A Fully Automated, Demonstration Scale Carbothermal Reduction Reactor

June 6th, 2024

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Carbothermal Reduction Overview & Prior Efforts

Carbothermal Reduction Process

Mature terrestrial technology for producing high-purity silicon from silica

- Can also reduce iron, calcium, aluminum
- Process works with both mare & highlands regolith
- Demonstrated with JSC-1A, GreenSpar 250, NUW-LHT-5M simulants

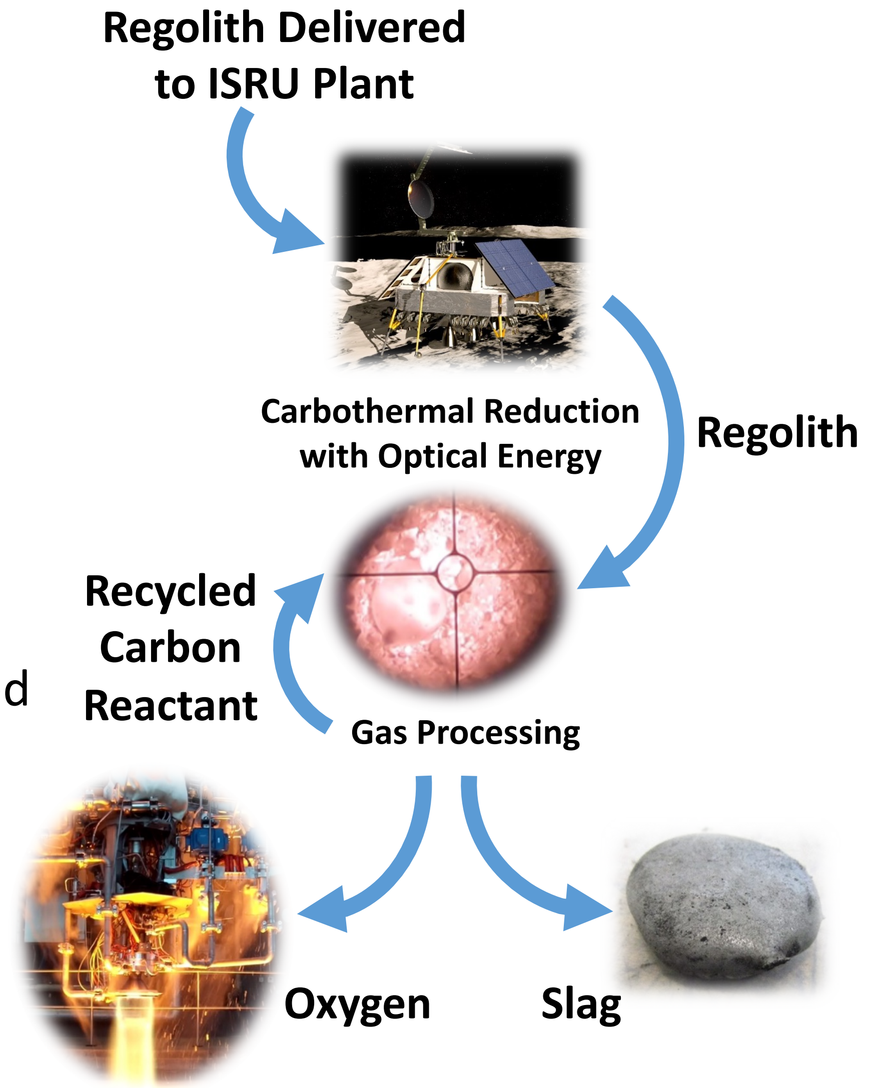
Carbon-based reactant and heat extracts the oxygen from the regolith metallic oxides to produce CO/CO_2

- Typical processing conditions: <10 minutes at >1650 °C and under 5 psia

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

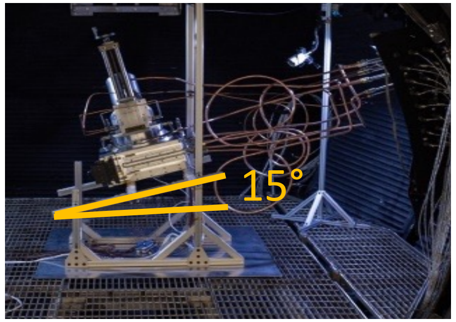
$MO_x(l) + xCH_4(g) \rightarrow M(l) + xCO(g) + 2xH_2$	Carbothermal Reduction
$xCO + xH_2(g) \rightarrow xCH_4 + xH_2O(g)$	Carbon Recovery Process
$xH_2O(l) \rightarrow xH_2(g) + 0.5xO_2(g)$	Water Electrolysis
$\boldsymbol{MO_x(l) \rightarrow M(l) + 0.5xO_2(g)}$	**Net Reaction**

M = Metal elements present in the regolith/simulants



Carbothermal Benefits

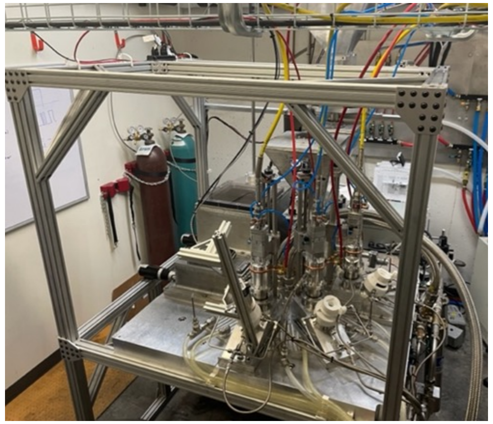
Flexibility



- Accommodates up to 15° slope at landing site
- Process works effectively with both mare and highlands regolith

Scalability

- Very low electrical power requirements
- Demonstrated, scalable material handling and production
- Waste heat can be utilized for downstream processes

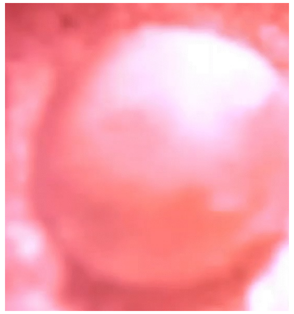


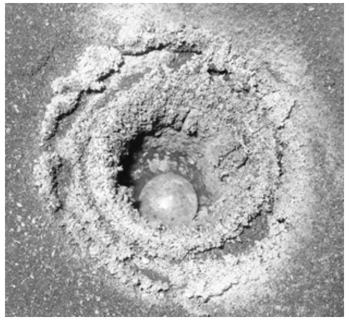
Mars Synergy

- Use of methane regeneration in the process allows for use of LOX/LCH_4 architecture
- Lower CH_4 liquefaction cost/mass compared to LH_2
- Carbothermal can convert the H_2 from water ice mining to CH_4 while providing the remaining oxygen
- Condenser and water electrolysis overlap with water ice mining

Durability

- No exposure of hardware to, or handling of, molten materials
- Mechanisms protected from regolith ingress
- Demonstrated regolith transport and valve performance beyond 10,000 cycles
- Optics protected from regolith & particulates

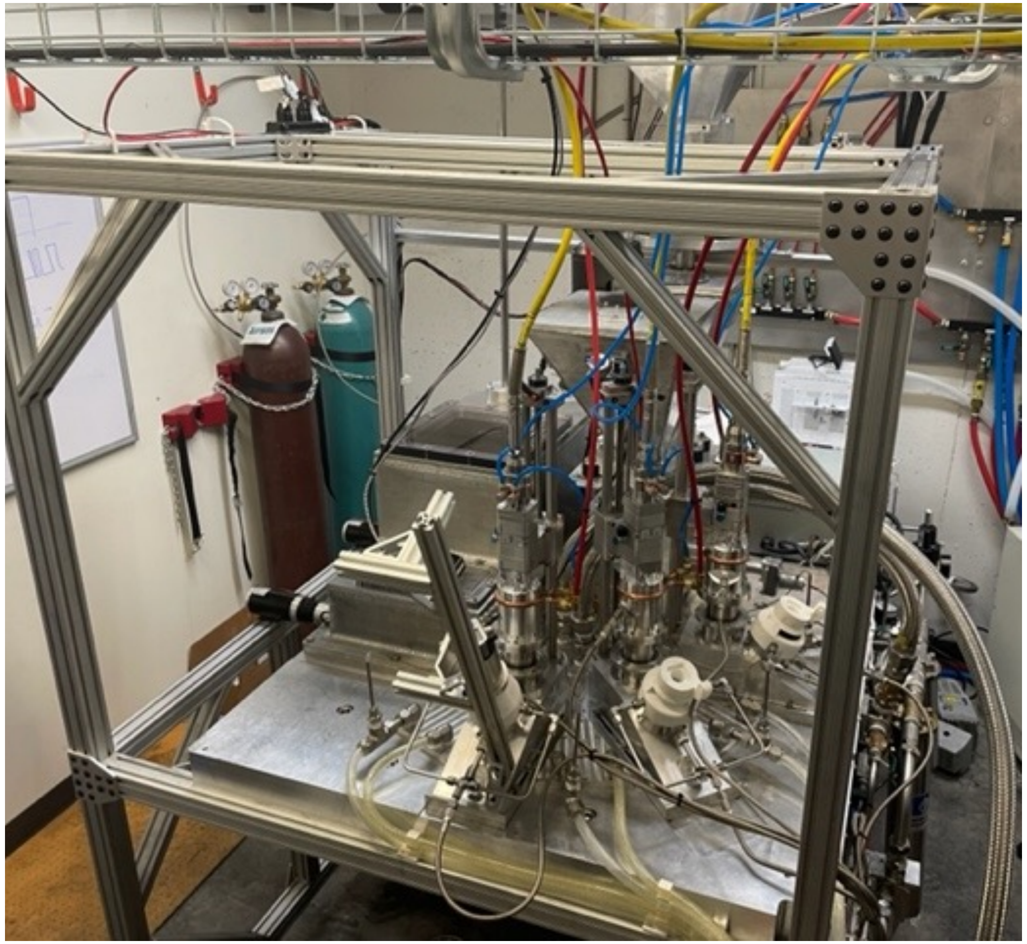




Simplicity

- Regolith is used as a buffer to protect hardware
- Allows conventional materials without degradation from thermal & corrosive environment
- Carbon loss/methane production can be replenished with direct carbon or ECLSS waste streams

Development of the Integrated Reactor System



Designed, built, and tested an automated integrated reactor using full-size melts and processes that are directly scalable to a full-scale production plant (3.5 mt O_2/year)

Successfully demonstrated brass-board carbothermal reactor in the NASA JSC thermal vacuum chamber, advancing the reactor to TRL 6

https://www.nasa.gov/feature/nasa-successfully-extracts-oxygen-from-lunar-soil-simulant

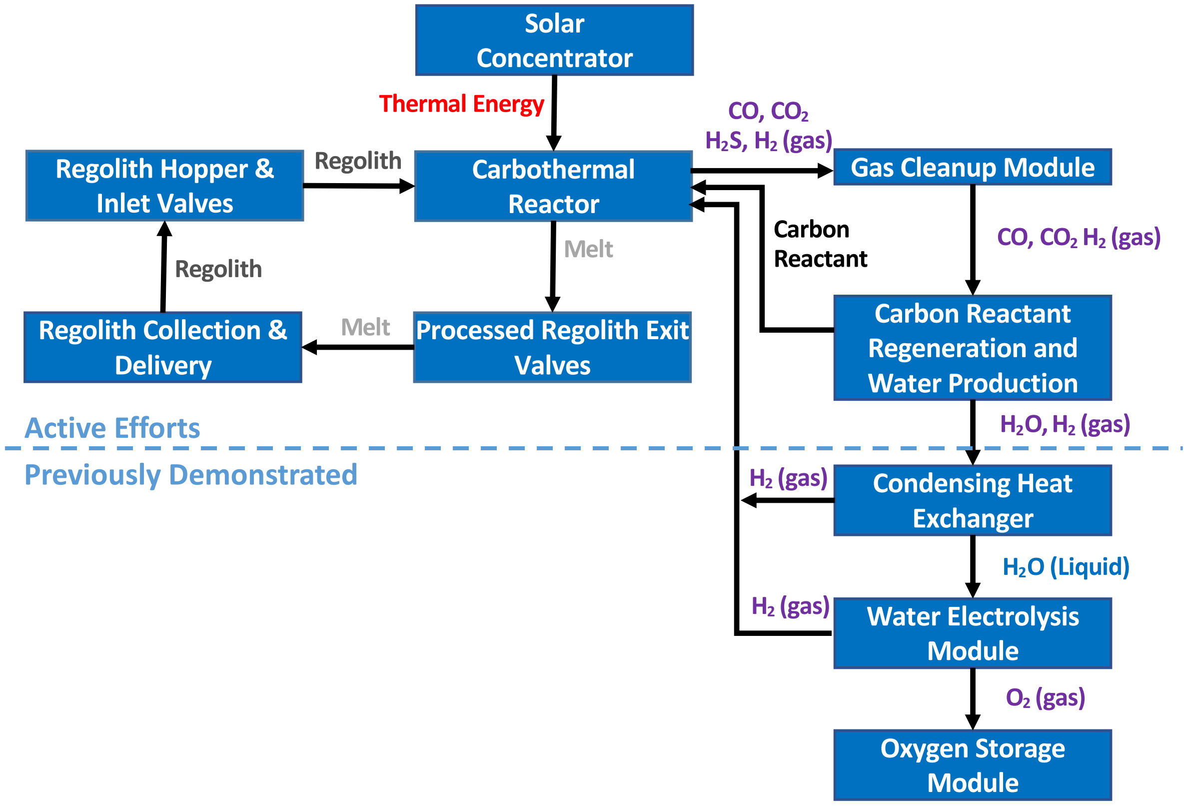
Image from NASA

Lessons learned from these efforts were integrated into the design of the COPR Tipping Point Flight-like demonstrator

Integrated Reactor Ground System

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 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



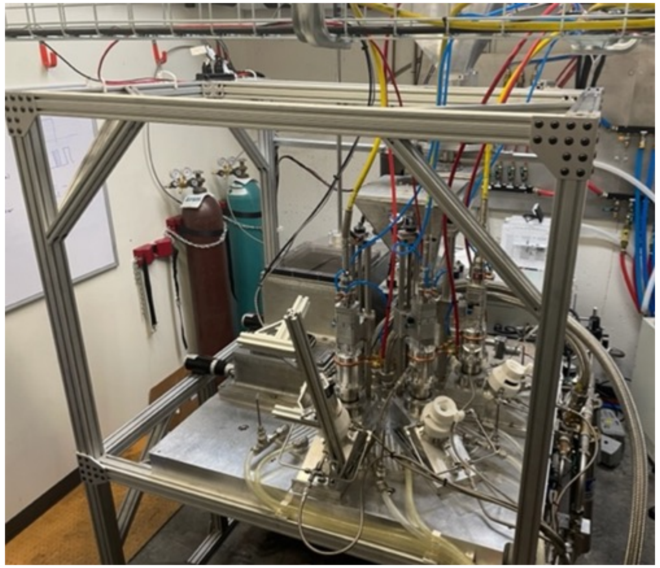
These operations are carried forward into the COPR Tipping Point flight-like technology demonstrator design

Carbothermal Oxygen Production Reactor (COPR) Tipping Point Program

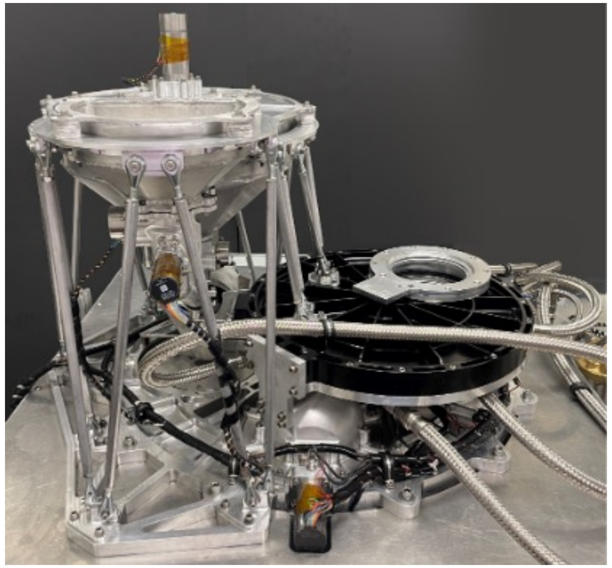
Carbothermal ISRU Technology Demonstrator

Demonstrate the technologies of a carbothermal oxygen production pilot plant in a payload that is sized for a CLPS lander

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



CTOP



COPR TP

A flight demo would address a strategic knowledge gap by understanding the reaction products and byproducts of using real lunar regolith

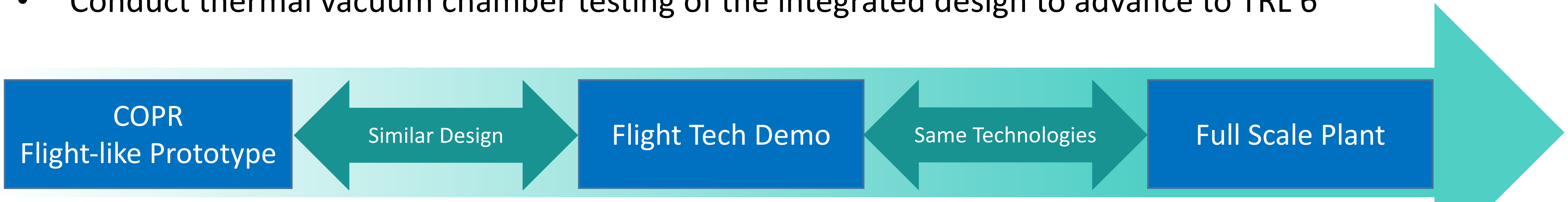
Development of Flight-Like System

Baseline Architecture Assumptions and Requirements

- Demonstrate and characterize processing at the scale relevant to a lunar pilot plant
- Demonstrate end-to-end regolith handling operations in the carbothermal system
- Design the hardware to be flight-like to smooth the transition to a flight program and reduce risk
- Requirements were decomposed from the NASA CaRD Level 1 and 2 system requirements

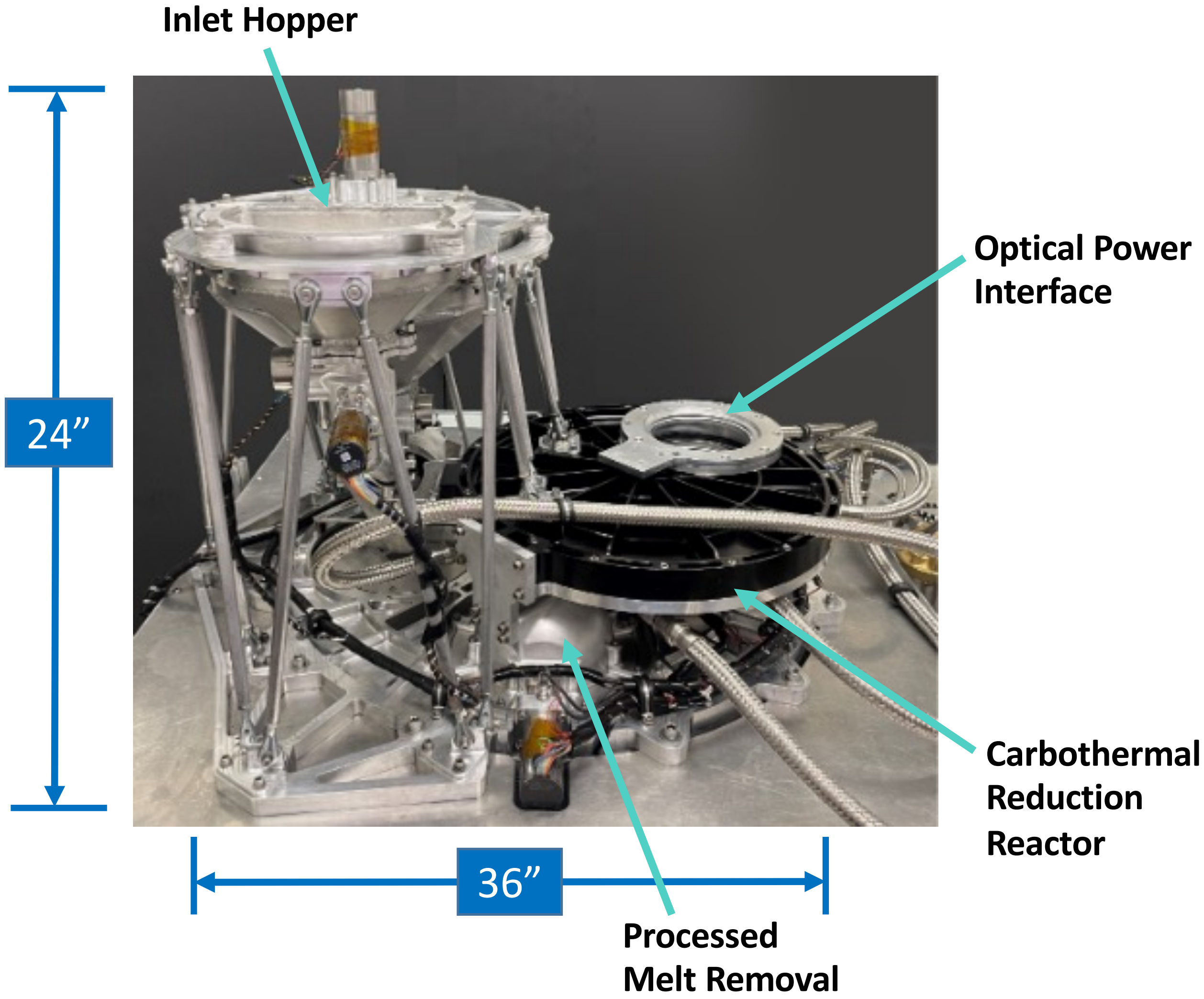
COPR Tipping Point Objectives

- Flight-like hardware designed and in built to:
  - Process a full-size melt using laser and concentrated solar to produce CO/CO_2
  - Demonstrate end-to-end regolith handling operations and regolith/processed melt removal
  - Obtain data necessary to demonstrate production rates and efficiencies for design scaling
  - Conduct thermal vacuum chamber testing of the integrated design to advance to TRL 6



Technology flow leveraging flight proven designs into scalable, larger systems supporting a full-scale plant

COPR Hardware Overview



COPR integrated with solar concentrator and other systems provided by multiple NASA Centers and industry through the NASA CaRD Project.
Image from NASA

Current Test Results & Lessons Learned

Ambient Testing Summary

Demonstrated All Required System Functionality

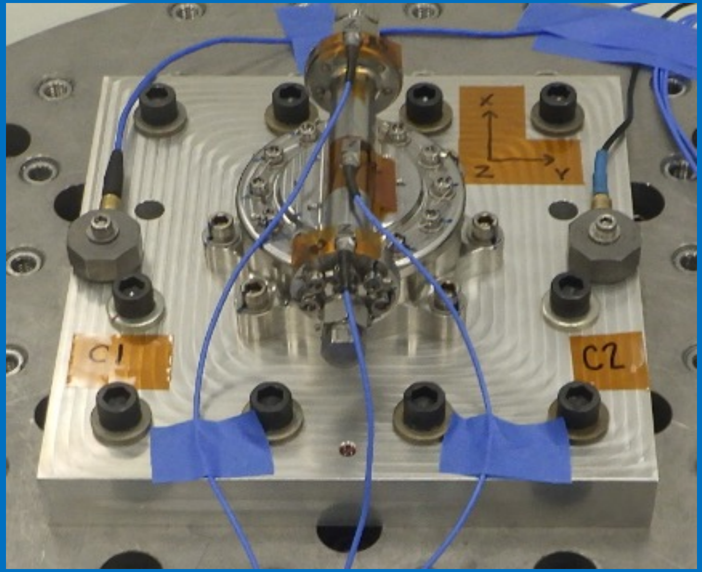
- Regolith and melt transfer through regolith tolerant valves
- Regolith handling operations inside the reactor pressure volume
- Carbothermal reduction using direct optical laser energy, including survivability of the optical inlet
- Processed melt extraction
- Carbothermal production measurements independently validated at Sierra Space and NASA JSC
- Conducted 46 tests, likely exceeding tech demo mission requirement

All Key Performance Parameters Exceeded

Performance Parameter	Units	State of the Art	Threshold Value	Project Goal	Demonstrated in Ambient Testing
Oxygen Production Efficiency	g O_2/kWh	3.0	2.5	3.5	**20.3**
Oxygen Production Yield	g O_2/g Regolith	0.1	0.08	0.12	**0.218**

- Demonstrated over 99% carbon recovery from the processed melt

Under a separate effort, a TVAC rated flight-forward gas processing system was developed and is now incorporated into the COPR system

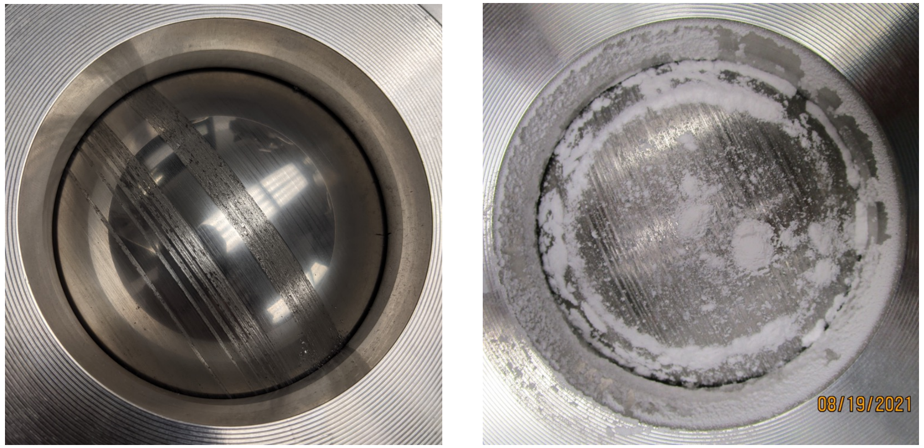


Sierra Space designed and built regulator for the gas processing system undergoing random vibe testing.

Regolith Tolerant Valve Technology

Current Commercial Technology Insufficient

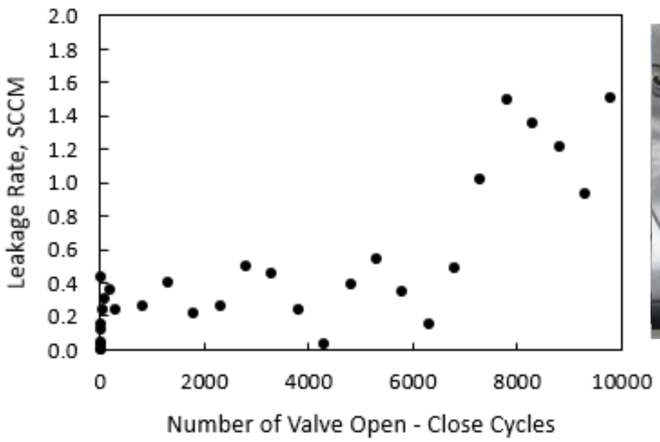
- Tested two vendor provided custom valves with hard coated sealing surfaces
- Both valves failed in under 300 cycles from galling of the hard coating

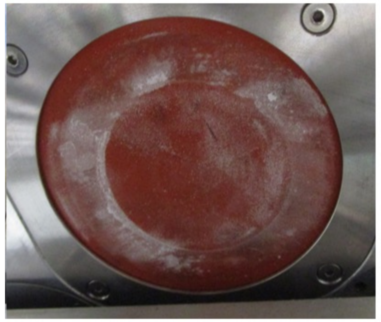


Protected (L) and directly exposed (R) valves tested with highlands simulant and experiencing galling failure at <300 cycles.

New Valve Technology Developed and Applied to COPR

- Developed alternate valve/mechanism design
  - Unique features used to minimize wear from material on exposed surfaces
- Tested new prototype valve to >10k cycles
  - Leakage maintained to below two sccm with ~1 atmosphere pressure differential
  - Potential for much higher cycle life
  - Design is adaptable for different geometries/sizes
- Provisional patent has been filed for this technology
  - Adaptable to large systems including airlocks



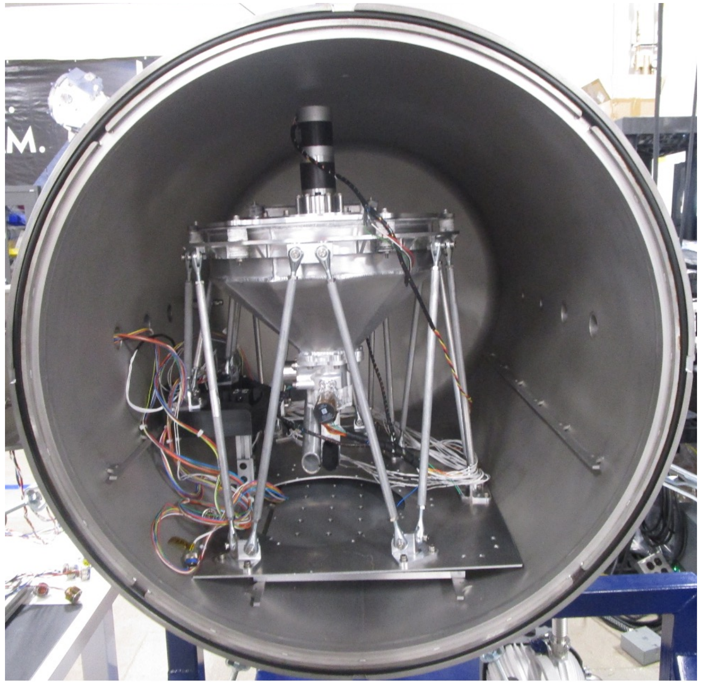


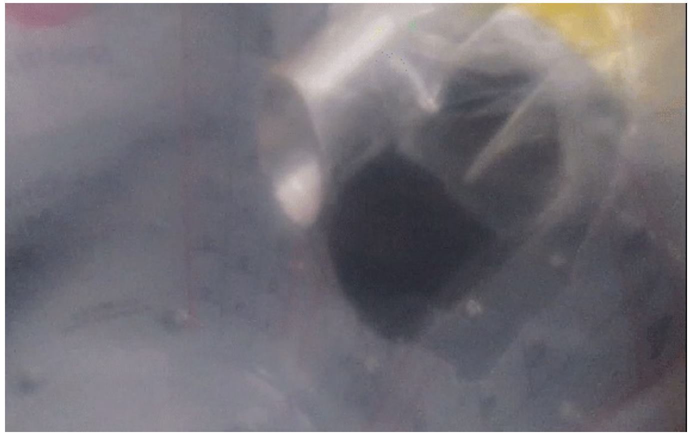
Thermal Vacuum Testing

TVAC Testing at NASA JSC Facilities Delayed due to Facility Maintenance

- Formal TVAC testing now scheduled for late June & early July
- Extended ambient test effort to demonstrate repeatability, durability, and to investigate some off-nominal operating points
- Used in-house facilities to demonstrate operations at -45 °C and at vacuum conditions


Operation of mechanisms at -45 °C (Regolith supply hopper removed)


Regolith supply system operated under vacuum conditions


Regolith Flow Functional Test at -45 °C

Lessons Learned

Trade studies informed by experimental data show that carbon loss is not the primary mass driver – radiator and solar concentrator masses are the primary mass driver due to the large amount of heat required for processing

- Utilization of the full available sunlit period maximizes mass leverage
- Demonstrated carbon recovery of >99%, exceeding target
- Waste carbon sources and propellant ullage are potential sources for carbon reactant resupply

Landing site topography will not adversely affect the carbothermal reduction process

Comparing technology efficiencies can be confusing and key performance parameters (KPP) for ISRU oxygen plants should be:

- $KPP = \frac{Mass\ of\ Usable\ Oxygen\ Produced\ per\ Lifetime}{Total\ System\ Lifetime\ Mass}$
- Many other mass drivers exist beyond thermal and electrical efficiency

Utilizing waste heat (~800-1400 °C) from processing to regenerate the carbon reactant and for outside processes can result in overall system mass reduction by reducing required radiator mass

SIERRA SPACE

Acknowledgements

The authors would like to thank the COTRs whose insights and guidance have been instrumental in the continued development of this technology:

Diane Linne – NASA GRC (retired)

Aaron Paz – NASA JSC

We would also like to recognize NASA STMD for their funding of the current and previous ISRU development efforts.