Integrated Solar Testing and TRL 6 Thermal Vacuum Test Results for a Fully Automated, Demonstration Scale Carbothermal Reactor

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Carbothermal Reduction Process

Mature terrestrial technology for producing high-purity silicon

- Works with mare & highlands regoliths to reduce iron, calcium, & aluminum
- Demonstrated with JSC-1A, GreenSpar 250, NUW-LHT-5M simulants

Carbon-based reactant extracts the oxygen from the regolith metallic oxides to produce CO/CO_2

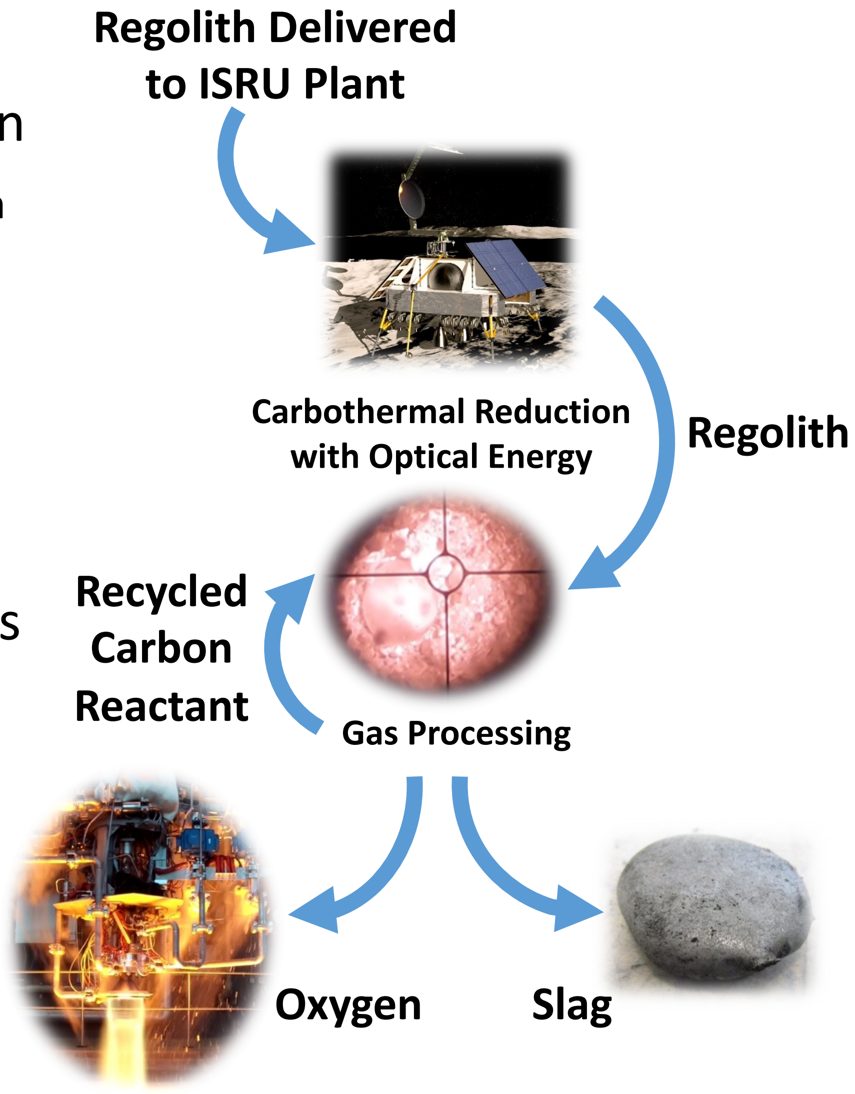
- Typical processing conditions: <10 minutes, >1650 °C, <35 kPa (5 psia)

A catalytic carbon recovery process regenerates the carbon-based reactant (i.e., methane) from the CO/CO_2 and produces water using recycled hydrogen from the electrolysis unit

Waste heat from the reactor can help drive the catalytic and electrolysis processes

$MO_x(l) + xCH_4(g) \rightarrow M(l) + xCO(g) + 2xH_2$	Carbothermal Reduction
$xCO + xH_2(g) \rightarrow xCH_4 + xH_2O(g)$	Carbon Recovery Process
$xH_2O(l) \rightarrow xH_2(g) + 0.5xO_2(g)$	Water Electrolysis
$\boldsymbol{MO_x(l) \rightarrow M(l) + 0.5xO_2(g)}$	**Net Reaction**

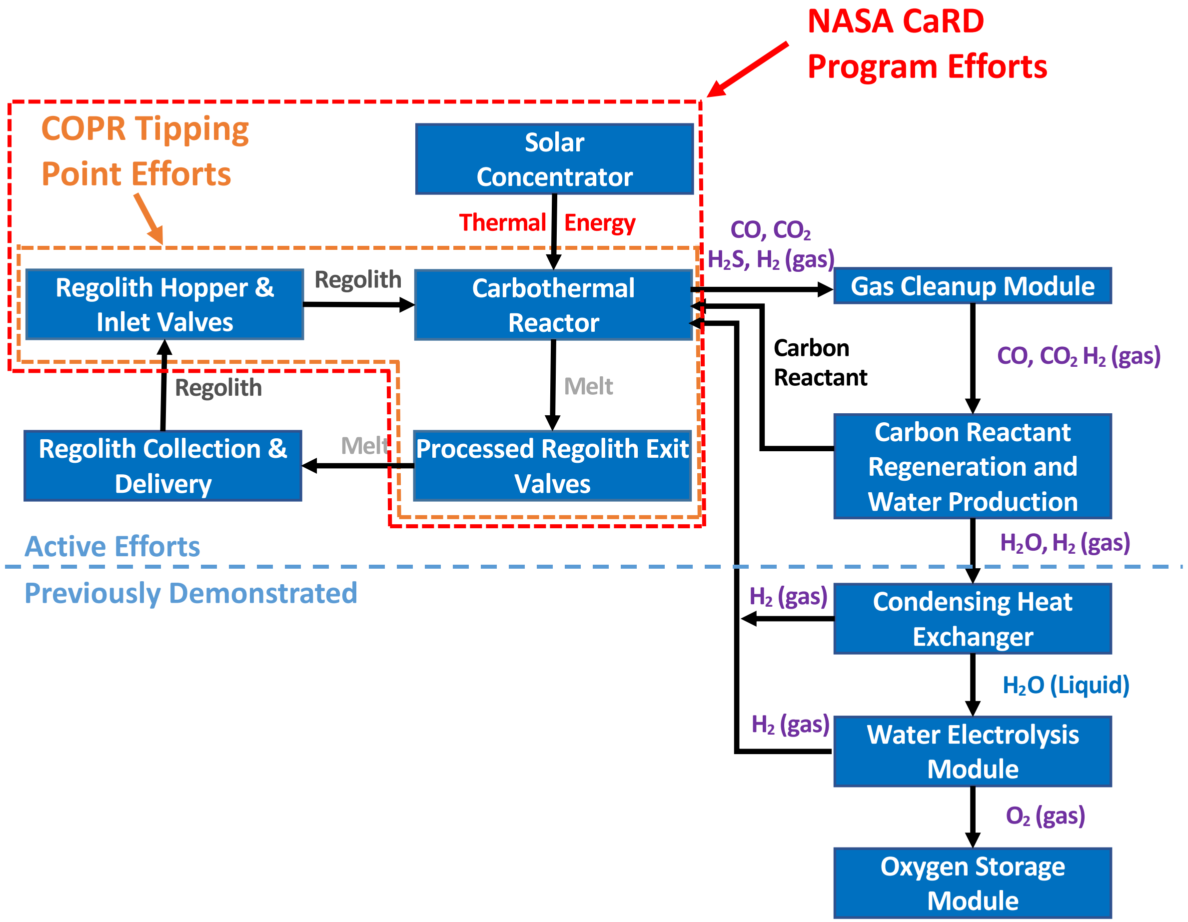
M = Metal elements present in the regolith/simulants



COPR Tipping Point Operations

Demonstrated integrated system operations via automated control:

- 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

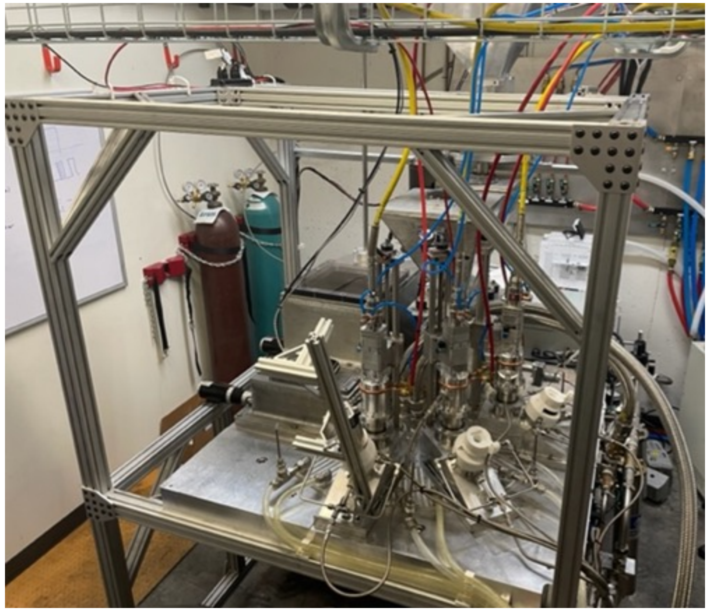


These operations are included in the COPR Tipping Point flight-like design & NASA CaRD integration system

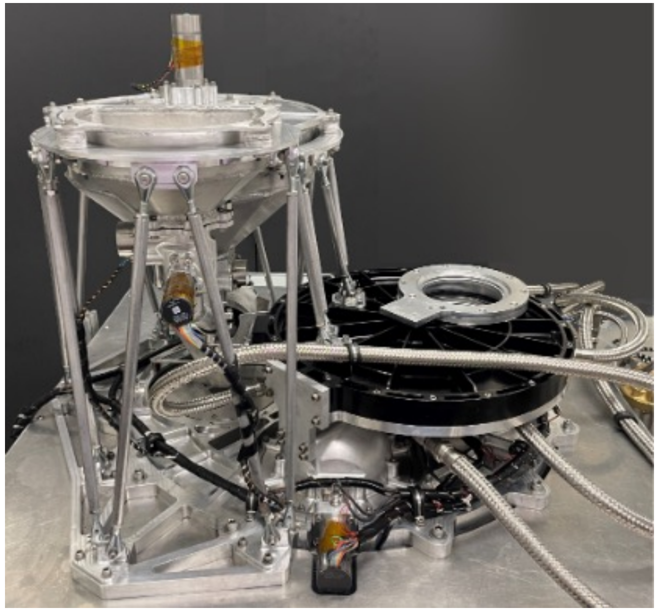
Scalable Flight-Like Architecture

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

COPR Integration to NASA TVAC

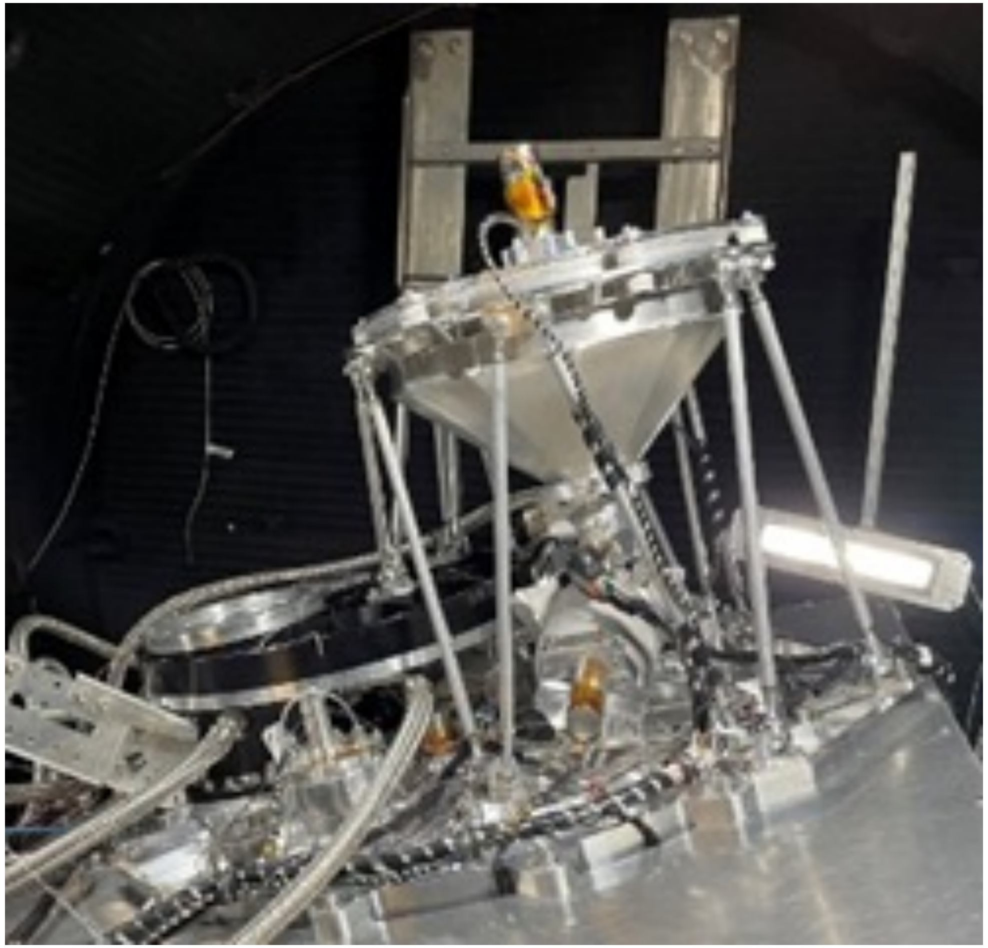
The COPR hardware was integrated into the NASA JSC B351 ‘dirty’ TVAC chamber and with the MSOLO mass spectrometer during the summer of 2024

Prior coordination with the NASA teams ensured that interfaces, safety requirements, and test plans were addressed prior to shipment and integration

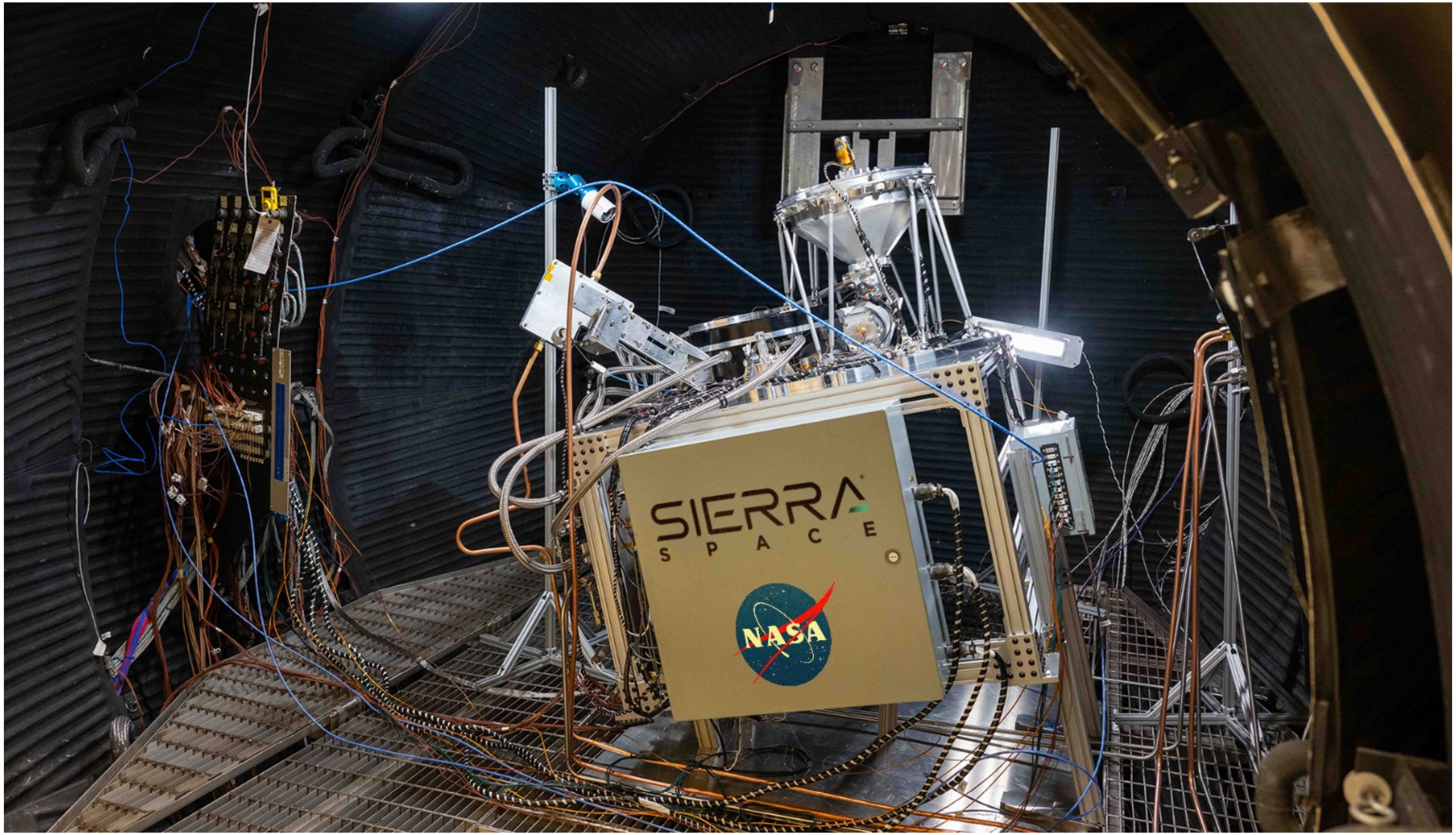
Ambient and subsystem thermal/vacuum testing was performed at Sierra Space prior to NASA TVAC integration – see 2024 Space Resources Roundtable presentation for details

COPR TVAC Test Conditions

- Temperature ranged from 20 °C to -40 °C based on NASA modeling of the expected lunar south pole daytime conditions for a lander
- Vacuum conditions were ~10^{-5} torr achieved by two large oil diffusion pumps
- The COPR hardware was placed at 15° from horizontal in the worst-case orientation for regolith flow
- GreenSpar 250 was used as the closest chemical analogue for lunar highlands regolith



Carbothermal Testing in Lunar Environment



COPR Testing Highlights

Successfully demonstrated all COPR program process steps:

- Regolith handling operations (metering, flow, transport)
- Regolith tolerant valve technology
- Carbothermal reduction processing via direct heating using a laser
- Gas/fluids handing systems
- Processed melt removal
- Autonomous remote operations

during repeated testing at vacuum & thermal vacuum conditions

Carbothermal Reduction Processing at -40 °C and vacuum environmental conditions

This testing successfully matured the COPR Tipping Point system to TRL 6

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

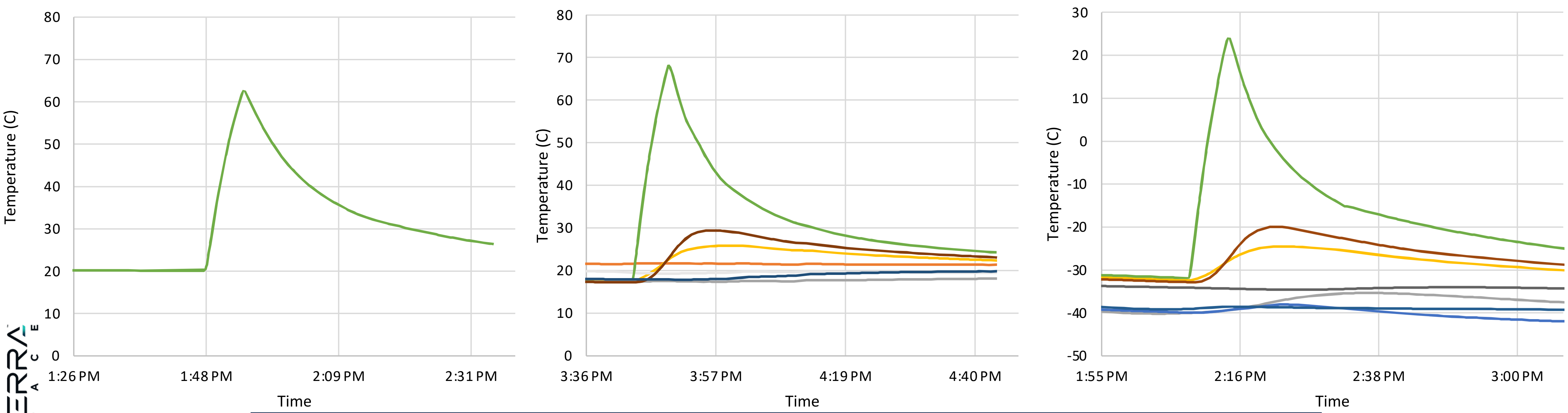
Thermal Performance Comparison

COPR uses a passive thermal system allowing for simplicity on a CLPS lander tech demo

Ambient Pressure & Temperature

Vacuum, Ambient Temp

Vacuum, -40 °C



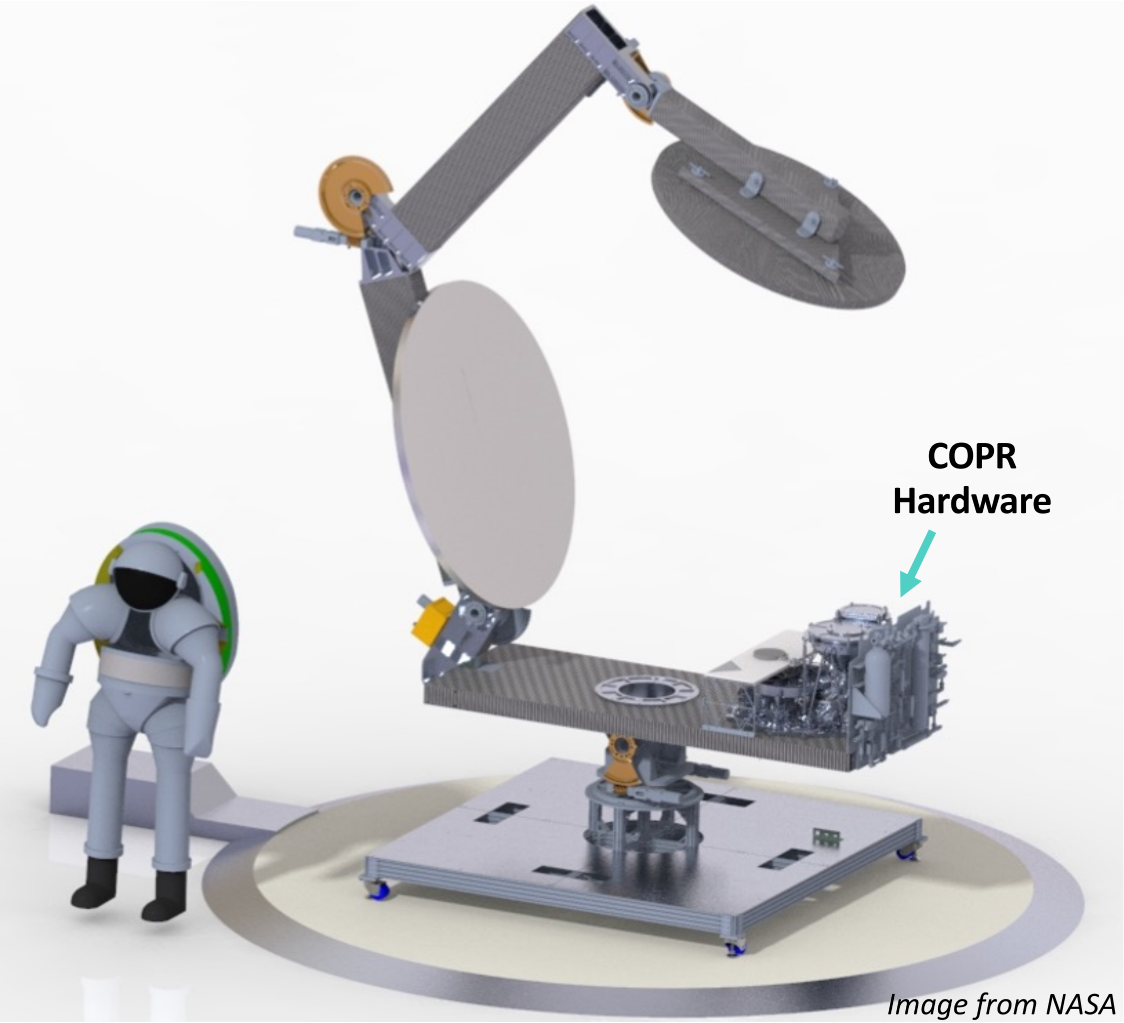
Short reset times and sufficient thermal capacity allow for many cycles during a flight mission

Upcoming Work

NASA is developing a flight-like solar concentrator, tracker, and avionics system

- Collaboration between JSC, GRC, KSC, and industry partners
- Utilizes flight heritage lightweight mirrors
- Hardware is currently being assembled

COPR hardware will be integrated with the NASA system during Summer 2025 and demonstrate the carbothermal reduction process in the fully integrated system using direct concentrated solar energy



COPR integrated with solar concentrator and other systems provided by multiple NASA Centers and outside industry partners through the NASA CaRD Project

Lessons Learned

Environmental chambers are not quite like the moon!

Vibration from chamber pumps & facility EMI affected some sensors

- Despite replicating full cable runs & connections from the TVAC facility, still saw differences. Addressed through filtering algorithms and some conops adjustments

Facility materials constraints can impose more stringent requirements than flight

- Some operations would have been even more successful will less constraints

Zero-point drift or other shifts in behavior at low temperature with some sensors

- Developed calibration/re-tuning procedures to address

“Trust, but verify” with vendor claimed temperature compatibilities/ranges

- Identified in subsystem testing and corrected prior to full TVAC testing

Test at the subsystem level at your TVAC conditions prior to full system testing

Thank you to everyone at NASA & the community for your support of the COPR Tipping Point effort!