**INTEGRATED SOLAR TESTING AND TRL 6 THERMAL VACUUM TEST RESULTS FOR A FULLY AUTOMATED, DEMONSTRATION SCALE CARBOTHERMAL REACTOR.**

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**Introduction:** Obtaining oxygen in-situ enables space commercialization and exploration through dramatic reduction of the mass cost associated with lunar launch, landing, and propellant supply for missions beyond Earth orbit. Carbothermal reduction is one method to extract oxygen from lunar regolith [1]. Sierra Space developed a flight forward Carbothermal Oxygen Production Reactor (COPR) through a NASA funded Tipping Point program. COPR was successfully tested in the relevant lunar thermal and vacuum environment using NASA JSC facilities in July and August of 2024, elevating this reactor system to Technology Readiness Level (TRL) 6 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 upcoming integrated system test in summer 2025. The CaRD project goal is to increase the 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.

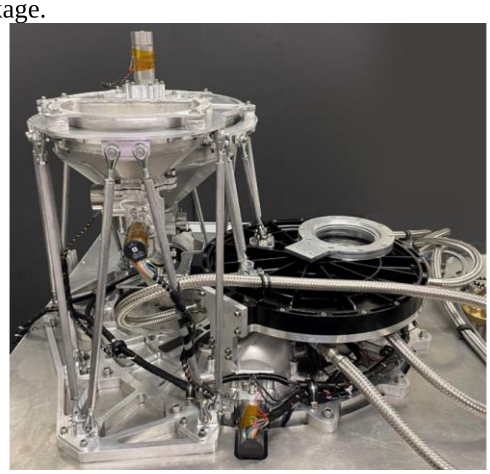

**Fig. 1 Completed Carbothermal Reactor**

**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.

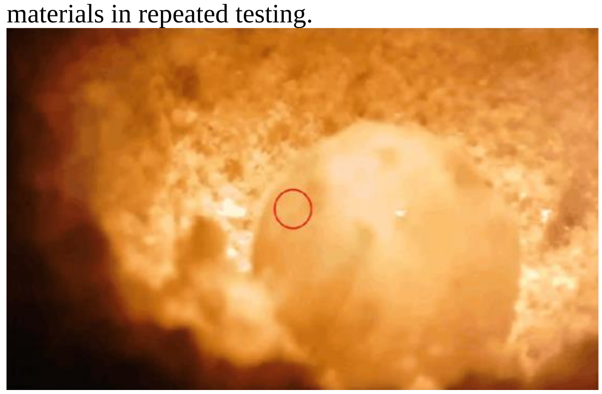

**Fig. 2 Carbothermal reduction using concentrated optical energy**

**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.

**Thermal Vacuum Testing Results:** In summer 2024, Sierra Space demonstrated repeated use of the automated material handling, gas handling, and carbothermal reduction processing systems inside NASA JSC's dirty thermal vacuum (TVAC) chamber while at the relevant lunar topographical, vacuum, and temperature conditions. This testing matured the carbothermal reduction and its regolith handling systems to TRL 6. The COPR test hardware in Figure 3 is shown inside NASA's TVAC chamber.

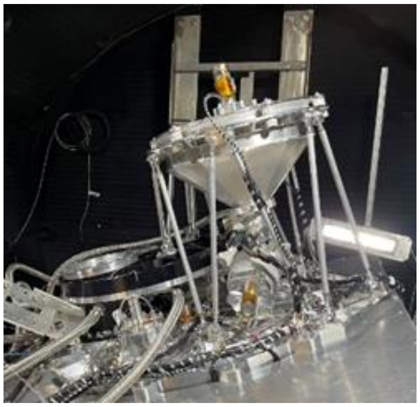

**Fig. 3 COPR Carbothermal Reactor in TVAC**

The COPR hardware utilized GreenSpar 250 lunar highlands simulant as a close chemical analogue to lunar highlands regolith, however the regolith handling systems and carbothermal reduction process have also been tested with NUW-LHT-5M highlands simulant as a closer analogue for the regolith's physical properties. The system was placed at a fifteen-degree angle relative to gravity to ensure than any anticipated landing site topography variation would not adversely affect system performance. Regolith flow metering, measurement, and bulk handling operations were validated under repeated use at lunar temperature and pressure. Sierra Space's regolith tolerant valve design was also demonstrated and validated in this environment to demonstrate the feasibility of transporting lunar regolith into a pressurized volume while at lunar conditions.

A total of four carbothermal reduction processing tests were completed in TVAC utilizing a laser to simulate concentrated solar energy. Oxygen extraction and performance measurements were taken by the NASA KSC Mass Spectrometer Observing Lunar Operations (MSolo) team using a commercial version of their flight instrument. The first three tests were conducted at the worst-case hot conditions as it was expected that these conditions would be the limiting case of the reactor's thermal control system. The final test was conducted at worst case cold conditions to ensure that all moving mechanisms and regolith handling hardware were tolerant to the coldest predicted hardware conditions. The thermal control system performance exceeded expectations. Figure 4 shows temperatures at several key locations on the carbothermal hardware.

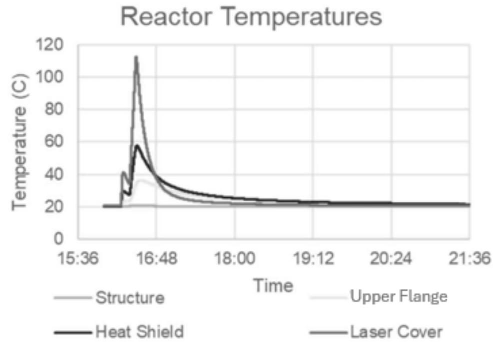


**Fig. 4 Reactor temperatures during processing**

Oxygen extraction energy efficiency and production yield from regolith exceeded the program goals. After a carbothermal reduction test was completed, the reduced, solidified regolith slag was removed by the regolith handling system. The unprocessed regolith remained in the system for subsequent reduction.

In addition to demonstrating the core carbothermal reduction process, Sierra Space successfully showcased the remote and autonomous operation of the system. This capability is essential for future lunar missions, where human intervention will be impractical. The ability to operate the system remotely and autonomously ensures that oxygen production can continue uninterrupted, even in the absence of human operators.

**Conclusion:** The successful COPR TVAC testing demonstrates the feasibility, maturity, and reliability of Sierra Space's carbothermal reduction process for oxygen production on the lunar surface. TRL 6 for the reactor and fluid system was achieved by successfully automating the material handling and reduction processes, and by validating the system's performance under simulated lunar conditions. We are continuing to work with NASA to integrate the COPR system with a NASA developed, deployable, flight like, crossed dragone solar concentrator and avionics systems. This fully integrated system will conduct performance testing with real sunlight at NASA JSC in the summer of 2025.

**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*.