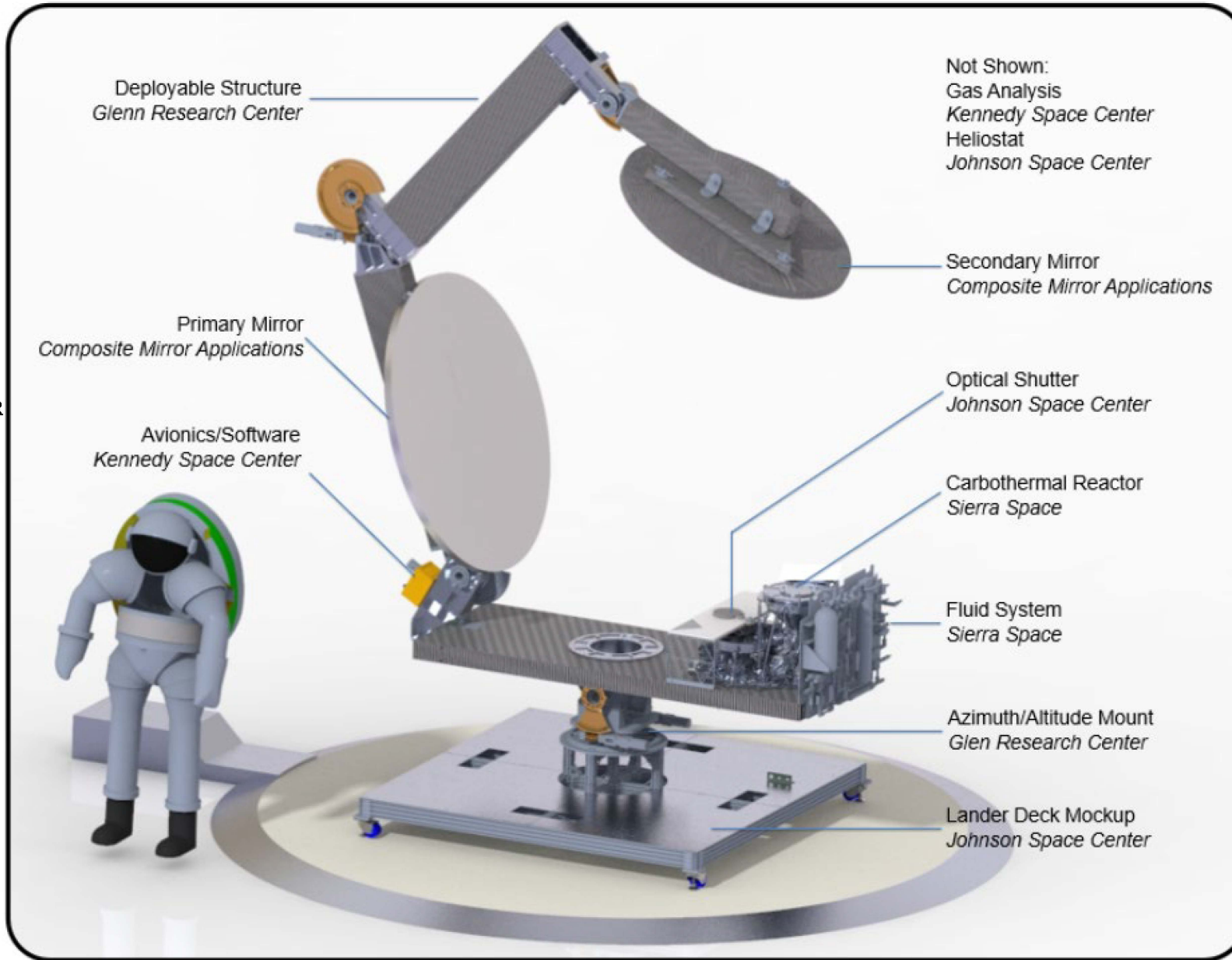
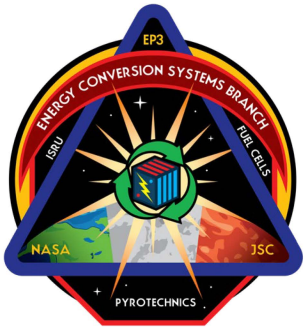
Solar-Carbothermal Reduction History

“Dust to Thrust” 2010

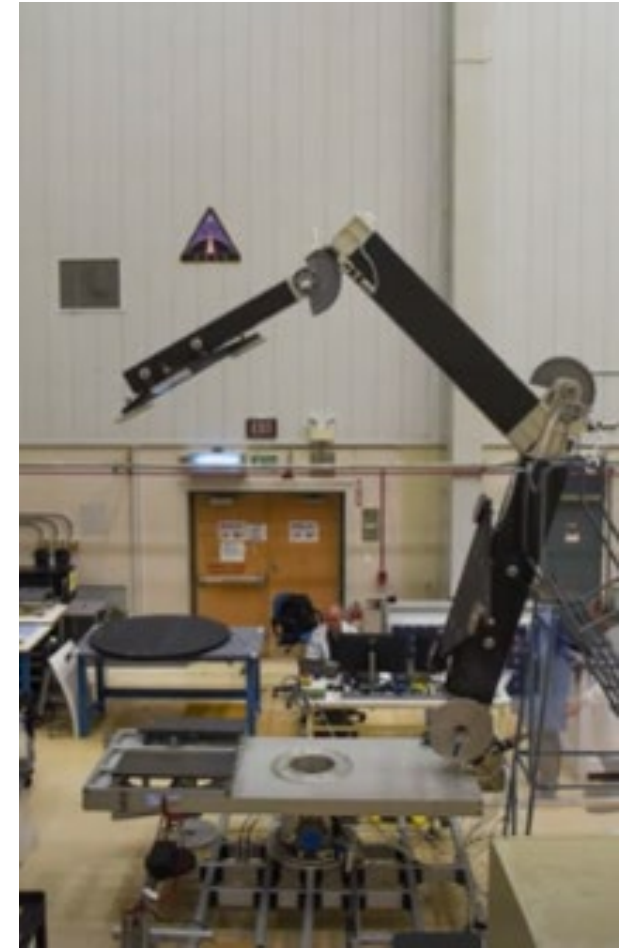
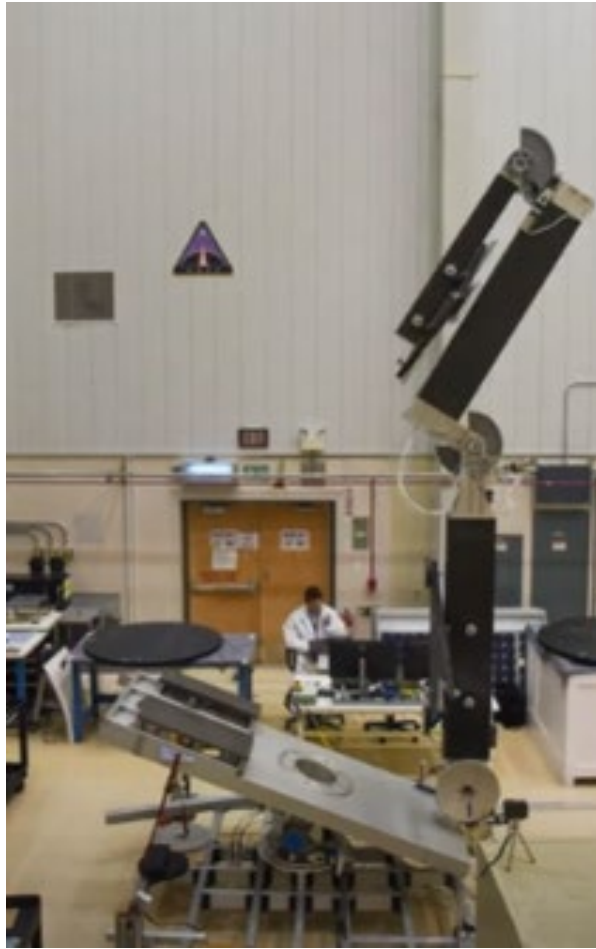
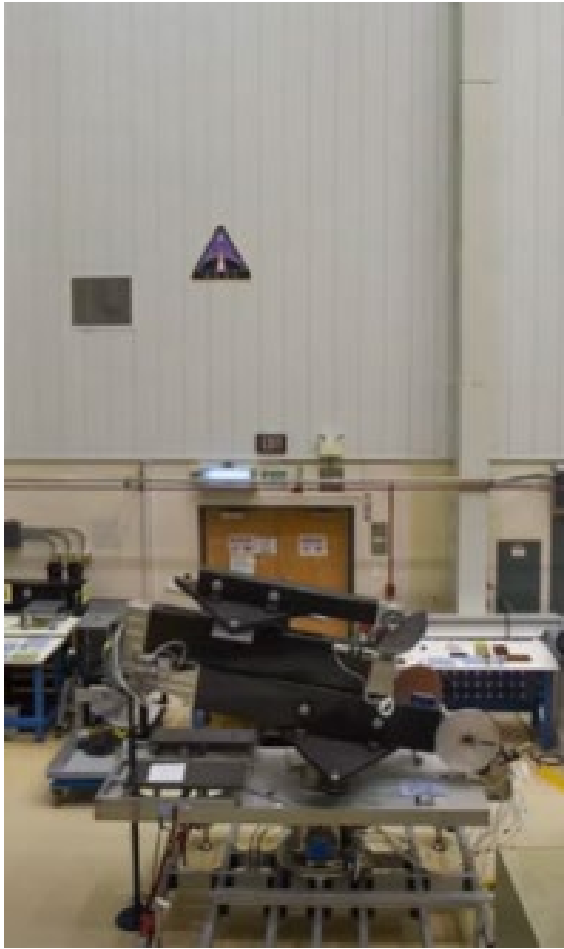




Carbothermal Reduction Demonstration (CaRD) Prototype Overview

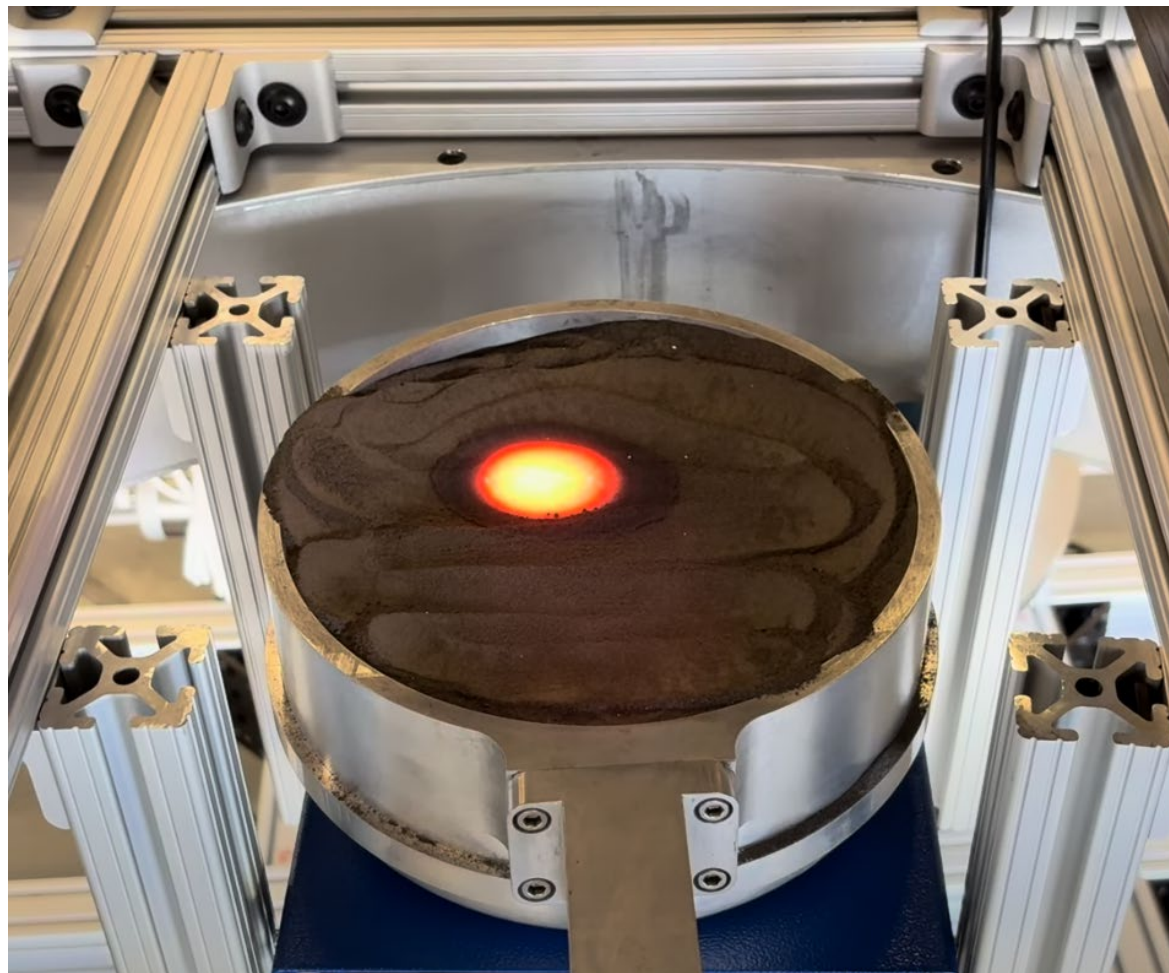


Deployable Solar Concentrator



- 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

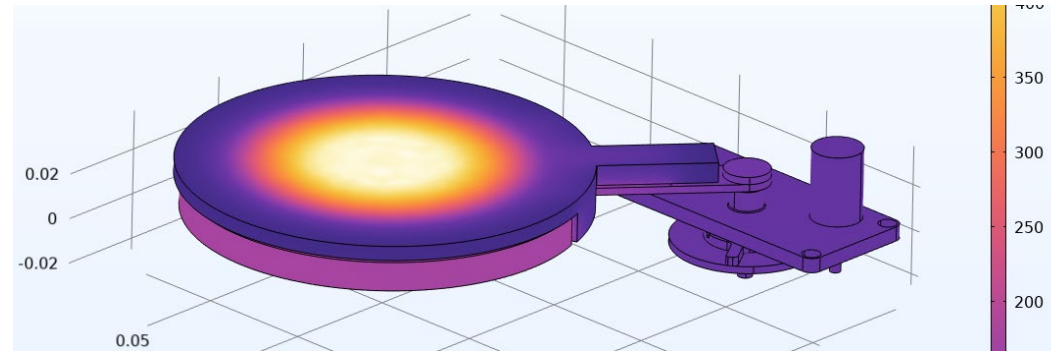


- The solar concentrator mirrors were developed by Composite Mirror Applications, LLC
- The primary mirror weighs 46.3 lbs (21 kg), the secondary mirror weighs 30.4 lbs (13.8 kg)
- Clear aperture diameter = 1.6m, Focal point diameter = 36 mm. Geometric concentration ratio = 1975

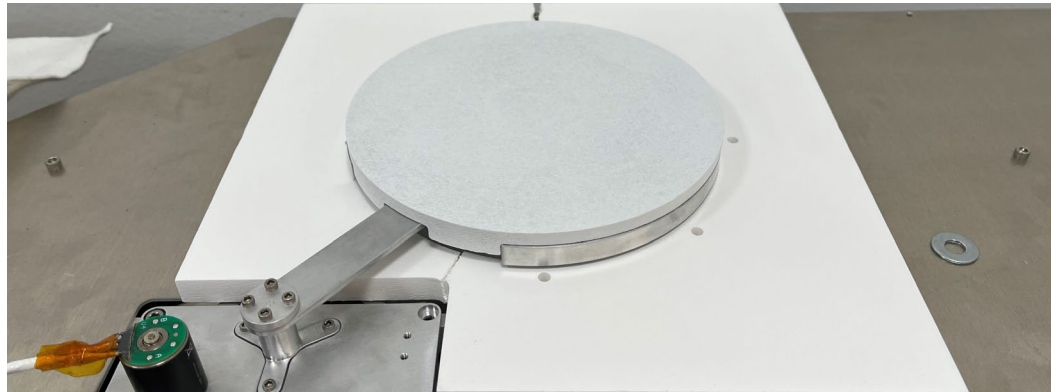
Optical Shutter & Splash Plate



Optical Shutter without LI-900 Installed



Thermal Analysis



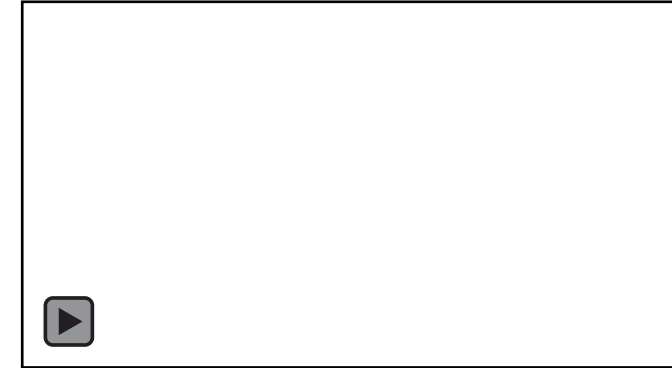
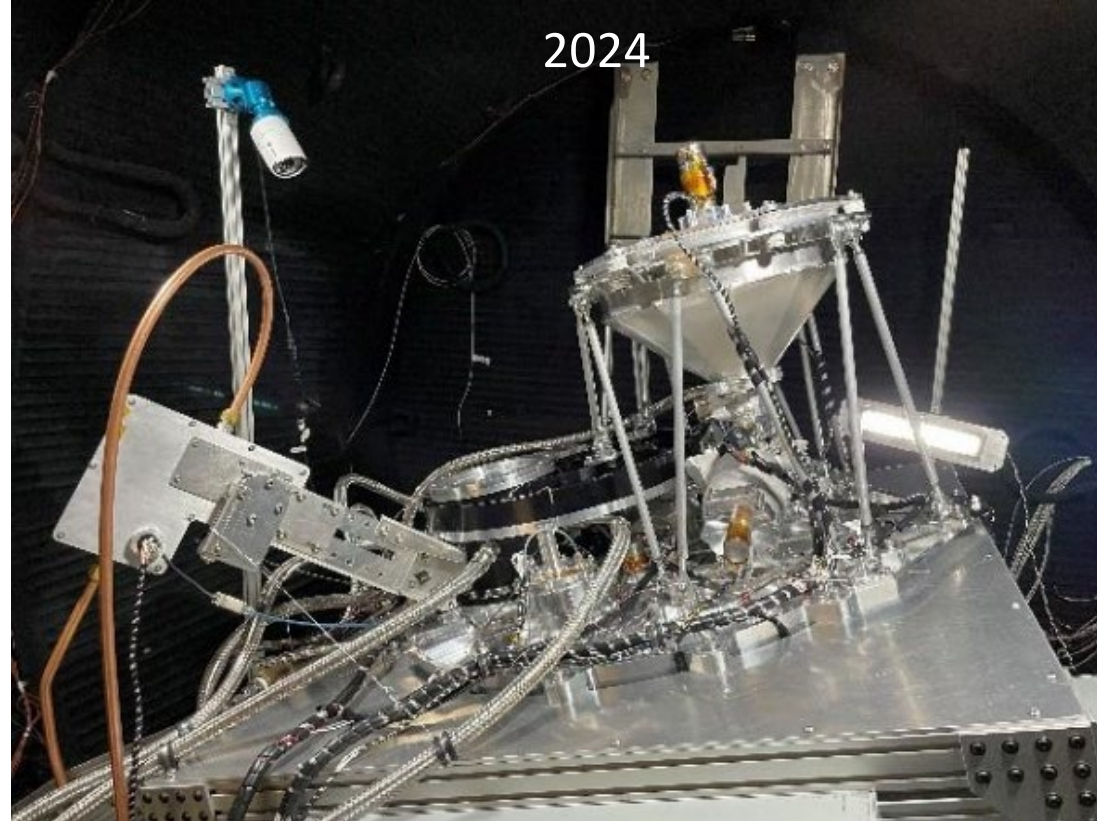
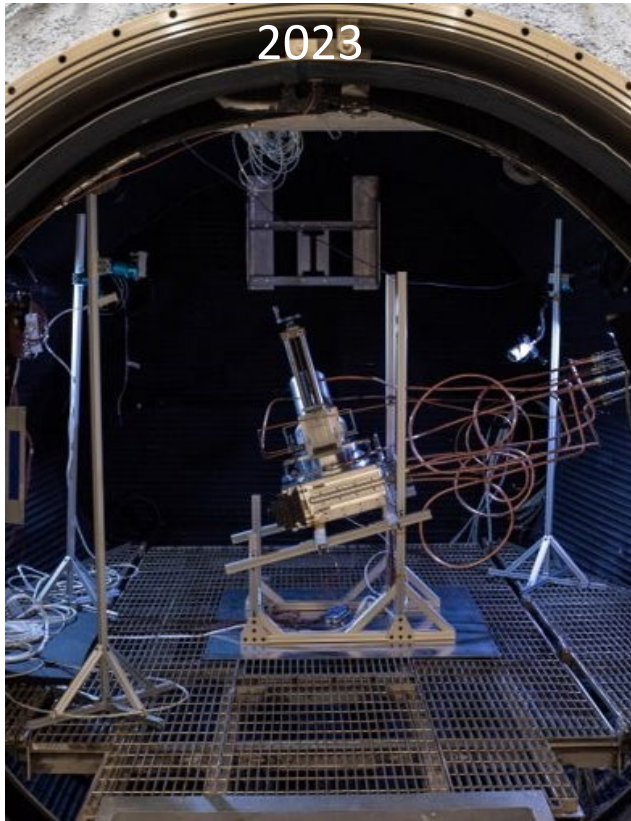
Fractured LI-900



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

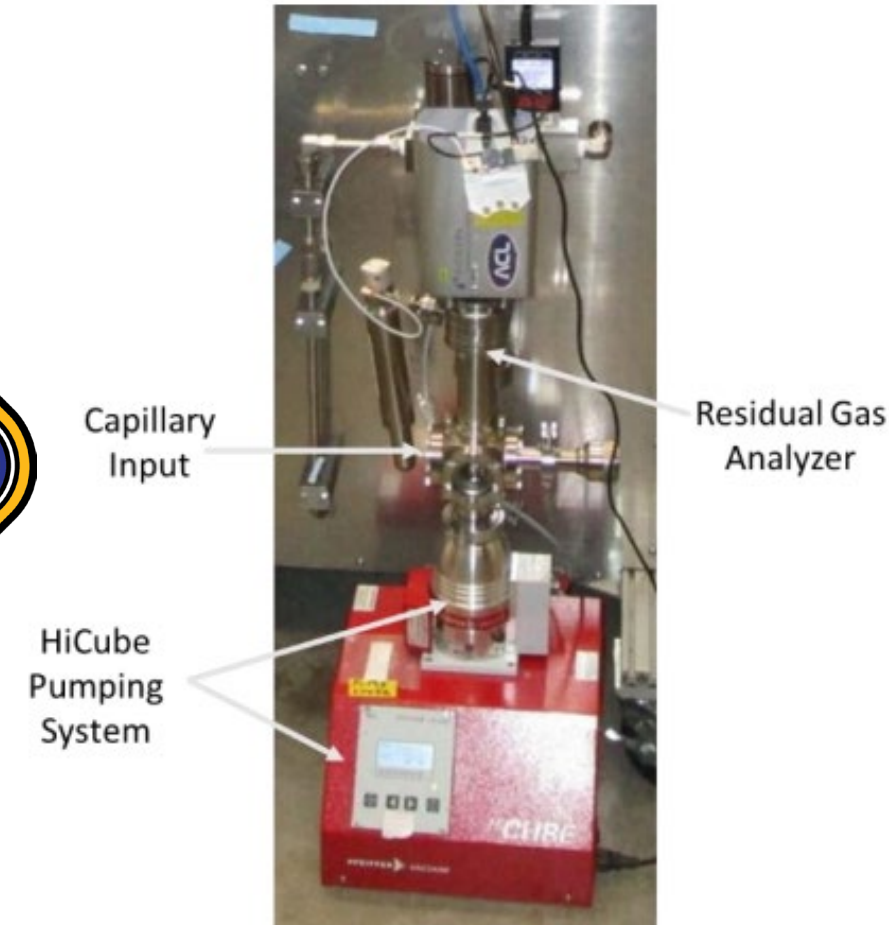


Test Number	grams oxygen extracted/ kWh thermal
CaRD ETU Ambient	13.42
CaRD ETU Vacuum 1	11.53
CaRD ETU Vacuum 2	15.79
CaRD ETU Vacuum 3	10.77

- 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

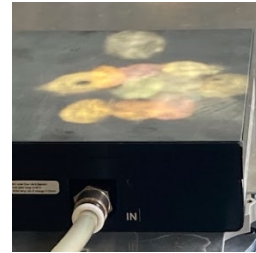
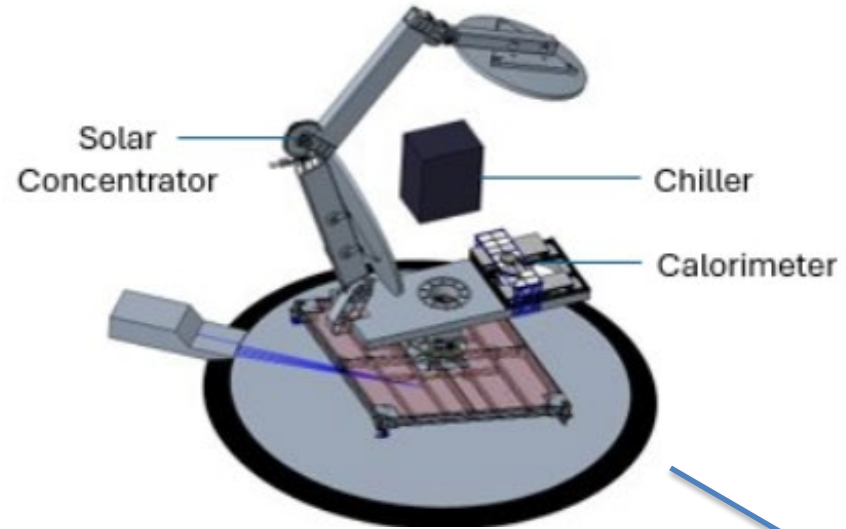
* Haggerty, N. P., White, B. C., Paz, A., O'Connor, D., Azim, N., & Captain, J. (2025, June). Environmental Testing of a Fully Automated Carbothermal Reactor for Lunar Oxygen Production. In *54th International Conference on Environmental Systems (ICES)* (No. ICES-2025-200). International Conference on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

- 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*

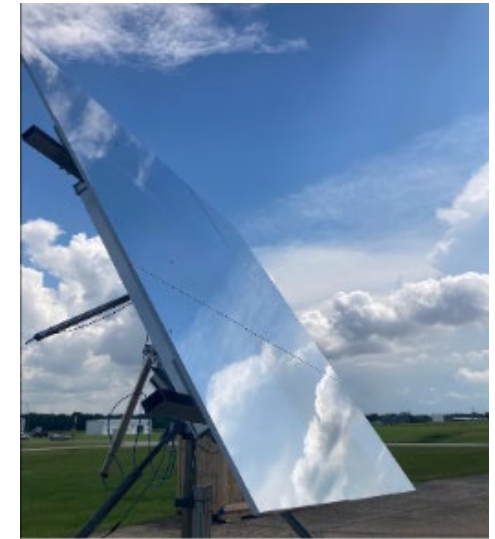
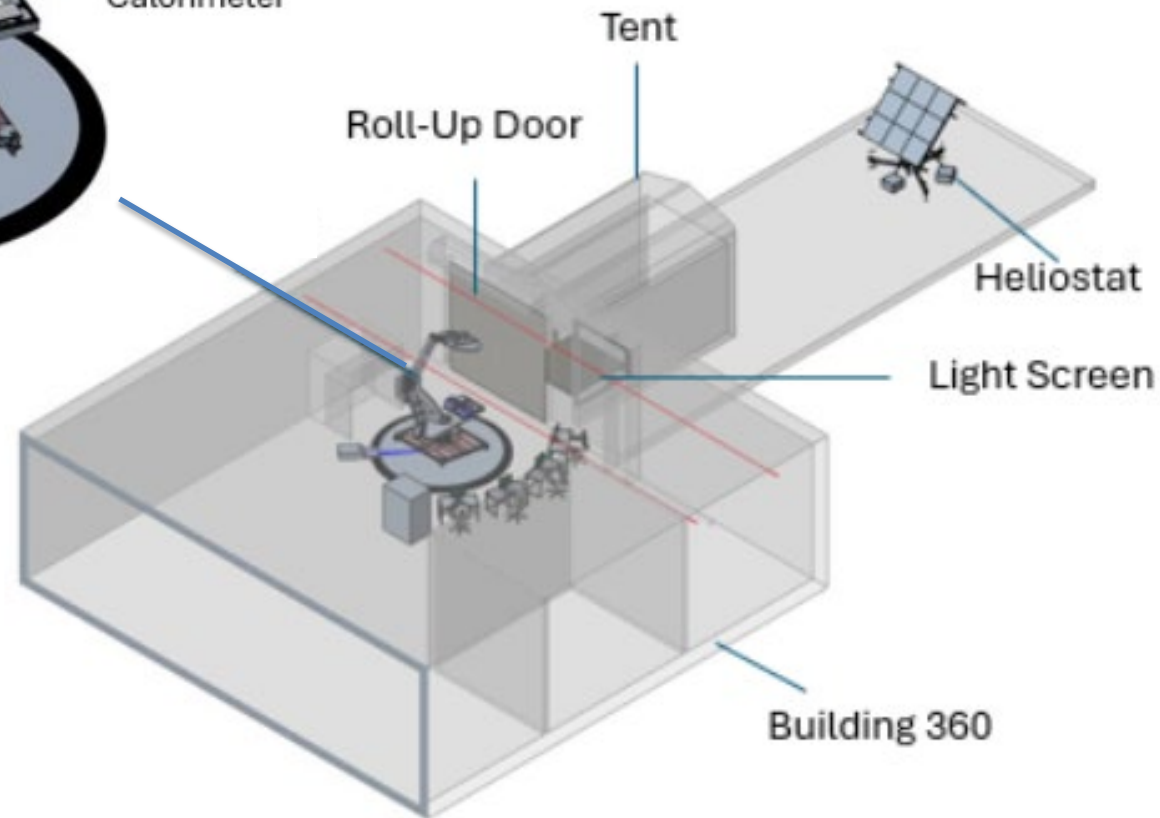


*Gott, R., Olson, J., Azim, N., Aguilar Ayala, R., Captain, J., Haggerty, N., ... & White, B. (2024, July). Carbothermal Reduction Demonstration (CaRD) Gas Analysis Subsystem Development. 2024 International Conference on Environmental Systems.

Integrated Prototype Test Configuration



Calorimeter Illuminated with Light Screen Hole Pattern



Heliostat



Primary Mirror Illuminated with Light Screen Hole Pattern



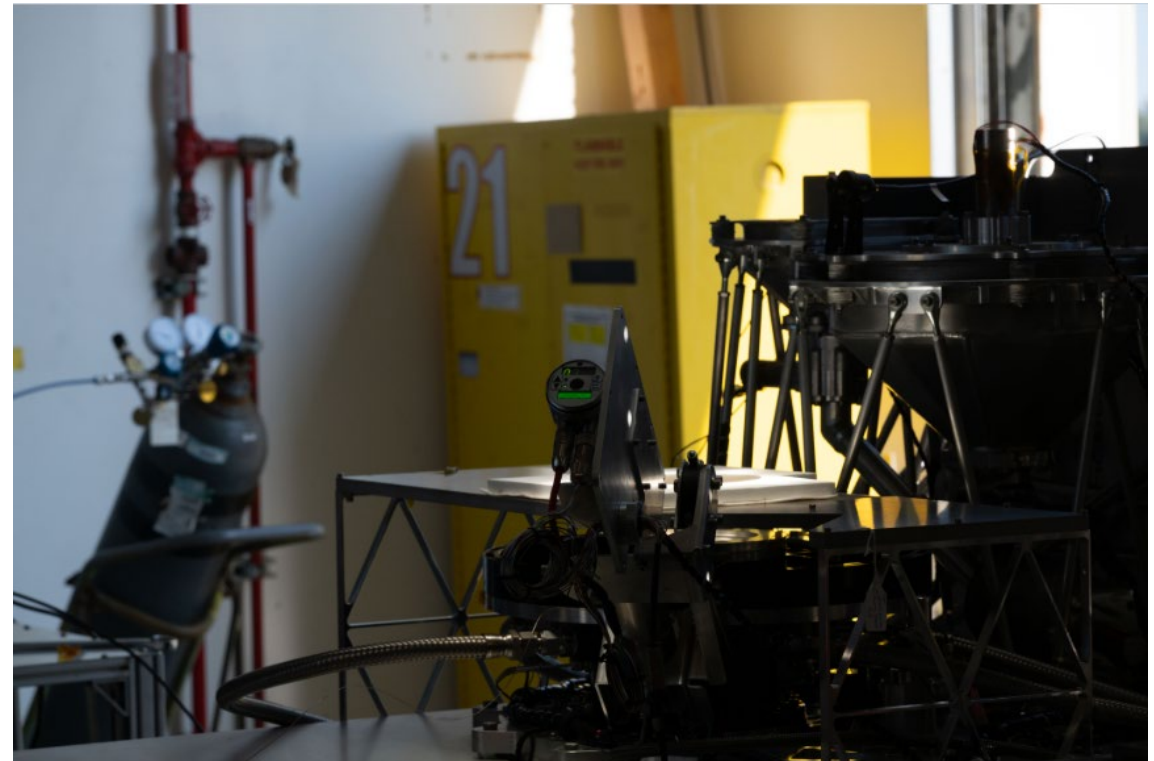
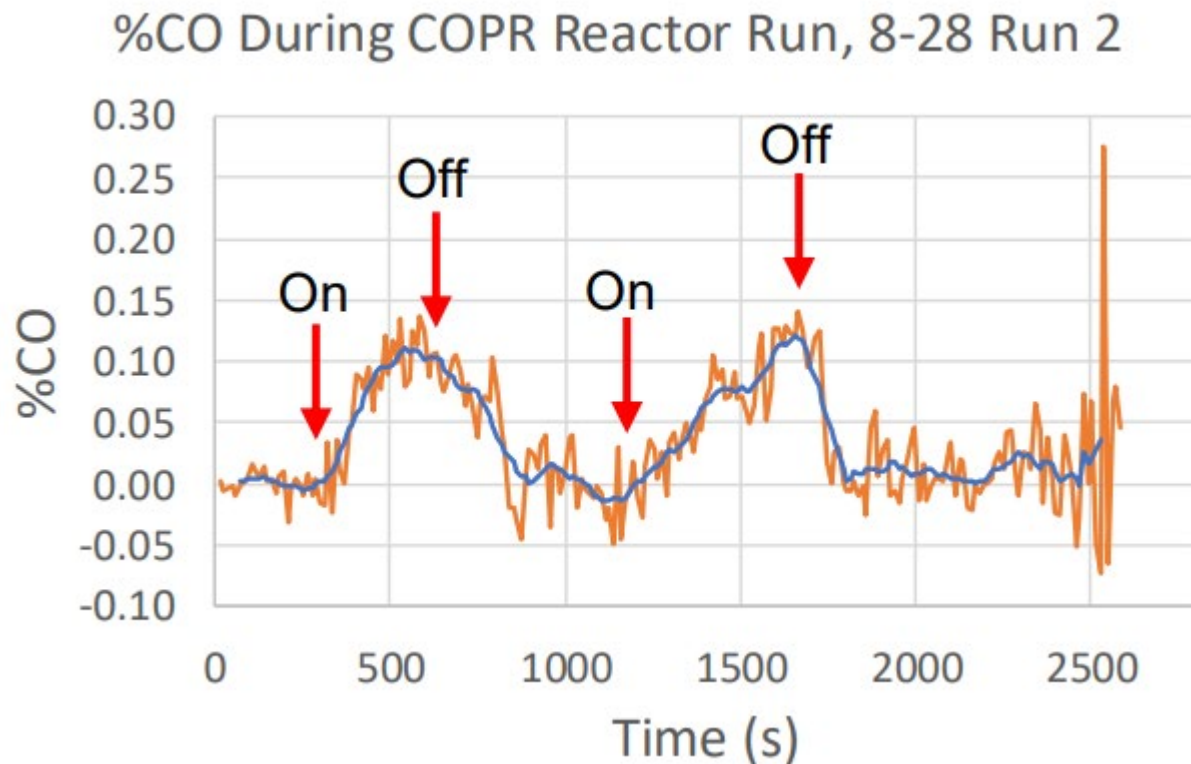
Light Screen

Calorimeter Testing

- Test with no splash plate in place recorded a value of 86.9 Wh at the calorimeter, with 101 Wh of 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%



- 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.



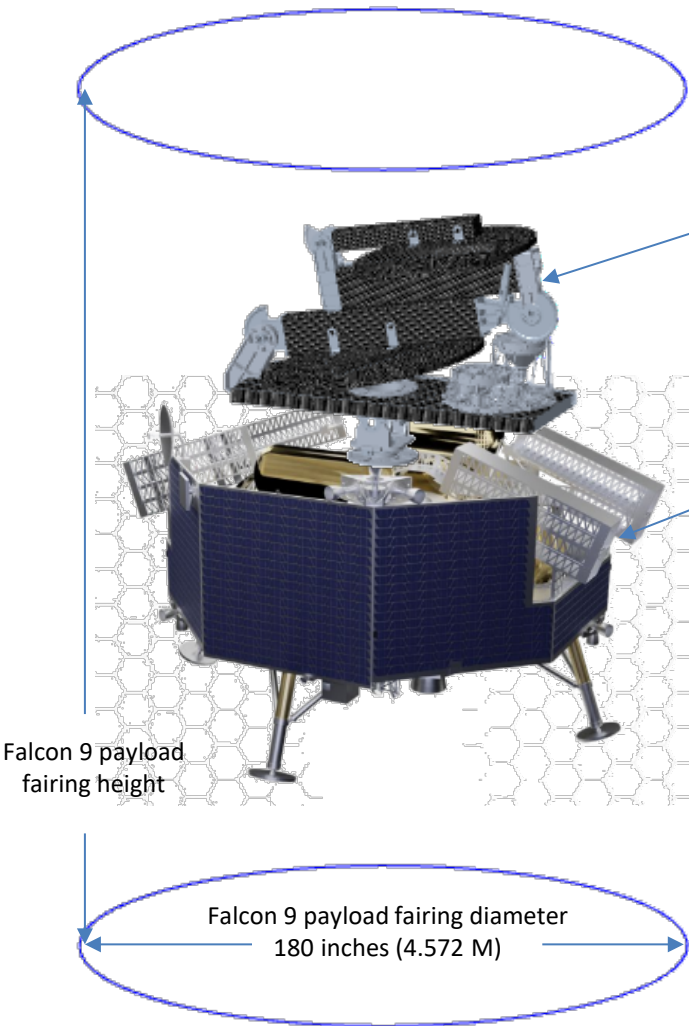


Results

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.

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



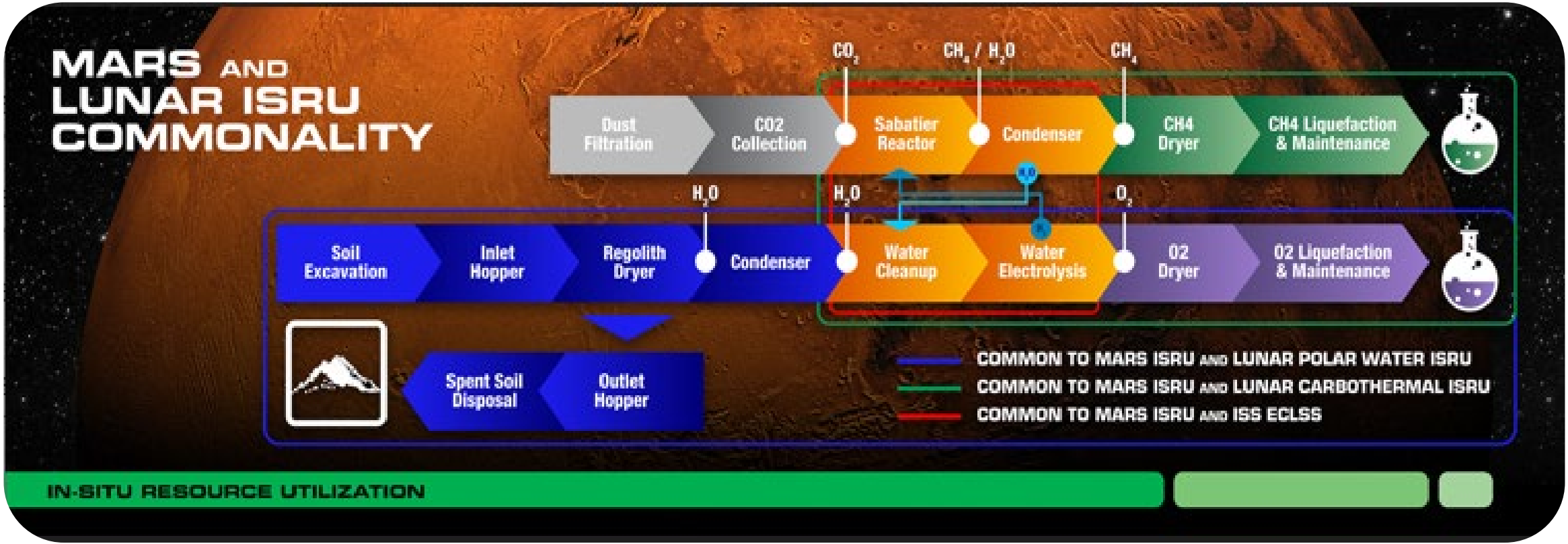
Direct concentrated solar on JSC-1A simulant melted within seconds



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.
- The system was designed for a flight demonstration but is currently not manifest on any mission

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.



Questions?

