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

- 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

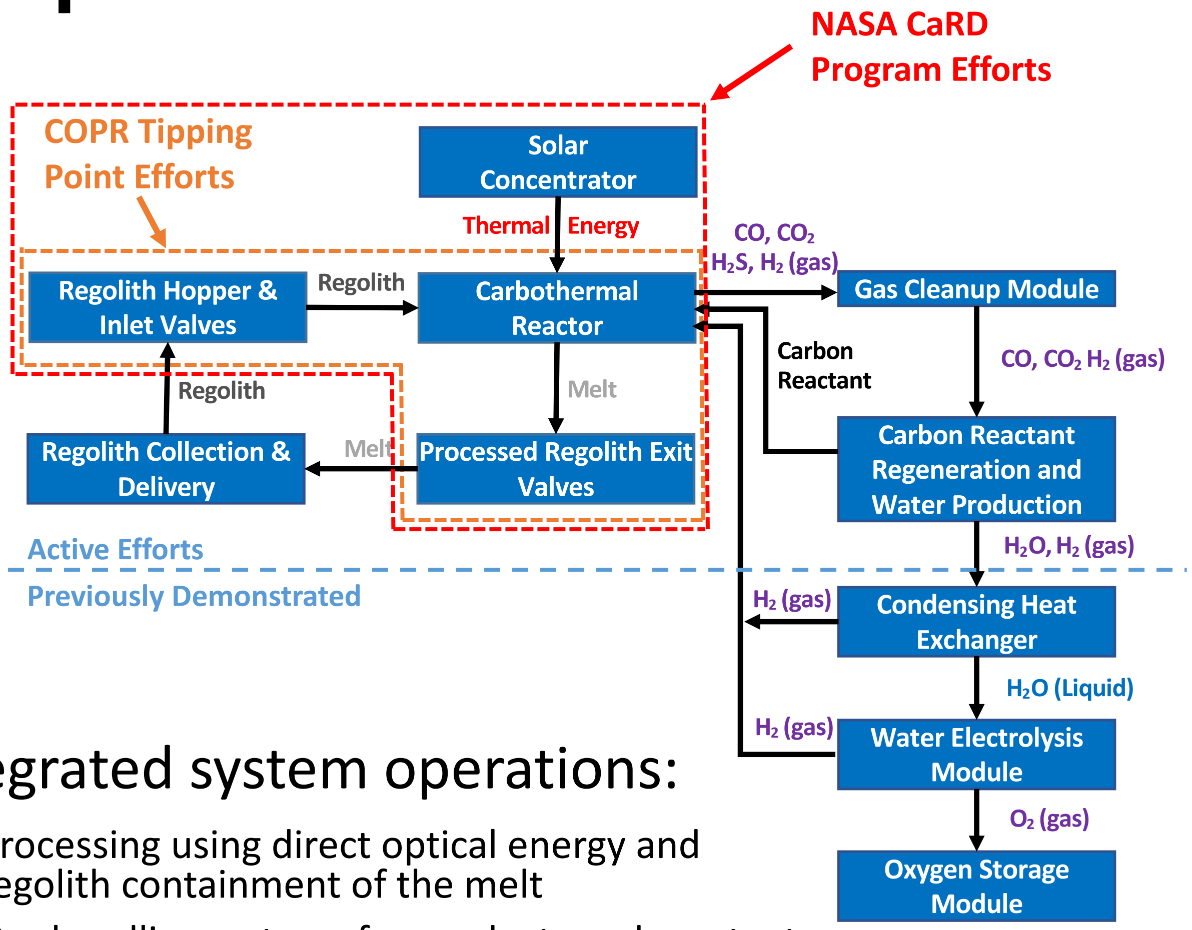
- Carbothermal reactor integrated system was previously demonstrated and matured to TRL 6 in 2024 using NASA JSC TVAC facilities

- 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:

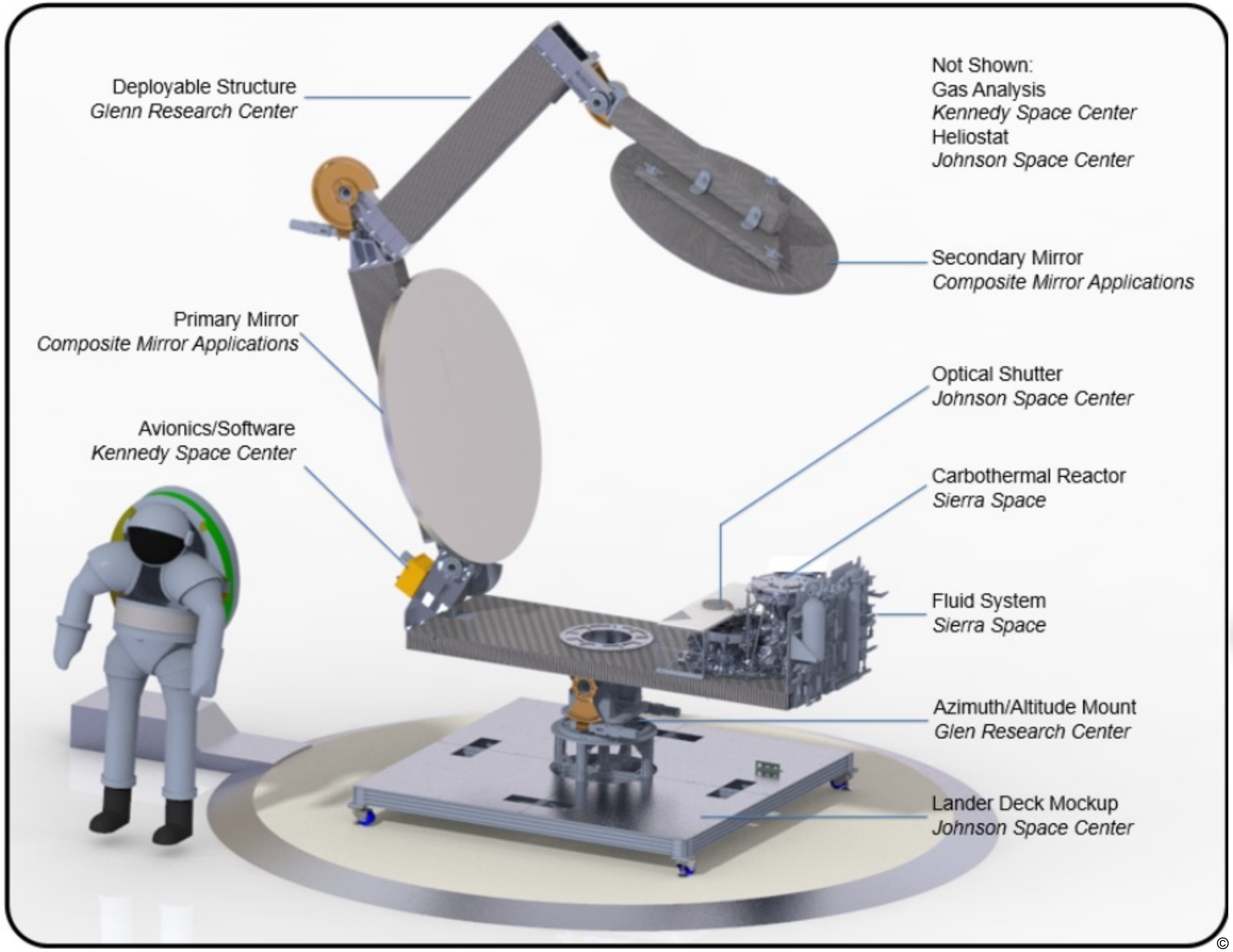
- Crossed Dragone lightweight mirror system deployment
- Direct sun tracking
- Splash plate protection of system from concentrated solar energy
- Carbothermal reduction inside the COPR reactor using direct concentrated solar energy
- Validation of optical protection approaches with solar energy
- Product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



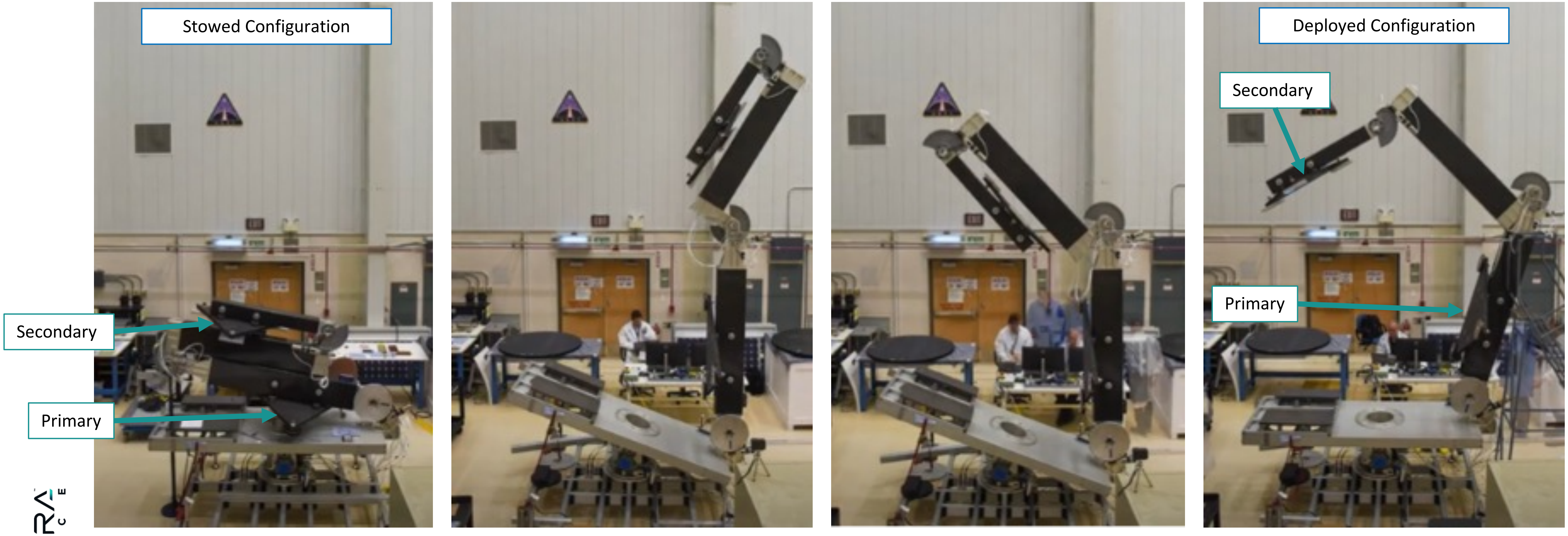
Previously demonstrated automated integrated system operations:

- 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

CaRD Prototype Overview



Deployable Solar Concentrator

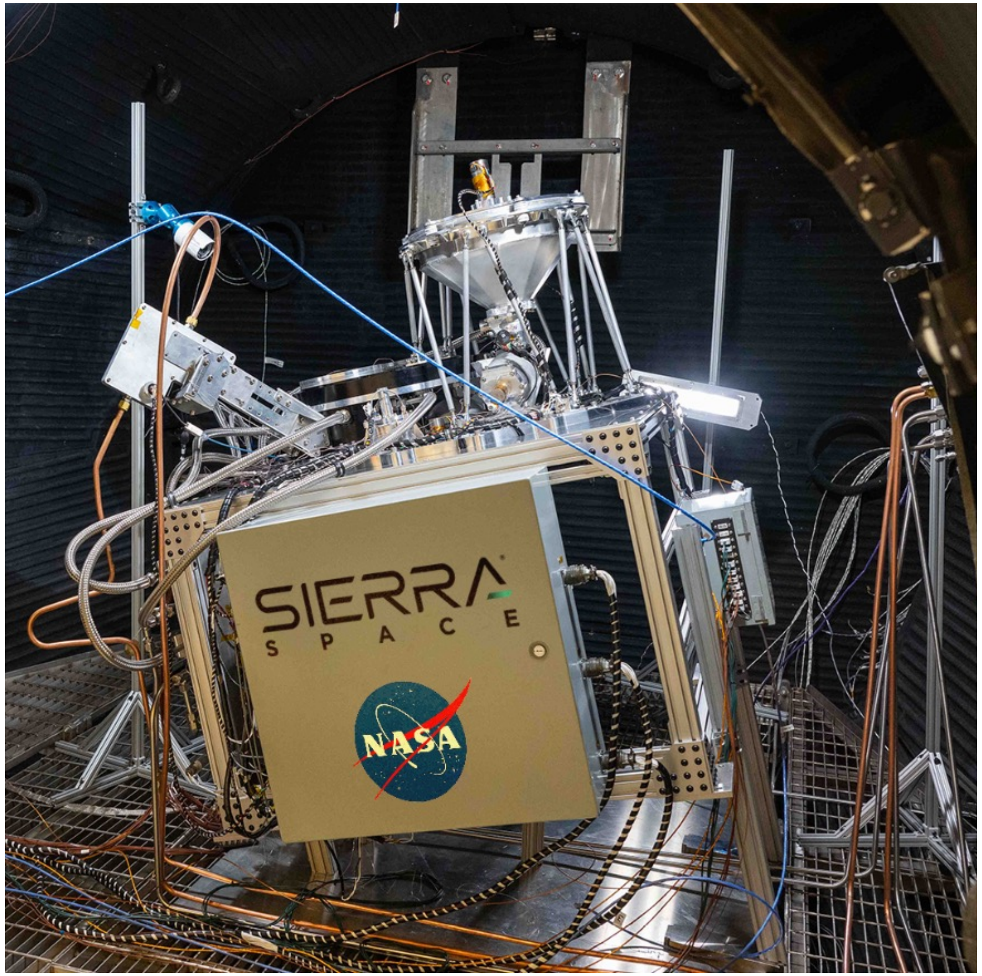


- The deployable solar concentrator mechanisms and structure were developed at Glenn Research Center
- Avionics and Software for the solar concentrator were developed at Kennedy Space Center
- Electrical harnesses for the solar concentrator were developed at Johnson Space Center

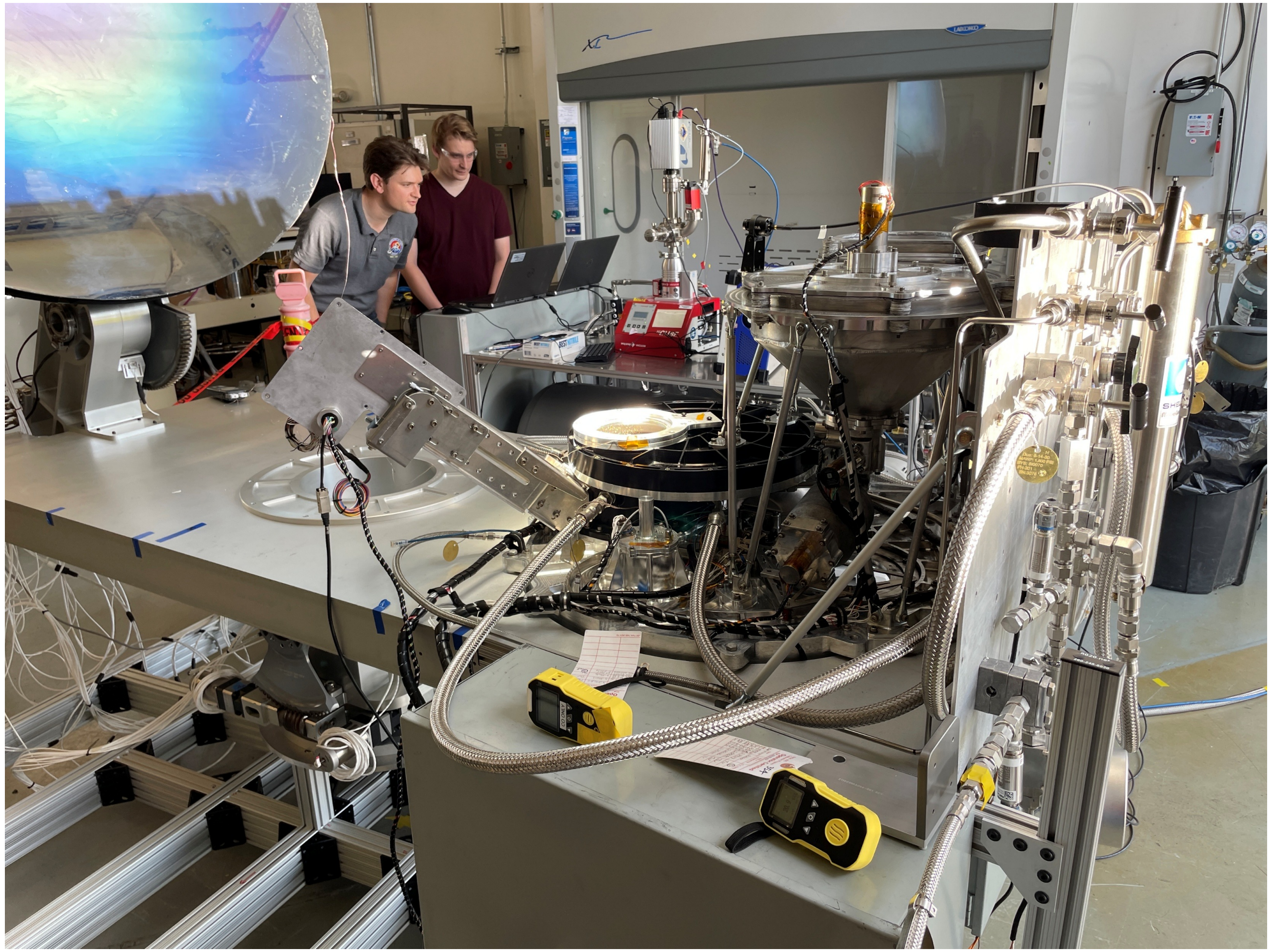
Solar Concentrator Mirrors

- 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)
- Heliostat used for testing
- Mirrors sized to provide the correct power at lunar polar locations

Carbothermal Reactor & Fluid System



Automated System Testing to TRL 6 in 2024 Using Laser Heat Source at JSC



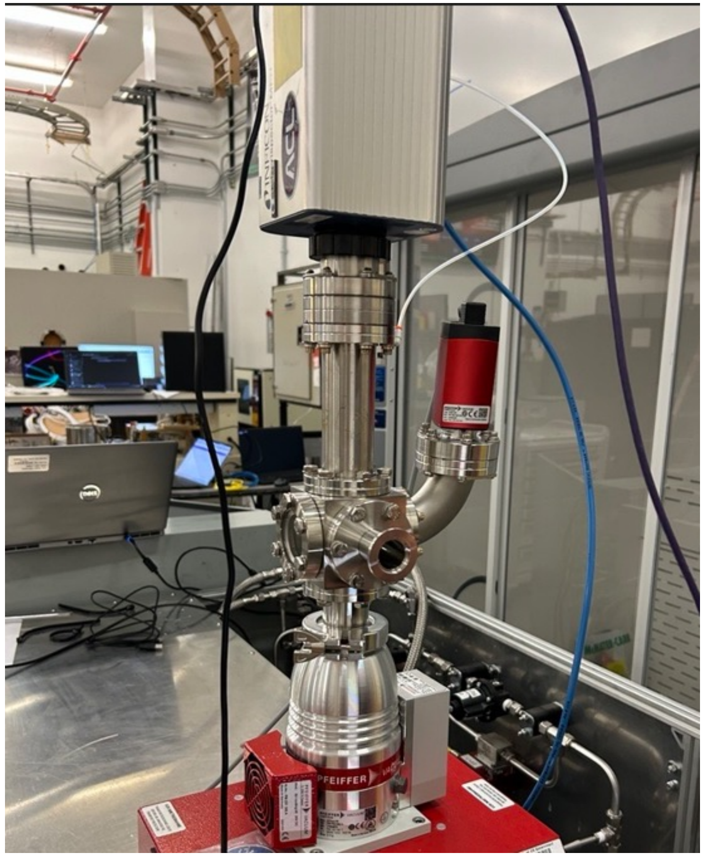
Integrated Testing in 2025 with Direct Concentrated Solar at JSC

Gas Analysis

- CaRD used a commercial version the Mass Spectrometer Observing Lunar Operations (MSolo) instrument that recently operated successfully on the Moon during the PRIME-1 mission

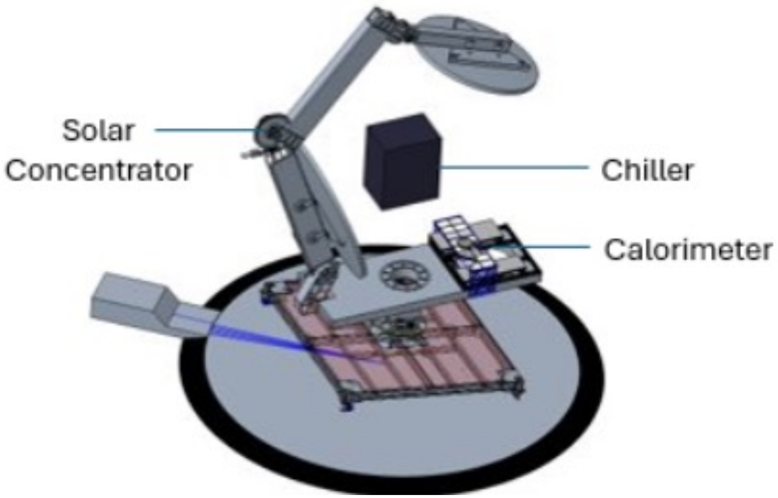
- This gas analysis system was used during the 2023 & 2024 thermal vacuum tests, successfully demonstrating the ability to differentiate between nitrogen and carbon monoxide without the use of a gas chromatograph

- 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*



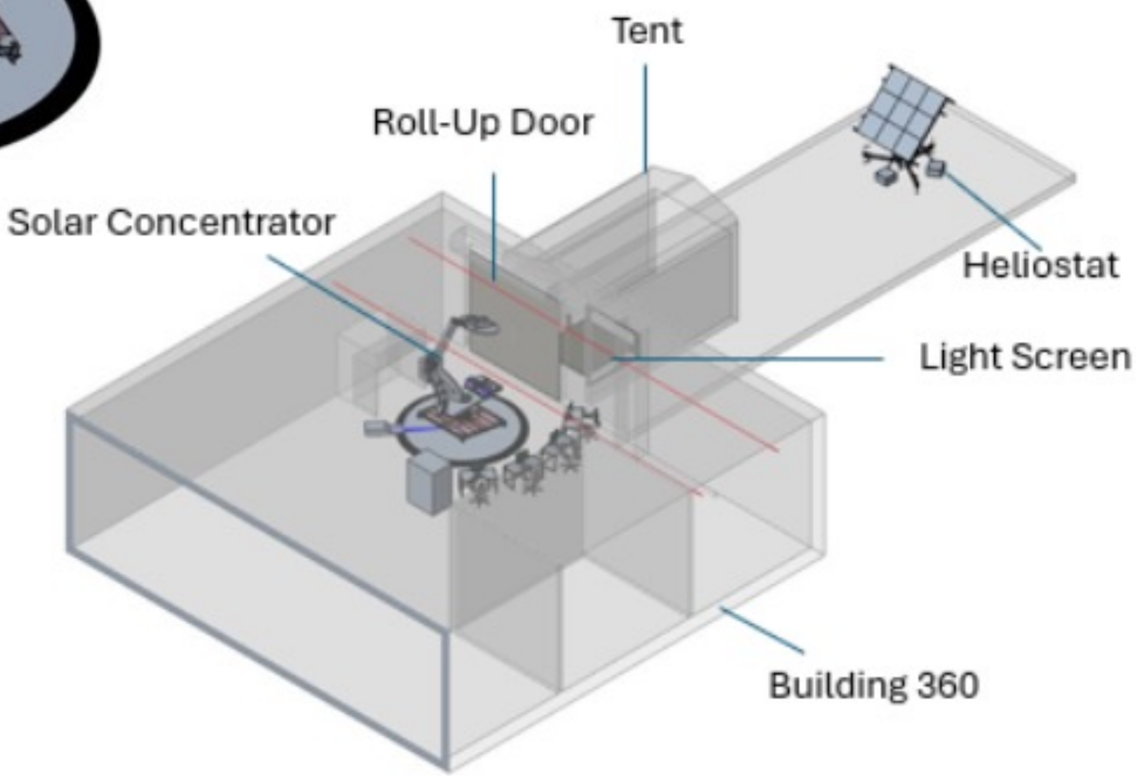
*Gott, R., Olson, J., Azim, N., Aguilar Ayala, R., Captain, J., Haggerty, N., ... & White, B. (2024, July). Carbothermal Reduction Demonstration (CaRD) Gas Analysis Subsystem Development. 2024 International Conference on Environmental Systems

Integrated Prototype Test Configuration



Calorimeter Illuminated with Light Screen Hole Pattern

Heliostat

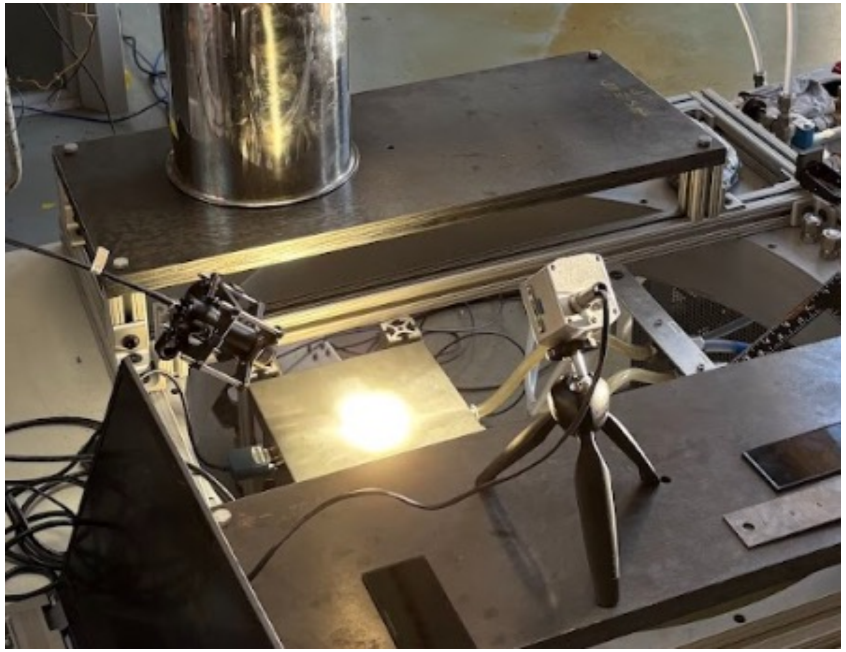


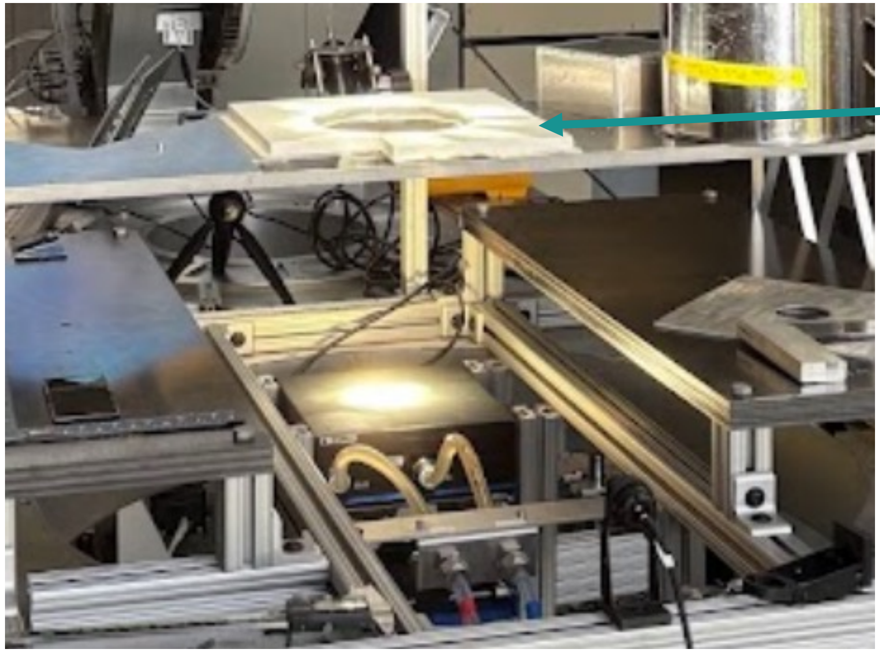
Primary Mirror Illuminated with Light Screen Hole Pattern

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%

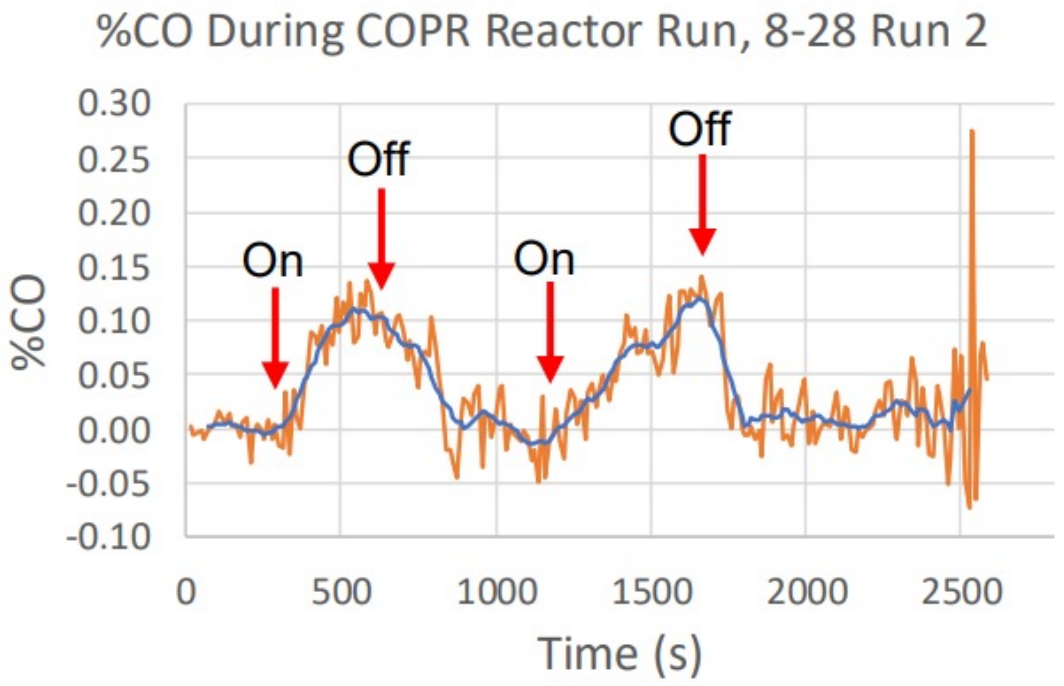


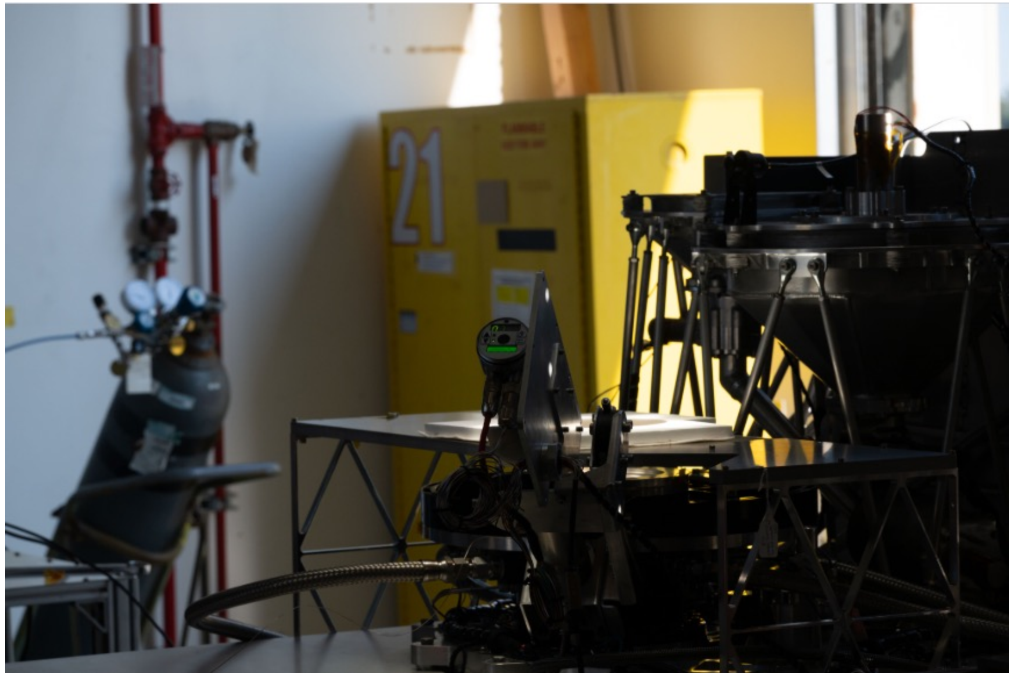


Note some clipping of solar illumination on splash plate due to mirror and alignment imperfections

Solar Carbothermal Reduction Testing

- Test in Houston on 8/28/25 extracted 0.195 grams of oxygen in the form of carbon monoxide with 0.38 kWh 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

- The performance of the CaRD solar-carbothermal prototype exceeded the threshold performance established by the first-generation system, despite poor weather conditions in Houston
- 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 that of laser at 1380 W, 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

System	Test Date	Location	Simulant	~Input Solar Flux (W/m^2)	Aperture Area (m^2)	Delivered Power (W)	gO_2/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

Key Program Requirements Achieved

Regolith Handling

- Repeated handling operations with multiple simulants, including agglutinates
  - Simulant metering, pressure sealing, melt containment, and melt separation/removal
- Operations while exceeding worst-case landing site topographies

Carbothermal Reduction

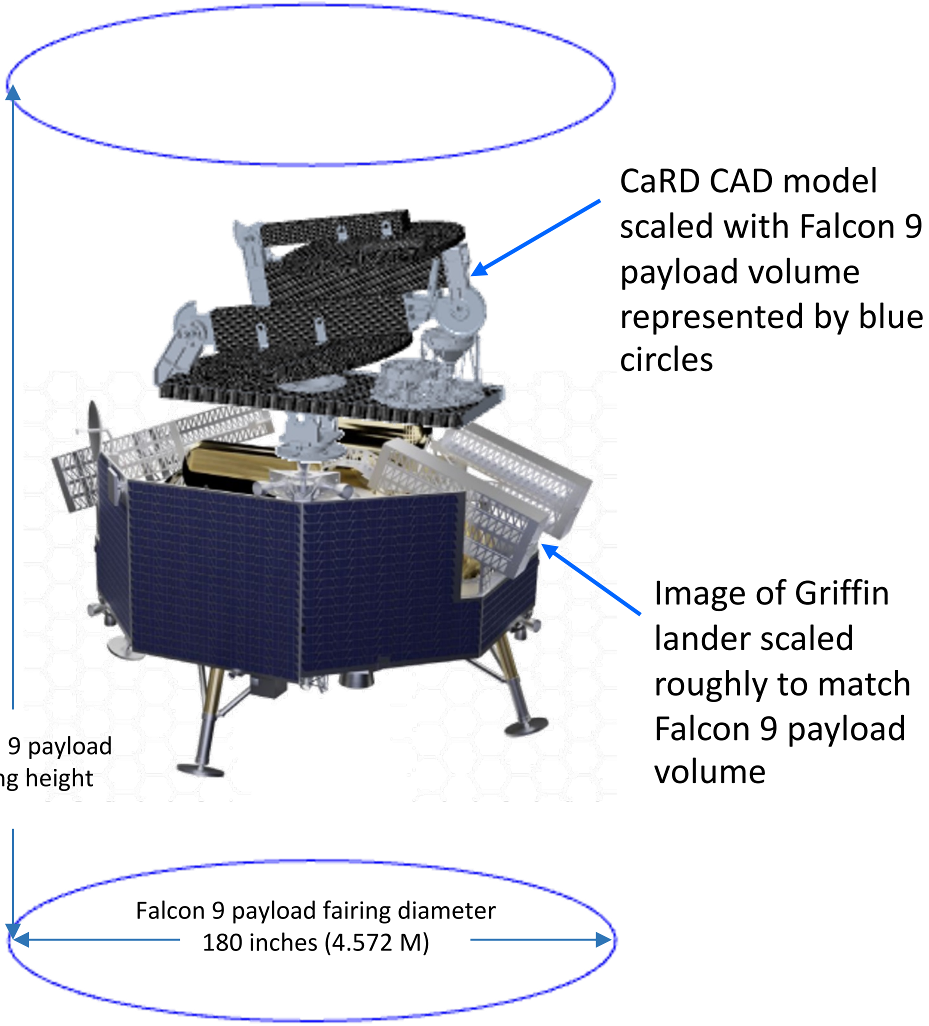
- Oxygen extraction exceeding KPP goals for thermal energy efficiency (g O_2/kWh) and production yield (g O_2/g regolith)
- Performance of the optical protection system with no issues encountered throughout the test sequence
- Carbon reactant recovery of 99.7% in the processed melt

Overall System

- Demonstrated technologies are scalable to a 3.5 tonne/yr O_2 pilot plant
- Integrated direct solar concentrator operations including deployment
- Demonstration of oxygen extraction via the carbothermal reduction reaction directly with solar energy

Next Steps

- 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 a reliable indicator of performance with true lunar regolith in 1/6 g
- Flight-like system design for a CLPS scale flight demonstration; forward work needed to manifest



Griffin Lander Image Credit: Astrobotic

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

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

Future Work

- Carbothermal reduction can be paired with ECLSS for both oxygen generation and carbon recycle
- Pairing with water ice and a bulk carbon source provides the ability to make methane with far less intensive liquefaction requirements and easier access to the required oxygen