# Environmental Testing of a Fully Automated Carbothermal Reactor for Lunar Oxygen Production

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**Oxygen comprises the majority of propellant mass required for ascent from the lunar surface and for in-space chemical propulsion. Using in-situ resource utilization (ISRU) technologies to produce oxygen on the moon enables a robust lunar economy through a dramatic reduction in lunar launch costs. In the Summer of 2024 Sierra Space completed thermal vacuum (TVAC) testing of a flight-like Carbothermal Oxygen Production Reactor (COPR) through a NASA Tipping Point program. The COPR reactor uses a mass efficient, scalable architecture optimized for a lunar technology demonstration mission. Concentrated solar energy is directly applied to the lunar regolith simulant. The insulating material properties of the regolith isolate the corrosive molten material from the reactor walls and other hardware. This approach allows for a completely passive thermal control system where high temperature (~1800°C) carbothermal processing is performed without requiring exotic materials or complex cooling systems. The reactor also includes an end-to-end automated solid material handling system capable of metering the lunar regolith simulant from a supply hopper into a pressurized volume, weighing it, distributing it into the carbothermal reactor, and removing the reduced metallic slag. Sierra Space demonstrated repeated use of the automated material handling, gas handling and carbothermal reduction processing systems inside NASA JSC's "dirty" TVAC chamber while at the relevant lunar topographical, vacuum, and temperature conditions. This testing matured key hardware to Technology Readiness Level (TRL) 6. 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. Oxygen extraction energy efficiency and production yield from regolith exceeded the program goals. The COPR system will be integrated with a flight forward solar concentrator, optical shutter, gas analysis system, avionics, and software as a part of the NASA CaRD program integrated testing in Summer 2025.**

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## Nomenclature

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| CaRD | = Carbothermal Reactor Demonstration |
| COPR | = Carbothermal Oxygen Production Reactor |
| CTOP | = Carbothermal Oxygen Production |
| ISRU | = In-Situ Resource Utilization |
| JSC | = Johnson Space Center |
| KSC | = Kennedy Space Center |
| MSOLO | = Mass Spectrometer Observing Lunar Operations |
| NASA | = National Aeronautics and Space Administration |
| ORBITEC | = Orbital Technologies Corporation |
| RGA | = Residual Gas Analyzer |
| SBIR | = Smal Business Innovation Research |
| SCCM | = Standard Cubic Centimeters per Minute |
| TRL | = Technology Readiness Level |
| TVAC | = Thermal Vacuum Chamber |

## I. Carbothermal Reduction Background

Space flight costs are driven primarily by the amount of mass of the overall spacecraft and rocket while the amount of oxygen (as a propellant) alone typically constitutes over 70% of the mass of the vehicle. Having the capability to produce oxygen on the Moon (the Lunar regolith contains approximately 45% oxygen by mass[1]) and to supply that oxygen for activities on the Moon, in Lunar orbits, exploration beyond the moon, and for missions returning to Earth, would provide enormous cost savings. Having a technology that produces oxygen from the Moon itself will therefore provide a significant cost savings and/or increase capabilities to the government and commercials entities operating on or around the Moon and in space.

The carbothermal reduction process is a well-established industrial method employed to produce high-purity silicon for the semiconductor industry through the reduction of silica. This process was initially demonstrated using lunar regolith in the 1960s by Aerojet[2]. In 1993, Orbital Technologies Corporation (ORBITEC), which was subsequently acquired by Sierra Space, commenced the development of the carbothermal process under the auspices of NASA's Small Business Innovation Research (SBIR) program[3]. The initial focus of the carbothermal reduction effort was on the bulk heating of regolith simulant while introducing the carbon reactant in the form of methane gas. However, bulk heating of the simulant in a furnace presented several technical challenges to sustainability. Thermal cycling led to mechanical failure of the ceramic crucible, and the methane gas reduction agent decomposed on hot surfaces away from the molten simulant, resulting in carbon loss[4].

To address these challenges, the operational concept was revised to utilize direct optical energy, simulated in the laboratory using a laser. This approach allowed the regolith simulant to function as its own processing container, thereby eliminating the issue of crucible failure. Furthermore, carbon deposition could be precisely controlled, as methane decomposition was restricted to the hot melt surface. These modifications provided the necessary technical advancements to continue the development of a sustainable carbothermal reaction and associated regolith handling processes at larger sub-scales[4].

The carbothermal reduction reaction is employed to extract oxygen ($O_2$) from regolith. This process is versatile and can be applied regardless of the metallic oxide source, making it suitable for use on the Moon, or other extraterrestrial bodies. The complete carbothermal reduction process is illustrated in Equations 1-4 below. The precise mineral composition does not need to be known prior to implementation. Therefore, in these equations, “M” Denotes a generic metal.

| | | |
|---|---|---|
| $\mathrm{MO}_x(\mathrm{l}) + x\mathrm{C(s)} \rightarrow \mathrm{M(l)} + x\mathrm{CO(g)}$ | Carbothermal Reduction | (1) |
| $x\mathrm{CO} + x\mathrm{H_2(g)} \rightarrow x\mathrm{C\ Reactant} + x\mathrm{H_2O(g)}$ | Carbon Recovery Process | (2) |
| $x\mathrm{H2O(l)} \rightarrow x\mathrm{H_2(g)} + 0.5x\mathrm{O_2(g)}$ | Water Electrolysis | (3) |
| $\mathrm{MO}_x(\mathrm{l}) \rightarrow \mathrm{M(l)} + 0.5x\mathrm{O_2(g)}$ | Net Reaction | (4) |

This scalable and sustainable system utilizes direct sunlight and recyclable materials to extract oxygen from minerals in the Lunar soil while minimizing the need for electrical power, system mass, and footprint on the Moon. Waste material contains reduced metals that can be used for construction. One implementation of this carbothermal process is shown in Figure 1. In this implementation, the carbon monoxide created by the carbothermal reaction is reacted with hydrogen in a Sabatier reactor to create methane as a carbon carrier and water. The water is condensed out of the gas stream and the methane is fed back into the carbon reactor for recycling. The water is split using water electrolysis to create oxygen and hydrogen. The hydrogen is recycled back into the Sabatier reactor and the oxygen is stored. This demonstrates a configuration that satisfies the mass balances for Equations 1-4 while recycling the hydrogen and carbon. Since existing Sabatier reactor and water electrolysis systems already exist at TRL 9, the contractual scope of Sierra Space's effort for carbothermal reduction development concluded with the extraction of oxygen from regolith in the form of the carbon monoxide and carbon dioxide, with our prior work having demonstrated this closed loop process[4].

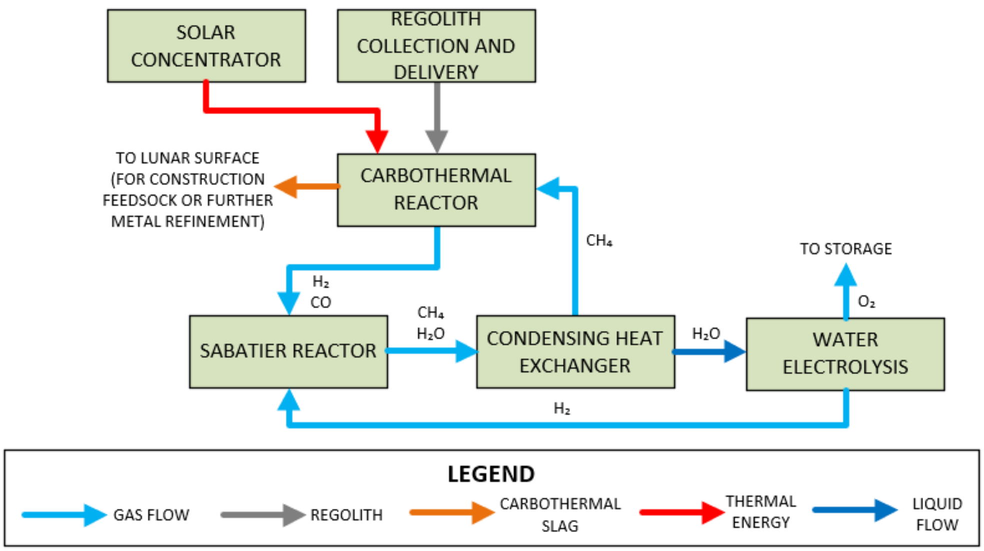


**Fig. 1. Carbothermal reduction process system schematic.**

## II. Reactor Overview

Sierra Space's Carbothermal Oxygen Production Reactor (COPR) uses a scalable architecture optimized for a lunar technology demonstration mission. Sierra Space's previous Carbothermal Oxygen Production (CTOP) program demonstrated a carbothermal architecture capable of mass production of oxygen from lunar regolith simulant. The technologies that enable mass production of oxygen were miniaturized from the CTOP program and integrated into the COPR design[5]. This results in a mass efficient design that demonstrates the technologies required for oxygen production that are applicable to a pilot plant or larger scales.

While the design details of the regolith handling system are proprietary, Figure 2 shows an overview of the high-level steps for a carbothermal reactor. Regolith is transported to the carbothermal reactor using an external system, likely a rover such as NASA's IPEX rover[6]. Regolith is stored in an external hopper above the carbothermal reactor until it is needed by the reactor. As the reactor transfers the regolith into the pressurized volume, weight measurements are conducted to ensure the correct amount of regolith is added. Next, a simple surface preparation step ensures that the regolith is ready for processing. The carbothermal reaction then extracts the oxygen from the lunar regolith. The carbothermal step creates a hard slag that contains reduced metals. Because the applied concentrated energy only melts a small portion of the regolith inside of the reactor, the slag is suspended in the un-melted regolith. This allows for a size sorting scoop to simply remove only the large pieces of deoxygenated slag from the reactor. The unprocessed regolith remains in the reactor to act as insulating material for the next processing batch. The slag exits the pressurized volume so it can be transported

away from the reactor using the same system that brought the regolith in the first step (for example NASA's IPEX rover[6]).

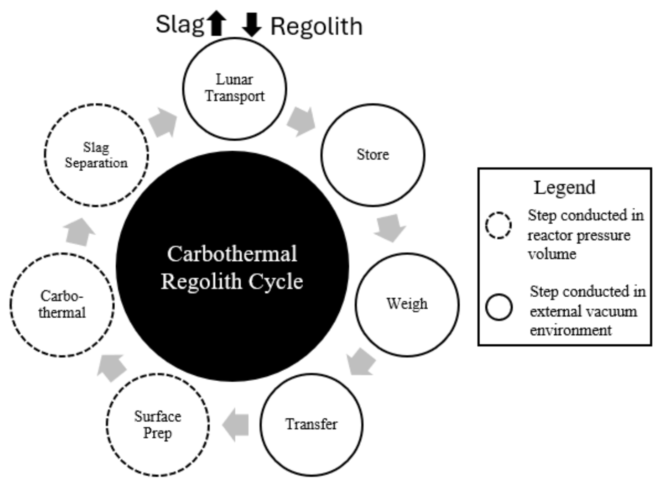


**Fig. 2. Carbothermal reduction regolith processing cycle.**

The COPR reactor includes an end-to-end automated solid material handling system capable of metering the lunar regolith simulant from a supply hopper into a pressurized volume, weighing it, distributing it into the carbothermal reactor, and removing the reduced metallic slag. The carbothermal reactor shown in Figure 3 includes all of the steps discussed in Figure 2 except for a rover transporting material to the reactor and a rover removing the solidified slag.

In the large-scale implementation, concentrated solar energy is directly applied to the lunar regolith simulant but the initial testing of the COPR unit used a high-powered continuous wave laser to provide the thermal energy required for the carbothermal reaction. This reactor is planned to be integrated with a direct solar concentrator at NASA JSC in Summer 2025[7]. The insulating material properties of the regolith isolate the corrosive molten material from the reactor walls and other hardware. This approach allows for a completely passive thermal control system where high temperature (~1800°C) carbothermal processing is performed without requiring exotic materials or complex cooling systems. Initial performance testing of this reactor showed that over 20 grams of oxygen was extracted from the regolith for every kilowatt hour of thermal energy input into the reactor.

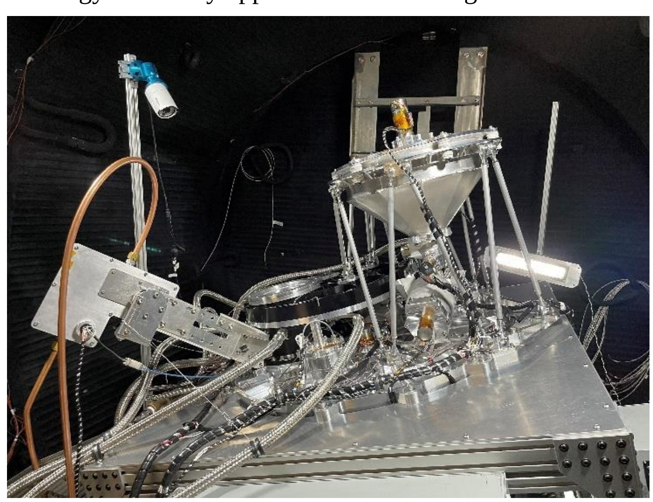

**Fig. 3. Close up of the COPR carbothermal reactor.**

## III. Thermal Vacuum Testing

In Summer 2024 Sierra Space successfully demonstrated repeated use of the automated material handling, gas handling, and carbothermal reduction processing systems inside NASA JSC's "dirty" TVAC chamber while at the relevant lunar topographical, vacuum, and temperature conditions. This testing is shown in Figure 4 and matured key system hardware to TRL 6. To ensure the accuracy and reliability of the results, the Kennedy Space Center (KSC) MSOLO team independently measured the system's performance using a COTS version of their flight rated Residual Gas Analyzer (RGA). In addition to integration with the COPR unit during TVAC, tests were conducted prior to integration[8]. Their TVAC measurements corroborated the extracted oxygen production rate data, providing third-party validation of the process. A pyrometer inside the vacuum chamber measured the temperature of regolith simulant during processing, while also providing video of the process. An image of lunar regolith simulant actively undergoing carbothermal reduction is shown in Figure 5. Figure 5 was captured using the camera built into the pyrometer and therefore shows some additional thermal data along the top of the image. The temperature inside of the red circle was measured to be 1782.9 ° C, assuming an emissivity of 0.8.

The initial goal for the program was to extract 3.5 grams of oxygen for every kilowatt-hour of thermal input into the system. Oxygen extraction energy efficiency and production yield from regolith exceeded the program goals. There was no evidence that the thermal vacuum conditions affected the amount of oxygen extracted per unit of thermal energy input into the system. This is because the reaction is occurring inside of a pressurized volume and the thermal control system was able to hold the reaction site at nearly the same temperature that was observed outside of TVAC. Structure and heat shield temperatures for the testing in TVAC are shown in Figure 6. The thermal control system's performance exceeded expectations. Initial calculations showed that the heat shield temperature could exceed 350 °C during operation while the measured temperatures remained less than 60 °C.

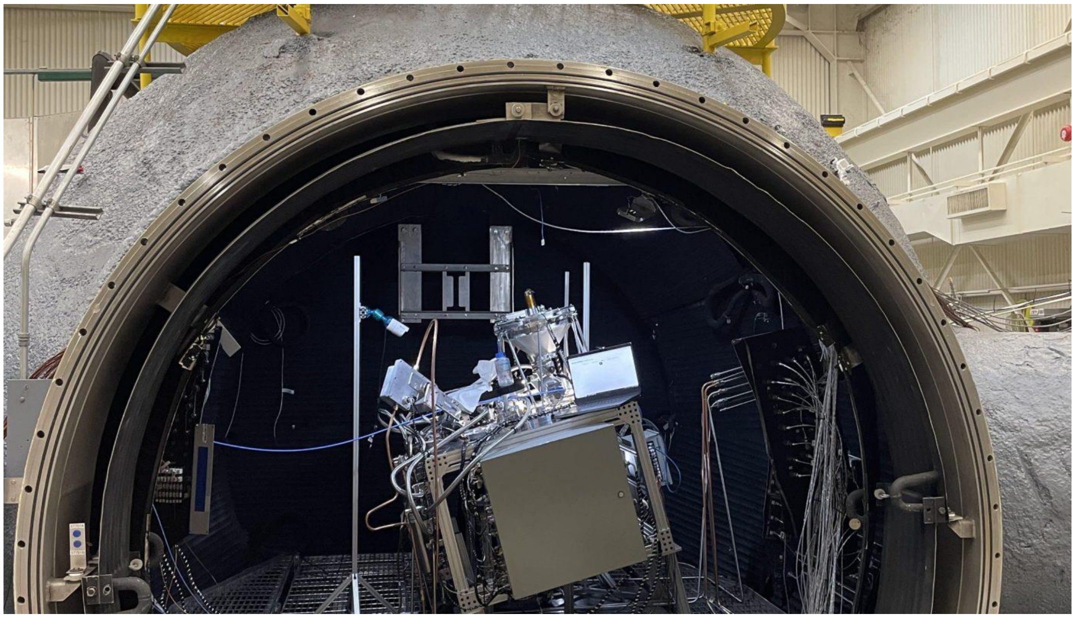

**Fig. 4. COPR Carbothermal Reactor inside NASA JSC's B351 Dirty Thermal Vacuum Chamber.**

A total of 4 carbothermal tests were completed in TVAC. 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. This was assumed to be the worst case because of the hot temperatures inside the carbothermal reactor required for carbothermal processing. The hot cases were conducted at +20°C because thermal finite element modeling of a representative lander at a lunar polar location predicted that this would be the hottest hardware temperatures. This was conveniently close to the ambient laboratory environment, so no additional heaters were installed on the inside of the TVAC chamber. Instead, the cryogenic nitrogen system of the TVAC chamber was turned off and walls of the TVAC chamber were allowed to equalize with the laboratory environment. This TVAC phase was critical for validating the system's performance in an environment closely mimicking the harsh conditions of the lunar surface.

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.

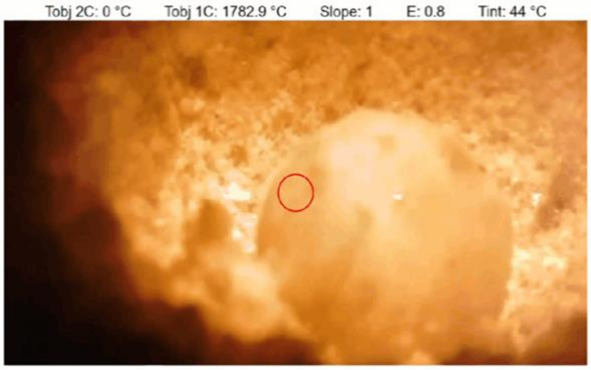


**Fig. 5. Lunar regolith simulant actively undergoing carbothermal reduction. The circled area is the pyrometer temperature measurement location that reads 1782.9 °C assuming an emissivity of 0.8.**

## IV. Regolith Handling Operations

Lunar regolith handling operations present significant technical challenges that must be addressed for any system operating on the Moon. The abrasive nature, dust concerns, and resistance to flow of the regolith are well-documented properties[1,9]. Sierra Space has focused its regolith handling operations on: receiving regolith with the appropriate size fraction, transferring the regolith into the pressurized volume, preparing the regolith for the carbothermal reaction, and removing the processed slag from the pressurized volume. Once the processed slag exits the carbothermal system, third-party systems will either dispose of them, use the solidified material as a building material, or supply the reduced material as a feedstock for other processes.

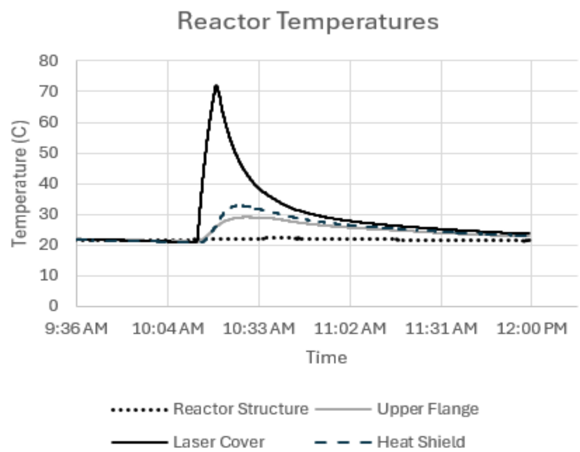


**Fig. 6. Reactor temperatures during TVAC processing.**

Prior to conducting the thermal vacuum testing, throughout the first half of 2024, Sierra Space successfully demonstrated repeated, automated material handling and carbothermal reduction processing of GreenSpar 250 and NUW-LHT-5M regolith simulants under ambient conditions. GreenSpar 250 was used for TVAC testing given the quantity available. GreenSpar 250 and NUW-LHT-5M are both lunar highlands simulants with high anorthosite content. GreenSpar 250 has a Ca/Ca+Na ratio of 83[10]. This is slightly lower than both NUW-LHT-5M and what is expected on the lunar surface. The Ca/Ca+Na ratio of is of particular importance for high temperature lunar processes because it affects the melting point and molten viscosity. This can impact processes like bubble evolution out of the molten regolith. The particle size of Greenspar 250 is primarily less than 250 μm and has a quartz content that is higher than the lunar surface. While quartz is not abundant on the lunar surface, this quartz content was useful for the COPR testing because it provided some additional abrasive properties for testing the material handling mechanisms. NUW-LHT-5M is arguably a more realistic lunar highlands simulant because it has more realistic glass content, higher Ca/Ca+Na ratio of 89[11], and more realistic particle size distribution.

This initial regolith handling testing phase was instrumental in establishing the foundational processes and mechanisms required for efficient regolith handling and oxygen extraction. The carbothermal reduction process involves heating lunar regolith to high temperatures resulting in the production of oxygen as carbon monoxide and carbon dioxide, and a slag byproduct that contains the reduced metals. The ability to automate this process is crucial for future lunar missions, where human intervention will be limited. Sierra Space's demonstrations in early 2024 focused on refining the automated handling of regolith simulants and ensuring that the system could consistently process material without manual oversight.

In the summer of 2024, Sierra Space progressed to demonstrating full regolith handling cycles within a thermal vacuum chamber at as low as -45°C with a vacuum pressure of <1e-4 torr. The successful operation of the system under these conditions provided confidence in its robustness and reliability for future lunar missions.

During the thermal vacuum testing, there was an unexpected event when the initial weighing was performed during the first test. The load cells were experiencing noise far above and beyond what was observed in prior testing. Initially, electrical noise was suspected because the system was operating in a new electrical environment. However, upon further investigation, it was found that the large pumps used to keep the vacuum chamber at vacuum conditions were slightly physically oscillating the entire thermal vacuum chamber. Within Figure 8, at about 6:00 pm there is a sharp decrease in the noise of the signal. This correlated with the chamber pumps being turned off. For the remainder of the test, the chamber pumps were turned off each time that the system needed to weigh the reactants as it is expected that the lander will provide a stable platform. The short load cell spikes that occur from 6:00 pm to the end of the test are simply caused by the reactor's vibration motors turning on. This method of using a loadcell to control the flow of regolith allows for accurate dosing of material. Figure 9 shows the software setpoint (dotted line) compared to the measured values.

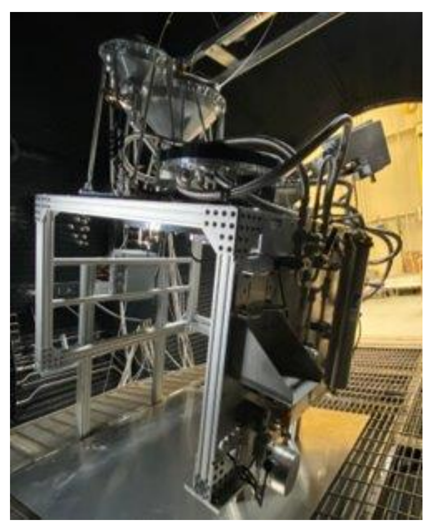

**Fig. 7. Back Side of the Carbothermal Reactor inside NASA JSC's B351 Dirty Thermal Vacuum Chamber.**

Following the weighing process, the geometry of the regolith surface in the processing zone is controlled to ensure the desired distribution of concentrated energy. (Lasers were used in this initial test but solar concentrators are anticipated to be integrated with this reactor in summer 2025[7]) This preparation step is critical for achieving proper reaction formation during the carbothermal reaction. By controlling the surface geometry, Sierra Space ensures that the energy is evenly distributed, leading to efficient melting and reaction of the regolith.

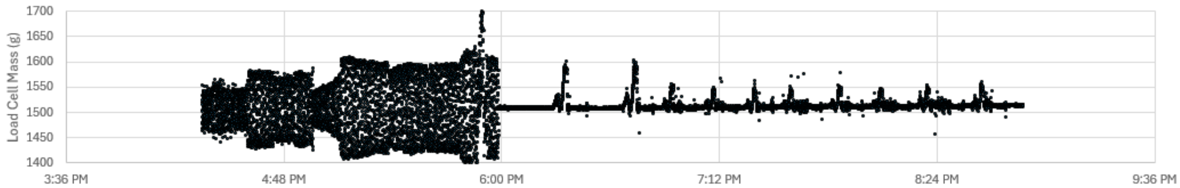


**Fig. 8. Load cell total mass measurements while operating in TVAC with and without the TVAC vacuum pumps operating.**

After the carbothermal reaction is complete, the system separates the slag from the unreacted powdered regolith using a rake mechanism. This separation process is essential for recycling the unreacted regolith for further processing and limits the burden on the external regolith delivery systems that supply material to the reactor.

This same rake mechanism is able to clear the reaction chamber completely of regolith. Several passes of the rake mechanism are required to remove all of the material in the reaction chamber. Figure 10 shows the mass of regolith inside the reaction chamber as a function of the number of passes of the rake. Note that removal of the regolith from the reaction chamber is only done in off nominal conditions. Nominal operations remove the slag without removing the unreacted regolith.

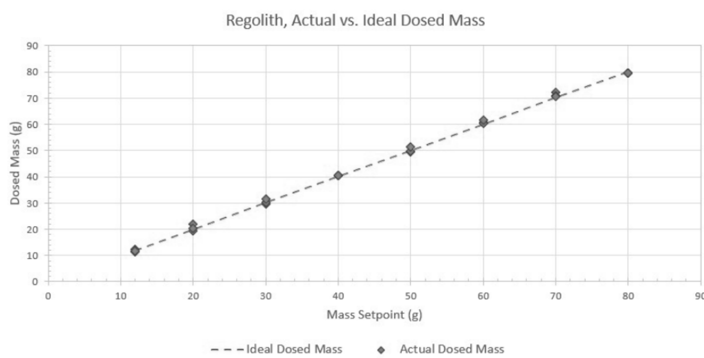


**Fig. 9. Load cell mass compared to the software setpoint.**

A key aspect of the testing involved the successful transfer of regolith into the pressurized chamber of the reactor. This was achieved using an innovative regolith tolerant valve sealing technology. This technology has been rigorously tested, demonstrating over 10,000 regolith flow and valve actuation cycles with a leakage rate of less than 2 standard cubic centimeters per minute (SCCM) at a pressure differential of 1 atmosphere[5]. This low leakage rate is critical for maintaining the integrity and efficiency of the pressurized system during operation. The valve sealing technology is designed to prevent the fine, abrasive particles of lunar regolith from compromising the seals, ensuring long-term reliability and performance.

While all material handling operations were conducted in the thermal vacuum chamber, the reactor transported the regolith inside of a pressure volume for some of the steps so that the gases produced by the reaction could be contained. See Figure 2 for an overview of the regolith handling cycle and which of these steps were conducted internally to the pressure volume and which steps were conducted under hard vacuum conditions. It is expected that flight carbothermal reactors will conduct some of the operations inside of a pressurized volume and some will occur in the raw lunar environment.

The carbothermal regolith transport system relies on gravity and vibration to transfer material through the system. Given that lunar landers are not guaranteed to land on flat ground, Sierra Space tested the carbothermal reactor at a 15-degree angle inside the thermal vacuum chamber. This testing scenario was designed to simulate landing on uneven terrain, providing confidence that the system is robust and adaptable to various landing site conditions. The ability to operate effectively on uneven terrain is crucial for ensuring the reliability of the oxygen production process, regardless of the specific landing

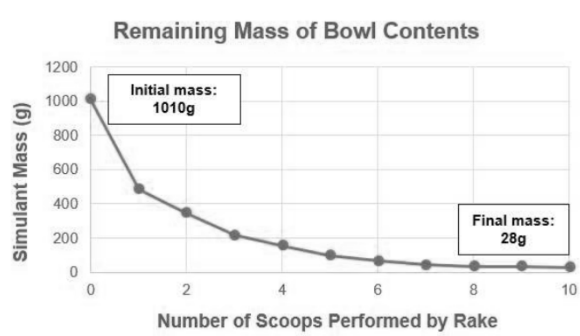


**Fig. 10. Simulant mass inside the reaction chamber during the removal process.**

site characteristics. While the moon does have slopes in excess of 15 degrees, landing locations are expected to target flatter regions where rovers can traverse the landscape to deliver lunar regolith to the reactor.

## V. Conclusions

This test demonstrates the feasibility and reliability of Sierra Space's carbothermal reduction process for extracting oxygen from regolith on the lunar surface. By successfully automating the material handling and reduction processes, and by validating the system's performance under simulated lunar conditions, Sierra Space has paved the way for sustainable lunar exploration and habitation. The ability to produce oxygen on the lunar surface is a critical step towards establishing a permanent human presence on the Moon, reducing the need for costly resupply missions from Earth, and enabling longer and more ambitious lunar missions.

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 may be limited or impractical. The ability to operate the system remotely and autonomously ensures that oxygen production can continue uninterrupted, even in the absence of human operators.

The passive thermal control system exceeded expectations while operating inside the thermal vacuum chamber. Initial calculations showed that the heat shield temperature could exceed 350 °C during operation while the measured temperatures remained less than 40 °C. While full scale reactors are expected to need larger thermal control systems, this shows that a fully passive thermal control system is a viable option for initial lunar demonstration missions. Finally, lessons learned from the thermal vacuum chamber inducing error into the load cell measurements, or limitations on materials selection based on test facility requirements, further reinforce the criticality of careful system level planning and consideration when conducting integrated tests.

## VI. Future Development

The COPR reactor will be pared with a NASA-developed, flight-like solar concentrator and avionics system. This integration is scheduled for Summer of 2025[7] and aims to demonstrate our process using direct solar heating. This approach was previously demonstrated in 2010 during the International Lunar Surface Operations field test on Mauna Kea[4], and we are excited to build on that experience. The use of direct solar heating in the carbothermal reduction process offers several advantages. Solar energy is abundant on the lunar surface, making it a sustainable and cost-effective energy source for oxygen production. By leveraging direct solar heating, we aim to enhance the efficiency and sustainability of the oxygen production process, making it more viable for long-term lunar exploration and habitation.

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