**A Fully Automated, Demonstration Scale Carbothermal Reactor.** B. C. White[1], N. P. Haggerty[1] and, A. J. Paz[2], [1]Sierra Space,1212 Fourier Drive, Madison WI 53717, [2]NASA Johnson Space Center, 2101 NASA Parkway, Houston TX 77058, (Contact: Brant.White@sierraspace.com)

**Introduction:** Obtaining oxygen in-situ enables space commercialization and exploration through dramatic reduction of the mass cost associated with lunar launch, landing, and propellant resupply. Carbothermal reduction is one method to extract oxygen from lunar regolith [1]. Sierra Space developed a flight forward Carbothermal Oxygen Production Reactor (COPR) and tested it in ambient conditions and at reduced thermal and pressure conditions through a NASA funded Tipping Point program. COPR will be tested in the relevant lunar thermal vacuum conditions in June 2024 through NASA's Carbothermal Reduction Demonstration (CaRD) project. The CaRD project will then integrate the COPR hardware with a solar concentrator, optical shutter, gas analysis system, avionics, and additional ground support equipment for an integrated system test in late 2024. The CaRD project goal is to increase the Technology Readiness Level (TRL) of a full carbothermal reduction system to TRL 6.

**Scalable Flight Forward Architecture:** COPR demonstrates a mass efficient, scalable architecture sized for a lunar demonstration. A prior Carbothermal Oxygen Production (CTOP) program demonstrated an architecture capable of mass production of oxygen from lunar regolith simulant [1]. The technologies that enabled mass production were miniaturized from the CTOP program and integrated into COPR (Fig. 1). This produces a design that demonstrates the technologies required for mass production in a small flight package.

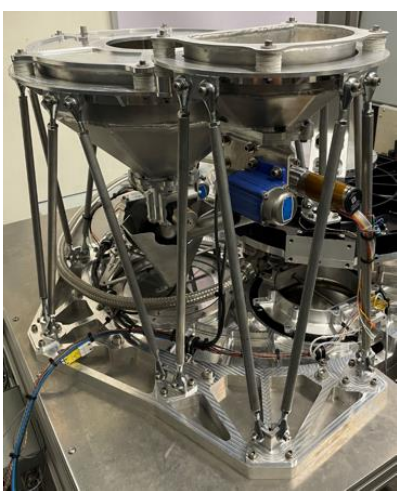

**Fig. 1 Completed Carbothermal Reactor.**

**Direct Energy Approach and Thermal Control:** The COPR design uses a direct energy processing approach where concentrated light is applied directly to the lunar regolith simulant surface. The insulating properties of the regolith itself are used to isolate the molten material from all hardware. This approach allows for a completely passive thermal control system where high temperature (>1650°C) carbothermal reduction is performed without requiring exotic materials, complex cooling systems, or consumables. Fig. 2 shows regolith actively undergoing carbothermal reduction using the direct energy approach. Optical interfaces were successfully protected from dust and other materials in repeated testing.

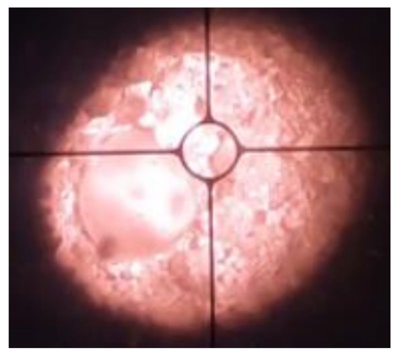

**Fig. 2 Carbothermal reduction using concentrated optical energy.**

The COPR design controls the carbothermal reduction reaction by simply applying or removing the incoming concentrated solar energy. This allows the reactor to quickly restart after a full lunar night or shorter periods of darkness without complex shutdown or dormancy procedures.

Scalability using the direct energy approach is accomplished by applying the direct energy over a larger area. This straightforward approach can employ both larger reaction sites and multiple reaction sites to facilitate solidified slag removal.

**Automated Material Handling:** The COPR hardware includes an automated solid material handling system. The system meters the lunar regolith simulant from a hopper into a pressurized volume, weighs it, distributes it within the reactor, separates and removes the processed slag from the regolith and the pressurized volume using a regolith tolerant valve design which has been demonstrated to 10,000 cycles with regolith simulant flow[1]. The design can also remove all regolith from the reactor to enable testing of alternate regolith sources on a lunar mission. Sierra Space has demonstrated repeated, automated material handling processes with the regolith simulant. Metering of the simulant was demonstrated with a standard deviation of 0.629 g over 30 trials.

**Ground Testing Results:** In January 2024 COPR was integrated with a commercial version of NASA's flight rated Mass Spectrometer Observing Lunar Operations (MSolo) instrument. The MSolo instrument measured the carbon monoxide produced by the carbothermal reduction reaction and was compared to the Sierra Space gas chromatograph (GC) data. This testing showed an average relative accuracy to the GC of 7.91% ± 4.13%. The COPR system produced 20.3 grams of oxygen per kWh of thermal energy input and 0.218 kg of oxygen per kg of lunar regolith simulant processed, exceeding program key performance parameter (KPP) goals at a scale directly applicable to a lunar oxygen production pilot plant.

In March 2024 Sierra Space demonstrated regolith handling operations in a vacuum chamber (Fig. 3) and an ambient pressure thermal chamber to the expected -45°C minimum lunar temperature for a technology demonstration mission. The COPR hardware demonstrated all required operations to perform the carbothermal process inside the ambient pressure thermal chamber (Fig. 4). Note that in 2023 the NASA CaRD project demonstrated the carbothermal reduction reaction step to TRL 6 through testing in relevant lunar thermal vacuum conditions using Sierra Space hardware.

**Fig. 3 Regolith handling system hardware installed for vacuum testing.**

**Fig. 4 Carbothermal reactor in a thermal chamber demonstrating operation at expected lunar temperatures.**

**Gas Processing:** Sierra Space completed a CDR for a flight forward gas processing system to support the carbothermal reactor in December 2023. This system includes the valves, flight forward regulator, sensors, and a Methanation reactor to convert the carbon monoxide produced by the carbothermal reactor into water. Key portions of the system underwent vibration testing in March 2024 (Fig 5).

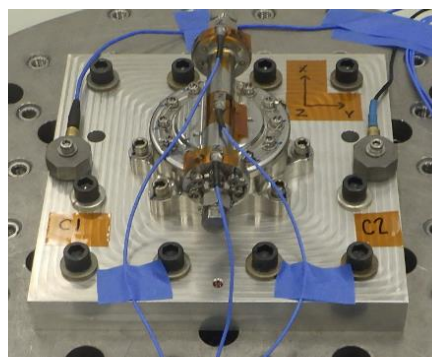


**Fig. 5 Sierra Space designed and built regulator undergoing random vibration testing.**

This system will help manage the carbothermal reaction inside the thermal vacuum chamber using the same architecture required for a lunar demonstration. The demonstration scale design utilizes common component types already widely used in spaceflight.

**References:**

[1] White B. C. and Haggerty N. P. (2023) Carbothermal Reduction System Overview and Developments in Support of the Artemis Program and a Commercial Lunar Economy. In *52nd International Conference on Environmental Systems*.