Prototype Demonstration of Solar-Carbothermal System to Extract Oxygen from Regolith

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The Carbothermal Reduction Demonstration (CaRD) project was an effort to develop a prototype system to demonstrate the extraction of oxygen from simulated lunar regolith using concentrated solar energy and a carbothermal reaction. The prototype consisted of a deployable solar concentrator capable of tracking the sun, optical splash plate and shutter, carbothermal reactor, fluid system, gas analysis, and a control system consisting of avionics and software. These subsystems were developed by multiple NASA centers and a private industry partner, Sierra Space. The various teams worked together to define requirements and interfaces to successfully assemble the complex system and demonstrate an integrated solar-carbothermal process.

I. Nomenclature

CaRD	=	Carbothermal Reduction Demonstration
COPR	=	Carbothermal Oxygen Production Reactor
ESTA	=	Energy Systems Test Area
ISRU	=	In-Situ Resource Utilization
MSolo	=	Mass Spectrometer observing lunar operations
O2FR	=	Oxygen from Regolith

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II. Introduction

NASA's Artemis program aims to establish a permanent human presence on the Moon. This is a significantly different endeavor than the Apollo program, which had the focused goal defined by President John F Kennedy of "Landing a man on the Moon and returning him safely to the Earth." The Apollo program is one of the greatest technological achievements in human history. However, the cost of the Apollo program resulted in only six human landings before the program was cancelled. If we are to establish a permanent human presence on the Moon, we will have to do everything we can to reduce the cost of lunar missions. The cost of any mission is driven by mass. Therefore, one very significant way to reduce the cost of lunar missions is to reduce the amount of mass that must be delivered to the lunar surface. Both vehicles currently being developed as human lunar landers will use liquid oxygen as a propellant. Fortunately, lunar regolith is made of approximately 45% oxygen, and it can be extracted using the technology described in this paper. An appropriately scaled system that uses this technology should theoretically be able to produce several times its own mass in liquid oxygen, which would drastically reduce the amount of mass that needs to be delivered to the lunar surface for each mission. This would not only reduce the cost of lunar missions, but could also be the key to opening a space economy beyond low earth orbit.

There are at least 20 different methods to extract oxygen from lunar regolith. such as hydrogen reduction, carbothermal reduction, molten regolith electrolysis, molten salt electrolysis, and vacuum pyrolysis [1]. The use of concentrated solar energy could theoretically be paired to a number of oxygen from regolith (O2FR) technologies. However, one of the most difficult aspects of any O2FR process is demonstrating the ability to autonomously move regolith through a reactor over multiple cycles. Of the many O2FR methods investigated to date, carbothermal reduction is the only process that does not rely on high iron oxide concentrations, and has demonstrated the difficult task of automated regolith ingress and egress in a laboratory environment [2], field demonstration [3], and simulated lunar environment [4]. The solar-carbothermal process was first demonstrated in 2010. The first design iteration used a solar concentrator and optical waveguide system developed by Physical Sciences Inc, and an automated carbothermal reactor developed by ORBITEC (now Sierra Space). The system was integrated and tested in Mauna Kea, HI and was part of a larger "dust to thrust" demonstration that included the excavation of regolith, methanation reactor, water condenser, water electrolysis, oxygen liquefaction, and thruster firing. The first-generation solar-carbothermal system is shown in Figure 1[5].

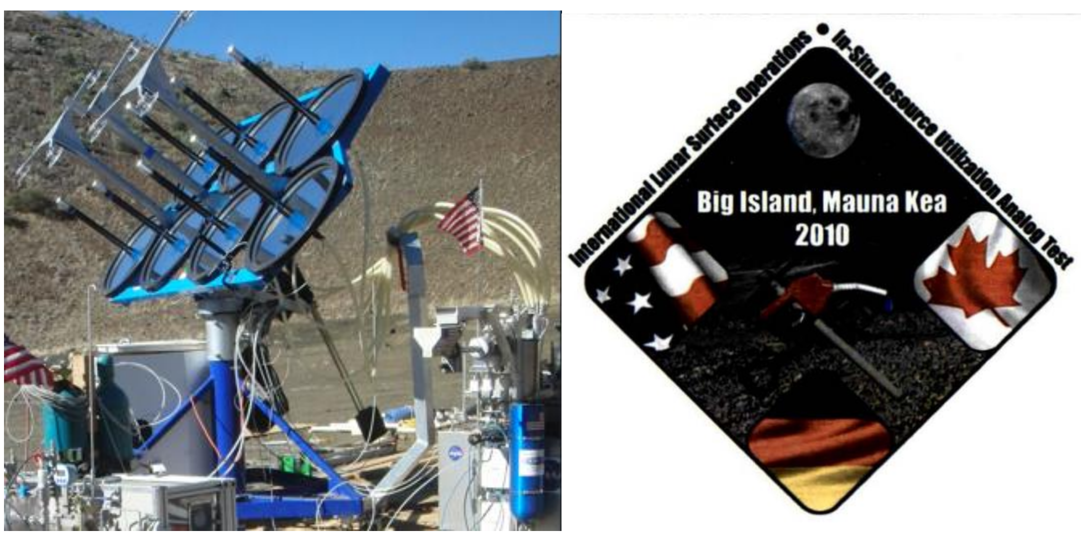

Figure 1: First-Generation Solar-carbothermal System

The first-generation system performed well and established the baseline key performance parameters for a solar-carbothermal system. However, it was not designed to withstand a launch or thermal-vacuum environment because the system was the first of its kind. The goal of the Carbothermal Reduction Demonstration (CaRD) project was to build on the progress of the first-generation system, and develop a new solar-carbothermal system that could survive a launch environment and operate in a lunar environment. The scale of the CaRD system was intentionally determined so that it could be deployed on a mid-class Commercial Lunar Payload Services (CLPS) lander while providing data and demonstrating key technologies that would be relevant to a larger pilot plant system that can produce 1 metric ton of oxygen per year and full-scale system that can produce 10 metric tons of oxygen per year.

Carbothermal reduction has been used terrestrially for decades to produce steel from iron ore, and silicon from quartz because it is the most cost-effective way to produce large quantities of those commodities. Terrestrial carbothermal reactors typically use electric arc furnaces to melt materials. In the solar-carbothermal process, concentrated solar energy is delivered directly to a pressurized reactor. The thermal energy delivered to the reactor is used to melt lunar regolith simulant contained within the reactor. The molten regolith reacts with a source of carbon to remove oxygen from silicate minerals and other metallic oxides in the form of mostly carbon monoxide and some carbon dioxide. In a complete system, carbon monoxide is reacted with hydrogen in a methanation reactor to produce methane and water. Methane is recycled as a carbon source back into the reactor and water is split into hydrogen and oxygen using water electrolysis. Hydrogen is recycled back into the methanation reactor and oxygen gas is liquefied as the final product. The overall chemistry is described in equations 1-4 below, where “M” represents metal. [6]

$MOx(l) + x\,C(s) \rightarrow M(l) + x\,CO(g)$	Carbothermal Reduction	(1)
$x\,CO + x\,H2(g) \rightarrow x\,C\ Reactant + x\,H2O(g)$	Carbon Recovery Process	(2)
$x\,H2O(l) \rightarrow x\,H2(g) + 0.5x\,O2(g)$	Water Electrolysis	(3)
$MOx(l) \rightarrow M(l) + 0.5x\,O2(g)$	Net Reaction	(4)

The CaRD project focused on the chemical reaction described in equation 1, and did not implement the downstream systems. The methanation reactor, water electrolysis, and oxygen liquefactions systems have a relatively low advancement degree of difficulty and can be designed to meet a specific liquid oxygen production rate for a pilot plant or full-scale system. The unknown for a pilot-plant or full-scale system is the size of the solar concentrator and reactor required to produce CO at rate that matches a target oxygen production rate. A flight demonstration with actual regolith is necessary to determine the size of a larger scale solar concentrator and reactor. It should be noted that a Sabatier reactor, designed to convert CO_2 and H_2 into CH_4 and H_2O could be used as a methanation reactor for equation 2 and a Sabatier reactor was demonstrated on the International Space Station (ISS). Water electrolysis is also used to convert water into breathing oxygen for the crew of the ISS. Further, the combination of a Sabatier reactor and water electrolysis can be used on Mars to convert water and CO_2 into oxygen and methane gas which can then be liquefied to produce propellants on Mars. Therefore, implementing the Sabatier/methanation and water electrolysis processes on the Moon for the sake of producing oxygen from regolith would prove much of the technology that is needed for Mars In-Situ Resource Utilization (ISRU), and would provide dissimilar redundancy to the Environmental Control and Life Support System (ECLSS) needed for a lunar base. A block diagram of the carbothermal reduction process and commonality with Mars ISRU and ECLSS is shown in Figure 2.

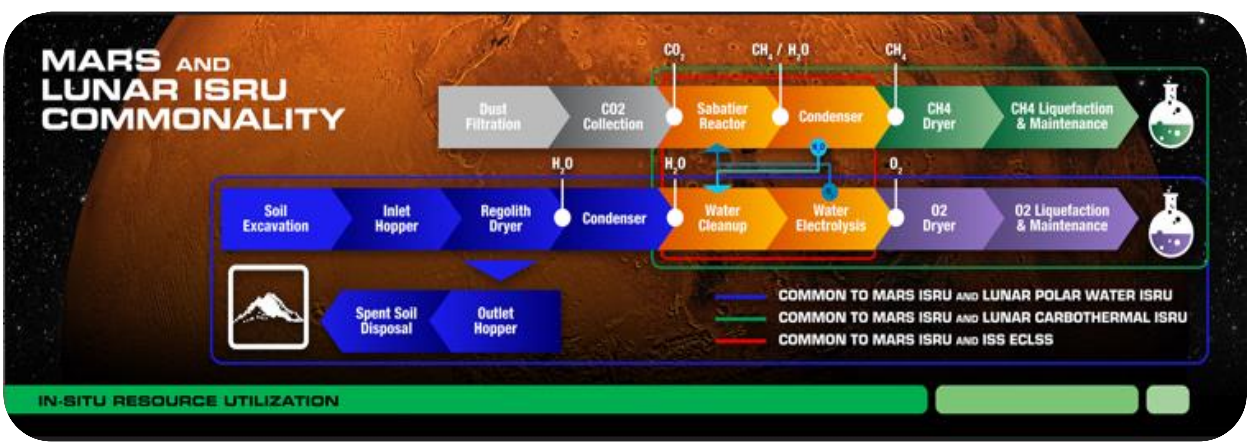

Figure 2: ISRU on the Moon and Mars

III. System Description

The carbothermal reactor used for the CaRD prototype system was developed through a Tipping Point project called the Carbothermal Oxygen Production Reactor (COPR) lead by Sierra Space. Both CaRD and COPR were funded by NASA’s Space Technology Mission Directorate (STMD)/ Game Changing Development (GCD) program and COPR was partially funded by Sierra Space. The scope of the CaRD project was to develop the other necessary subsystems (solar concentrator, fluid system, gas analysis, optical shutter/splash plate, avionics, software) that would be required for a solar-carbothermal demonstration on the lunar surface. Some subsystems (fluid system, carbothermal reactor, gas analysis) were tested in a thermal-vacuum environment as part of the CaRD project. The fluid system needed for the carbothermal reaction was also developed by Sierra Space. An overview of the CaRD prototype is illustrated in Figure 3, with an astronaut shown for scale. A more detailed summary of each major subsystem is described in the following subsections.

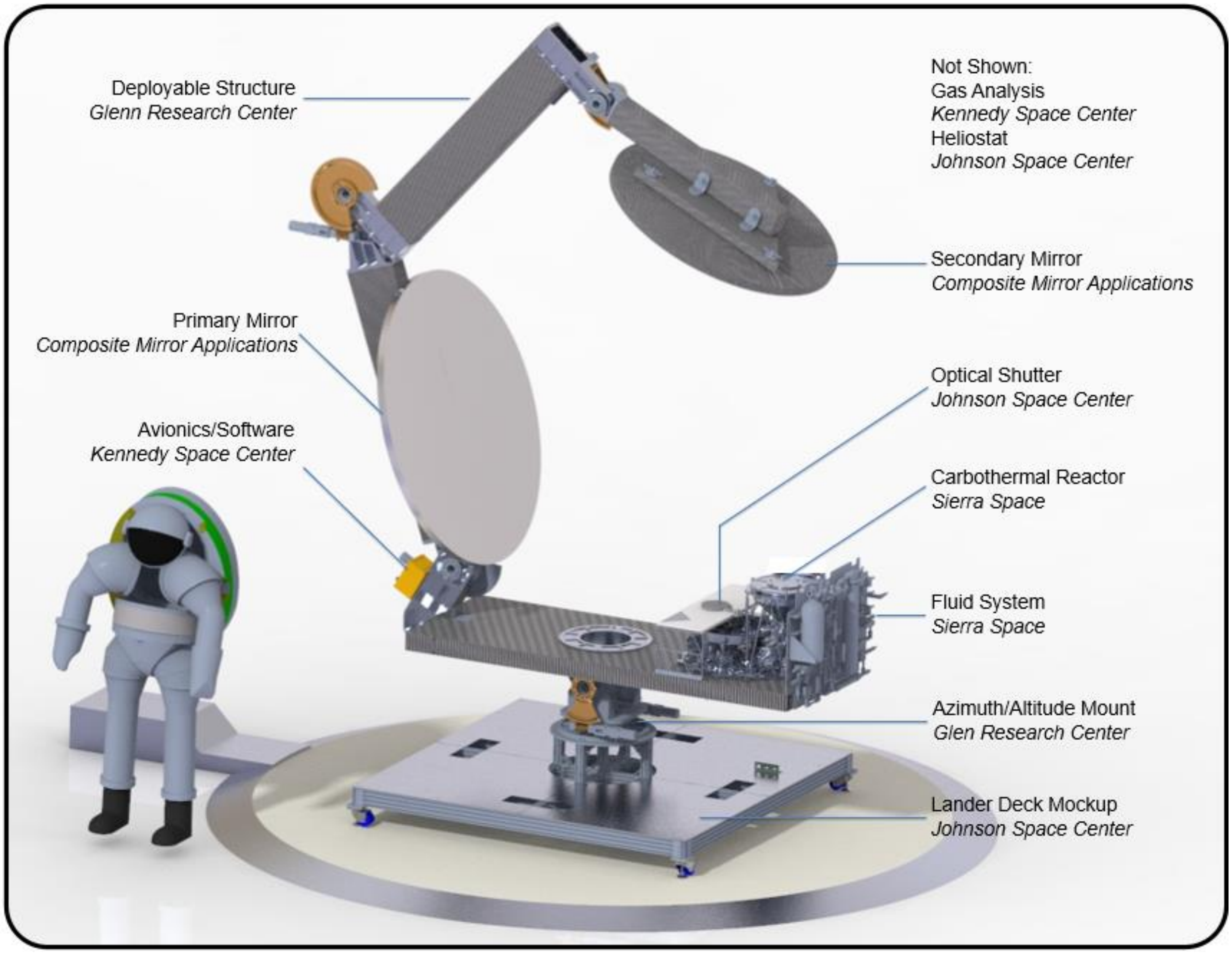

Figure 3: CaRD Integrated Prototype

A. Solar Concentrator

The solar concentrator was developed by Glenn Research Center with mirrors developed by Composite Mirror Applications. One of the main requirements that drove the design of the solar concentrator is the need to be in a stowed configuration for launch and then deployed on the lunar surface. This requirement led to the idea of using a crossed-Dragone configuration of mirrors rather than the Cassegrain approach used in the first-generation system. The crossed-Dragone configuration is compatible with a mechanized solar concentrator that can be deployed into position using motors. The limitation is that this configuration only works when the incoming light source is perpendicular to the target. Fortunately, sunlight will be roughly horizontal at the lunar poles so the cross-Dragone approach works with a reactor that has a zenith-facing window. Another driving requirement for the solar concentrator is mass. The first-generation solar concentrator weighed ~1400 lbs (635kg) [7] which exceeds the payload capacity of current mid-class CLPS landers. To reduce mass, the CaRD mirrors were made of a carbon composite material. The combined mass of the mirrors was measured to be 51.2 kg and the total estimated mass of the CaRD solar concentrator is 205 kg. The solar concentrator is mounted to an altitude-azimuth base, which provides the direct interface to the lander deck mockup. The alt-az mount would allow the entire deployed assembly to track the sun as it moves across the horizon of the lunar surface at the poles. The alt-az mount also accounts for the likely scenario of a lander being on a slope and can accommodate a slope angle of up to 10 degrees. Figure 4 shows a few steps in the deployment sequence of the solar concentrator without mirrors installed.

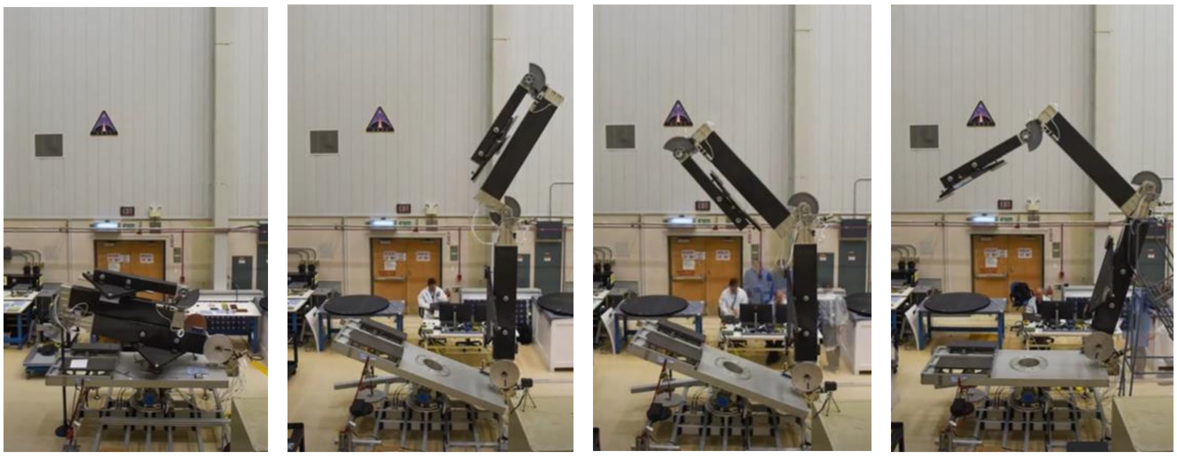

Figure 4: Stowed Configuration (Left), Deployed Configuration (Right) and Intermediate Steps (Middle)

The avionics and software needed to control the solar concentrator were developed by Kennedy Space Center. The same team that designed the avionics and software for the Mass Spectrometer observing lunar operations (MSolo) instrument supported the development of the CaRD avionics and software. For a lunar demonstration, MSolo would be used to analyze the gases so having the same team develop the avionics and software for the rest of the system would allow for a seamless integration. The electrical harnesses connecting the avionics to the solar concentrator components were developed by Johnson Space Center. Figure 5 shows what the fully integrated solar concentrator looks like during a test. To measure the focal point of the solar concentrator, a bowl of JSC-1A simulant was placed in the focal point and allowed to melt. The molten simulant solidified after being allowed to cool, and was measured to confirm that the solar concentrator design met requirements.

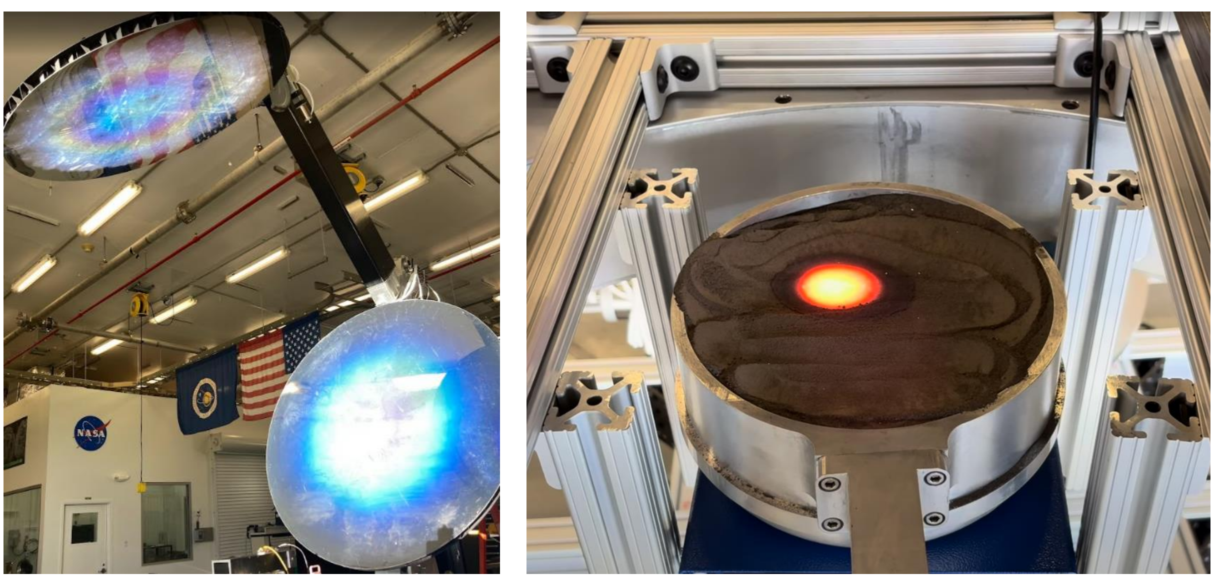

Figure 5: Illuminated Solar Concentrator (Left) and Molten JSC-1A Simulant at Focal Point (Right)

B. Optical Shutter & Splash Plate

The optical shutter and splash plate were developed by Johnson Space Center. The concept of operations for a solar-carbothermal system on the lunar surface involves deploying the solar concentrator while pointing away from the sun, then rotating toward the sun in a fully deployed configuration. This would result in a concentrated focal point moving across the system. The purpose of the splash plate is to prevent the high energy focal point of the concentrator from damaging the reactor as the focal point moves from the edge of the reactor toward the window. The splash plate must absorb the full intensity of the concentrated focal point so the upper surface of the splash plate was composed of LI900, the material developed for the Space Shuttle tiles. The splash plate design included a ring of optical sensors that could be used to verify focal point alignment prior to introducing concentrated sunlight into the reactor.

An optical shutter is located directly over the reactor window to absorb the energy of the focal point while alignment is being verified. The optical shutter includes an array of thermocouples that can be used to provide a rough estimate of the power being delivered to the reactor. The optical shutter also uses LI900 on the upper surface.

Unfortunately, the splash plate and optical shutter were not fully tested. Some of the upper plates made of LI900 were damaged during shipping. However, one undamaged splash plate was used during calorimeter testing to ensure that the calorimeter was only measuring light that would go into the reactor under nominal conditions. Figure 6 shows the completed assembly of the splash plate and optical shutter without the LI900 covers as well as the center splash plate being used during a test.

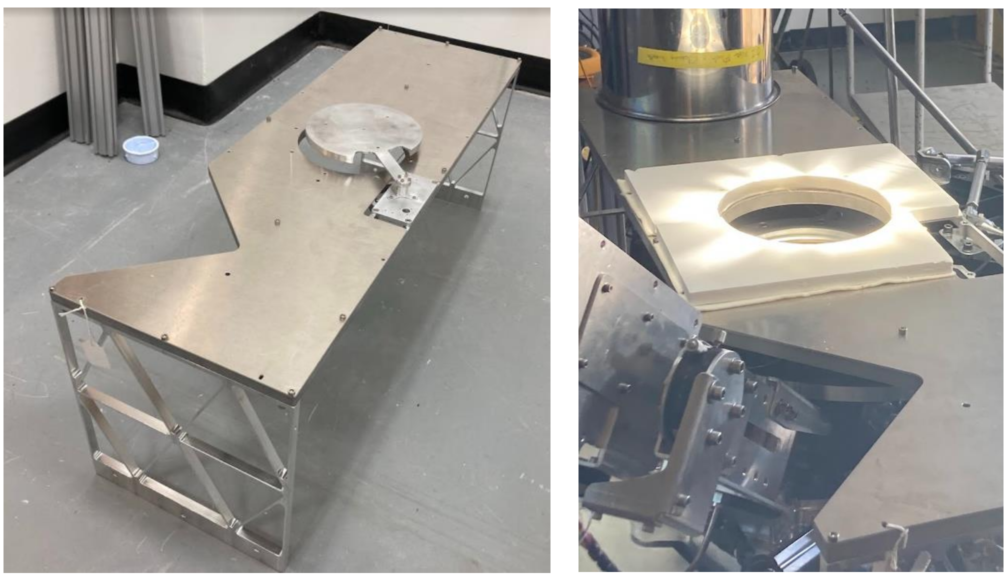

Figure 6: Splash Plate and Optical Shutter Assembly Without LI900 (Left) Center LI900 Splash Plate Used During Test (Right)

C. Reactor

The reactor was developed by Sierra Space through the Carbothermal Oxygen Production Reactor (COPR) Tipping Point project. This project drew from many years of earlier small business innovation research (SBIR) and internal development work to create a flight-forward reactor design scaled for deployment on a mid-class CLPS lander. The primary goal of the COPR project was to mature a system to TRL 6 that is capable of demonstrating the directly scalable key technologies required to perform carbothermal reduction of regolith in a CLPS mission scenario. A lunar technology demonstration mission would provide vital data on processing conditions and product output using actual lunar regolith. This demonstration would obtain data needed for scale up and operations in the 1/6g lunar environment. It would also provide a demonstration of successful regolith flow and handling operations with lunar regolith which will differ from operations performed with terrestrial simulants due to differences between simulants and the presence of agglutinates. The COPR design includes allowances and adjustability with key operations which allow the system to adapt to data obtained once on the lunar surface. This work would then inform a follow-on precursor pilot plant or higher maturity demonstration mission.

Prior to inclusion in the CaRD Integrated Prototype, the COPR hardware was tested extensively in the ambient environment during development and integrated with the NASA KSC MSOLO analysis equipment. In the summer of 2024, the COPR system was installed in the B351 dirty thermal vacuum (TVAC) chamber at NASA JSC where it successfully demonstrated the carbothermal reduction process in the relevant lunar thermal and vacuum environment. Key system capabilities demonstrated included: controlled flow and metering of regolith simulant into the sealed reaction chamber and through it; heating of the simulant using laser energy to perform the carbothermal reduction reaction; separation of the processed melt from the bulk regolith material; and removal of the processed melt from the reaction chamber. Several other key technologies and capabilities of the system were demonstrated in this testing, including: protection of the optical window through which the laser energy (or concentrated solar energy) enters the processing chamber; multiple strategies for protecting the mechanical components from regolith degradation; a novel regolith tolerant valve design capable of sealing successfully after thousands of cycles with regolith exposure to the sealing surfaces; and operation of the overall system in the most onerous configuration at an assumed lunar surface slope angle of 15 degrees to account for possible landing site topographies. The COPR system successfully demonstrated these capabilities during the testing, elevating these technologies to TRL 6 at the conclusion of the testing.

Following this work, NASA and Sierra Space continued to collaborate to integrate the COPR hardware into the CaRD Integrated Prototype.

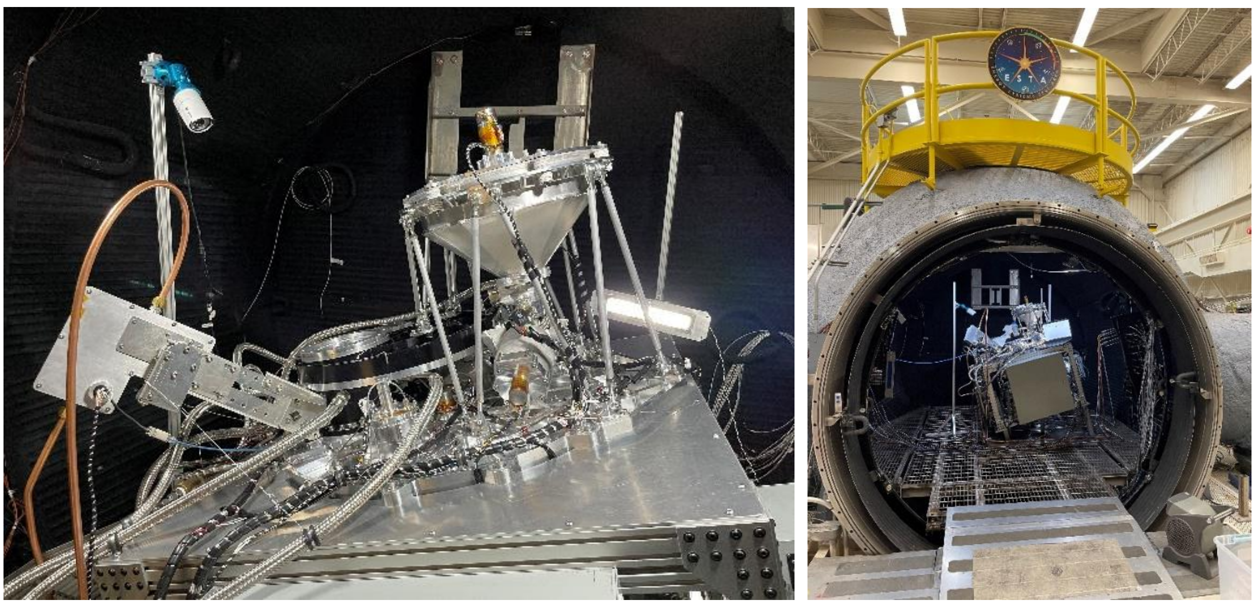

Figure 7: Carbothermal Oxygen Production Reactor (left), COPR Test in 15 ft Dirty TVAC chamber at JSC's Energy Systems Test Area (right)

D. Fluid System

The fluid system was developed by Sierra Space through the CaRD effort for utilization in the previously mentioned COPR TVAC testing, and for use in the CaRD Integrated Prototype. The fluid system comprised the necessary flow control and measurement components required to manage gas flow through the carbothemal reduction reactor and associated COPR hardware. During thermal vacuum testing, the MSOLO gas analysis system was paired to the fluid system to provide quantification of the carbothermal reduction output products. The 2024 COPR TVAC testing also elevated this system to TRL 6.

E. Gas Analysis

The gas analysis system was developed by Kennedy Space Center. A commercial version of the Mass Spectrometer observing lunar operations (MSolo) instrument was used to detect and quantify the CO and CO_2 products of the carbothermal reaction. The MSolo instrument is a flight-qualified residual gas analyzer (RGA) [8]. For the CaRD project, the gas analysis system was used for multiple tests. In each test, it was used to quantify the amount of oxygen removed from regolith. The MSolo instrument was already a high TRL instrument prior to use for CaRD, but it had not been used to quantify the products of a carbothermal reduction reaction. While the MSolo instrument now has flight heritage due to operation on the lunar surface during the PRIME-1 mission, the TRL for gas analysis as it applies to oxygen from regolith was raised to 6 as part of the CaRD project, with the relevant environment in this case being the carbothermal reaction product gases. In addition to quantifying oxygen yield, the gas analysis system was used to detect potential byproducts. In a lunar scenario, the RGA would theoretically be able to detect any solar-wind implanted volatiles that are released during the process of melting regolith.

F. Ground Support Equipment

The ground support equipment was developed by Johnson Space Center. The main pieces of ground support equipment were a lander deck mockup, heliostat, light screen, and turntable.

Lander Deck Mockup: The function of the lander deck mockup was to support the mass of the CaRD prototype and to be able to tilt the entire assembly up to 10 degrees to simulate tracking of the sun while on a slope at the lunar south pole. The lander mockup also included the structural and electrical interfaces that could translate to a lander in the future. The lander mockup was initially tested by placing an 800lb load on the prototype interface, then tilting the mockup 10 degrees. Figure 8 shows the lander deck mockup at a 10.1 degree tilt with an 800 lb load applied to the structural interface.

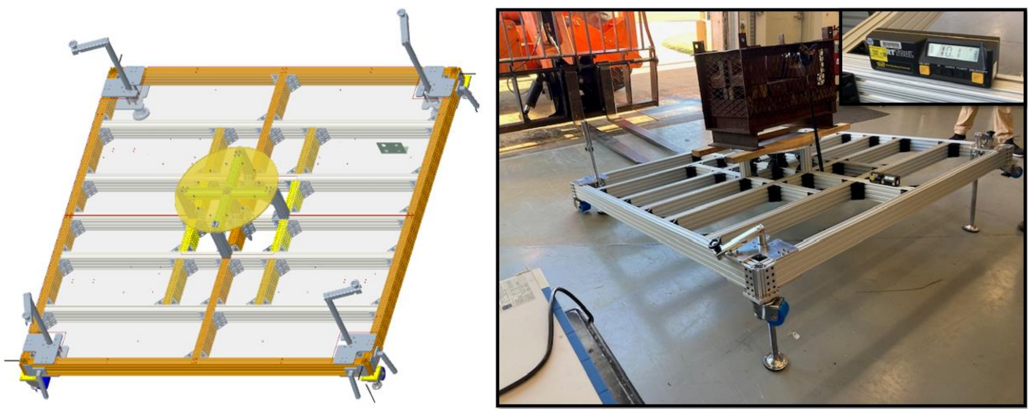

Figure 8: Isometric CAD model of Lander Deck Mockup (left) Lander Deck Mockup Test (right)

Heliostat: The function of the heliostat was to be able to track the sun and direct sunlight toward the CaRD prototype at a horizontal angle. The horizontal angle of incoming light is representative of the sunlight at the south pole of the moon, where the sun is only a few degrees above the lunar horizon during illuminated periods. The heliostat utilized a tracking system procured from Sat Control, and mirrors developed by Composite Mirror Applications. The tracking system was installed onto a mobile base so that the entire heliostat assembly could be moved into a tent for overnight storage. Figure 9 shows the complete heliostat assembly while anchored to the ground, the underside of the mirror assembly while in the stowed configuration, and the reflective side of the mirror assembly while tracking the sun.

Figure 9: Complete Heliostat Assembly (left), Stowed in Tent (middle) and Tracking (right)

Light Screen: The function of the light screen was primarily to help with alignment of the heliostat and solar concentrator, but was also used as an optical shutter. The light screen utilized a commercial off the shelf (COTS) welding screen that was modified by forming a series of holes to act as a rough Hartmann plate that would allow test personnel to determine the alignment of the heliostat and solar concentrator prior to running a test with full sunlight. The light passing through the holes was concentrated onto the target to ensure proper illumination of the target area before full power operations. The light screen was designed so that it could quickly be raised and lowered to safely engage and disengage full power operations when needed. The light screen was located within a large tent to prevent wind from moving the screen while in the raised configuration. The same tent was used to stow the heliostat at night to prevent the accumulation of dust and water spots on the heliostat mirrors.

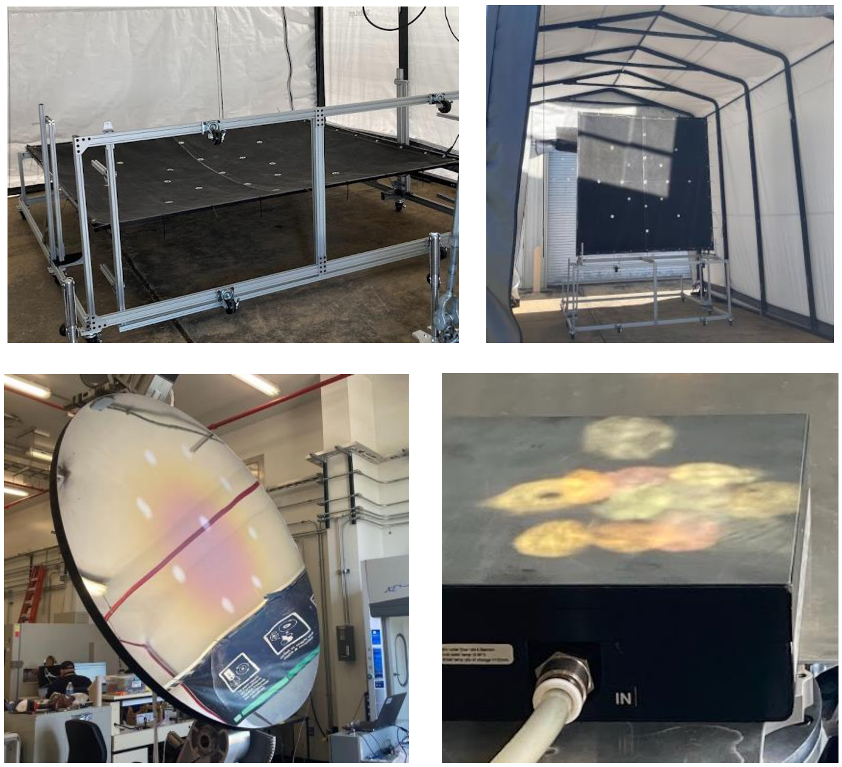

Figure 10: Light Screen in Stowed Configuration (upper left) Partially Illuminated Light Screen in the Raised Configuration (upper right) Sunlight Travels through Light Screen Holes and Partially Illuminates Primary Mirror (lower left) Calorimeter Target is Partially Illuminated with Sunlight that Travels through Light Screen Holes (lower right)

Turntable: Figure 11 shows the 4 meter diameter turntable that was purchased from Carousel USA and installed in the location where CaRD prototype testing took place. The concept was to have the entire CaRD prototype and lander mockup rotating while the incoming sunlight from the heliostat stays fixed. This would require the sun tracking algorithms to operate in a way that is applicable to sun tracking at the poles of the lunar surface. The sun tracking test with the turntable was not performed due to a combination of budget, schedule, and personnel constraints.

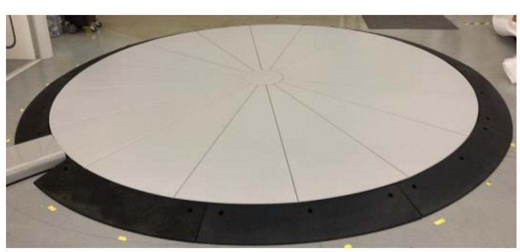

Figure 11: Turntable for Sun Tracking

IV. Test Results

A. Test Configurations

Two test configurations were used to determine the key performance parameters of the system. In both cases, the heliostat and light screen were used to project sunlight toward the solar concentrator at a horizontal angle. The difference between the two configurations was the target for the focal point of concentrator solar energy. To determine the optical transmission efficiency, the target was a water-cooled calorimeter. To determine the oxygen production efficiency, the target was the reactor. In both cases, the CaRD prototype was located within building 360 of the Energy Systems Test Area (ESTA) at JSC which contained a roll-up door large enough to fully illuminate the primary mirror of the solar concentrator when opened. Figure 12 shows the overall test configuration.

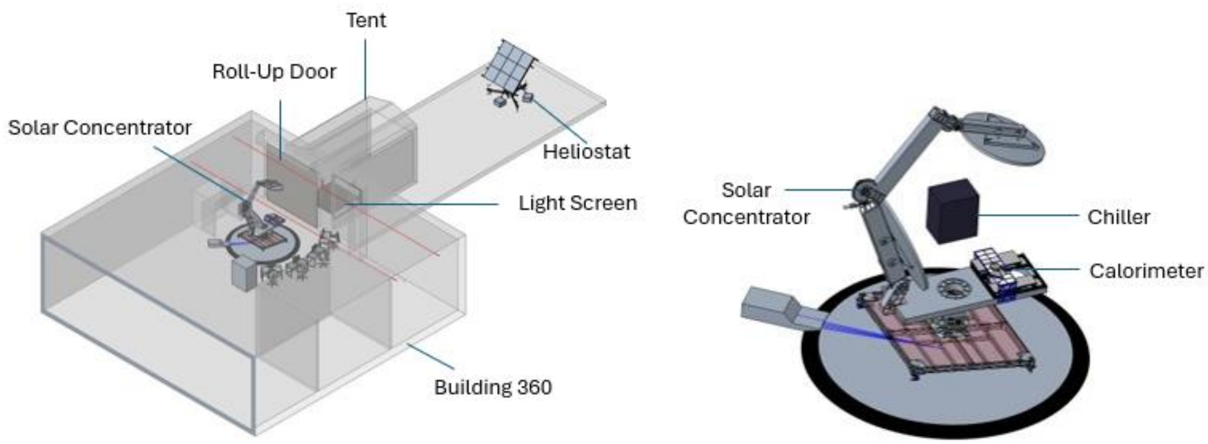

Figure 12: Overall Test Configuration (left) Prototype Configuration for Calorimeter Test (Right)

B. Optical Transmission Efficiency

The first-generation solar concentrator delivered 703W of power to the reactor with 2110W of solar power arriving at the primary mirrors, resulting in an optical transmission efficiency of 33%. This value represented the state of the art for a solar-carbothermal system prior to the development of the CaRD prototype and was established as the threshold for the performance of the CaRD solar concentrator. The optical transmission efficiency of the CaRD solar concentrator was defined as the power delivered to the regolith within the reactor as a percentage of the power arriving at the primary mirror.

Mirror reflectance was measured at 92.7%, which would result in a total system efficiency of 85.9% if there were no imperfections on the mirror surface. The difference between theoretical and measured efficiency is due to multiple factors, including the seams of the heliostat mirrors. To calculate the overall efficiency using calorimeter data, the area that represents incoming sunlight was first determined. By projecting the usable primary mirror surface onto a two dimensional plane, the clear aperture area was determined to be 1.889 m^2.

Incoming power is the solar flux entering the clear aperture area. However, a fill factor to account for imperfections in the heliostat mirrors and the gaps between the heliostat mirrors was needed. The fill factor was estimated to be 95% and verified empirically by running a calorimeter test without a splash plate. The splash plate was designed to keep the focal point on target while tracking and contained an aperture slightly larger than the diameter of the focused light. With a splash plate in place, any light that wasn't focused correctly would illuminate the splash plate. With no splash plate in place, any light that wasn't focused correctly would arrive at the calorimeter. Since the calorimeter has a time lag, the most accurate way to determine efficiency was to compare the total energy arriving at the concentrator to the total energy delivered to the calorimeter over the same period of time. The data showed that assuming a 95% fill factor of incoming light would mean an incoming energy of 101 Wh, and the calorimeter recorded 86.9 Wh. That translates to an overall efficiency of 86% which matches the expected value when the only factor is the reflectivity of the mirrors and not the surface imperfections that scatter light outside of the focal point.

Figure 13: Calorimeter Test without Splash Plate (left) and with Splash Plate (right)

To determine the true efficiency of the system, only light that was focused correctly was accounted for. When the splash plate was in place, any light that was not correctly focused hit the splash plate and did not register on the calorimeter underneath. From test data taken on 9/11/2025, with the splash plate in place, the total input energy was measured using a solar cell and determined to be 198.5 Wh. The total energy delivered to the calorimeter was 141.4 Wh. This translates to an efficiency of 71.2% when there was no reactor in place.

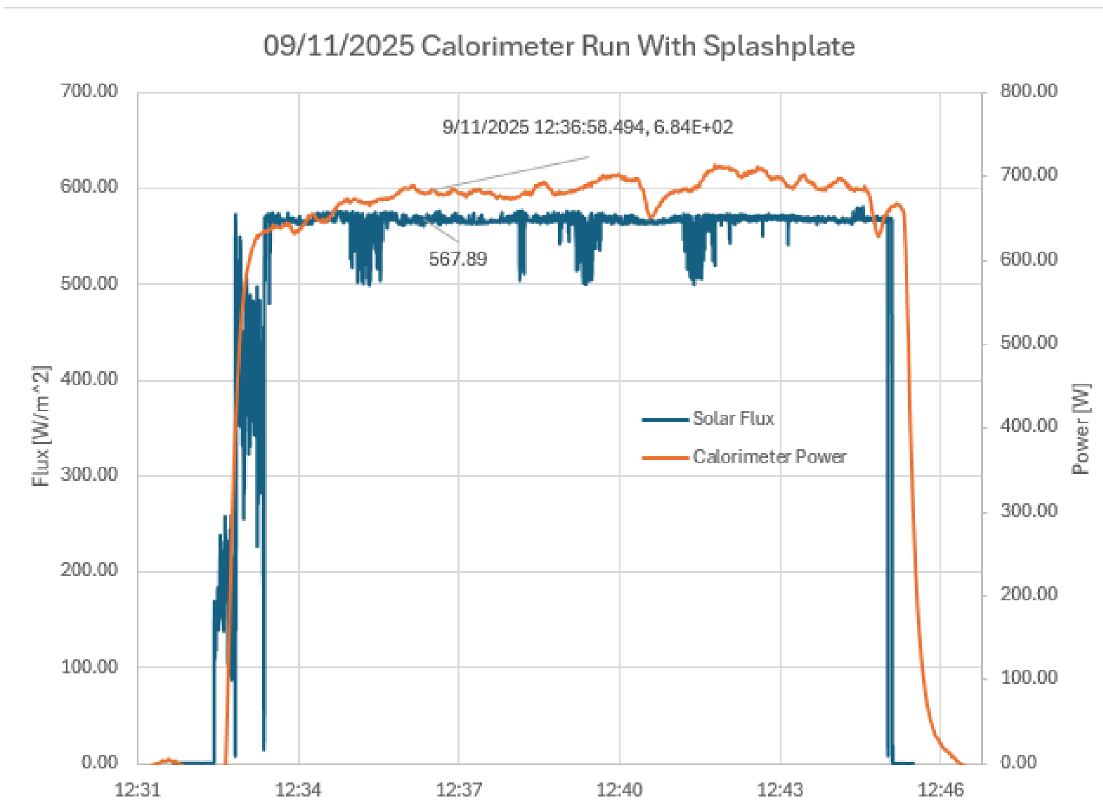

Figure 14: Solar Flux and Calorimeter Data Taken on 9/11/2025

To compare the solar-carbothermal performance to the first-generation, an assumption must be made about the losses at the reactor window. When accounting for the reactor window losses the overall optical transmission efficiency is **60.3%**.

C. Oxygen Production Efficiency

This key performance parameter represents the mass of oxygen produced from regolith for a given system input energy in the units of g/kWh. This value can be used to compare the performance of alternative methods to extract oxygen from regolith such as molten regolith electrolysis, vapor pyrolysis, and molten salt electrolysis. However, in the carbothermal process, oxygen is initially extracted from regolith in the form of carbon monoxide. A good comparison of alternative technologies should include the energy required to produce oxygen gas from carbon monoxide. The downstream components required for this conversion are a methanation reactor, and water electrolysis. The CaRD system was designed only to acquire information on the oxygen extracted from regolith in the form of CO.

The first-generation solar-carbothermal system was tested in Mauna Kea, HI on 02/24/2010 and extracted 1.1 grams of oxygen in the form of carbon monoxide with 3.313 kilowatt hours of solar energy arriving at the primary mirror, resulting in a value of 0.35g/kWh. However, it should be noted that the baseline value derived from the first-generation system assumes that the solar flux arriving at the primary mirror did not fluctuate. This is a reasonable assumption given that the test was performed at a high altitude above most clouds that could interfere with solar flux. During a test in Houston TX on 8/28/2025 the CaRD system extracted 0.195 grams of oxygen in the form of carbon monoxide with 0.380 kilowatt hours of solar energy arriving at the primary mirror, resulting in a value of 0.51 g/kWh. The CaRD prototype tests were performed at sea level in Houston, TX and the solar flux arriving at the system did fluctuate throughout the test duration. For this reason, the incoming solar flux was recorded throughout the tests, and the energy input was determined from the recorded data. An example of this data is shown in Figure 15.

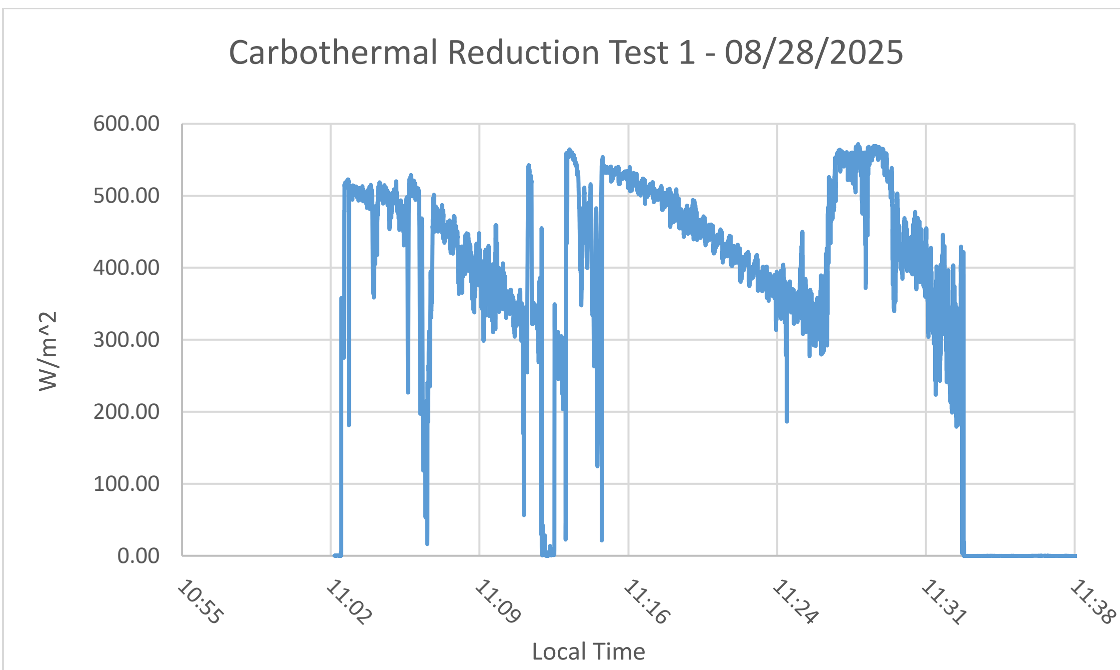

Figure 15: Incoming Solar Flux

The tests in Houston were affected by local weather, but sufficient to verify that system requirements had been met. The performance of the system in Houston can be used to extrapolate the estimated performance on the Moon, where the solar flux is considerably higher than Houston. In the lunar case, a solar flux of 1370 W/m^2 arriving at an aperture area of 1.889 m^2 would result in an incoming power of 2588W. With an optical transmission efficiency of 60.3%, the power delivered to the reactor would be 1561W. That is more power than what was delivered to the reactor with a laser during thermal vacuum testing (1380W). However, a slight reduction in mirror diameter of approximately 10 centimeters would result in a primary mirror aperture area of 1.67 m^2 and result in a delivered power of 1380W. We measured the amount of oxygen extracted with 1380W of laser power, so if the yield of actual regolith is similar to the Greenspar 250 simulant used during the 1380W TVAC test, and concentrated solar energy performs similarly to a laser, we can expect ~9.53 g/kWh on the Moon with only a slightly modified CaRD design. Alternatively, a TVAC test with 1561 W of laser power could be performed to ensure the reactor can handle the additional thermal input, and the CaRD prototype design could potentially operate on the Moon without changing the size of the mirrors.

Table 1: Compilation of CaRD Prototype Data, with Comparisons to Similar Tests and Predictions

System	Test Date	Location	Simulant	~Input Solar Flux (W/m^2)	Aperture Area (m^2)	Delivered Power (W)	gO/kWh Input Energy
First-generation	2/4/2010	Mauna Kea, HI	Tephra	989	2.3898	780	0.35
CaRD ETU Brassboard	2/15/2023	Houston, TX	Greenspar 250	laser		1380	N/A
CaRD Prototype	8/26/2025	Houston, TX	Greenspar 250	550	1.889	595	0.29
CaRD Prototype	8/27/2025	Houston, TX	Greenspar 250	675	1.889	730	0.39
CaRD Prototype	8/28/2025	Houston, TX	NUW-LHT-5M	550	1.889	595	0.51
CaRD Prototype	8/28/2025	Houston, TX	NUW-LHT-5M	550	1.889	595	0.28
CaRD Prototype	Prediction	Moon	Regolith	1370	1.889	1561	Unknown
CaRD Prototype	Prediction	Moon	Regolith	1370	1.670	1380	9.53

D. Oxygen Production Efficiency Comparison

In order to provide a better comparison of the solar-carbothermal method to other oxygen extraction technologies, the electrical energy required to convert CO into O_2 gas must be accounted for. The intermediate step of converting CO and hydrogen into methane and water is exothermic, however the energy required to convert water into hydrogen and oxygen gas can be estimated. The Oxygen Generation Assembly (OGA) on the International Space Station (ISS) is a space qualified water electrolysis system that can produce roughly 129 grams of oxygen per kilowatt hour of electrical energy input. Assuming a solar panel efficiency of 30% and OGA performance, then the production of oxygen gas from water on the moon is 38.7 grams of O_2 per kilowatt hour of solar energy arriving at a solar panel. Combining this value with the energy required for extracting oxygen from regolith provides a value of 7.65 grams of oxygen per kilowatt hour of solar energy arriving at the system. This value does not include the residual electrical power required to run components. For the CaRD prototype, the avionics had a continuous power draw of 12W, and the motors had an intermittent peak power draw of 34W. Assuming an average continuous electrical power draw of 24W supplied from a 30% efficient solar panel, the additional electrical energy required to run the CaRD prototype would reduce the key performance parameter to **7.44 g/kWh** of incoming solar energy. This is the value that should be used to compare the performance of the solar-carbothermal process to alternative oxygen from regolith technologies when assuming that electrical power is provided from solar panels with a solar to electric conversion efficiency of 30%. However, if nuclear power were to become available, it would be more appropriate to compare the energy of alternative oxygen production methods to only the electrical power required, as the majority of the thermal energy needed for the solar-carbothermal process would come from the solar concentrator and not a nuclear power source. For the nuclear case, a value of 113.06 g/kWh of electrical power would be appropriate for comparison, as this value represents only the electrical power needed to run the solar-carbothermal system and the electrical power required for water electrolysis. It should be noted that the residual electrical power required to run the solar-carbothermal system is only representative of the CaRD prototype and will change with scale.

V. Future Work

There were some aspects of the CaRD system that were not tested, such as the ability to track the sun as a moving target, and the ability to rotate the solar concentrator into the path of sunlight. Both of these untested operations would require a fully functional optical shutter and splash plate. Sun tracking operations would also require the lander deck mockup to be placed on a turntable, which was purchased and installed for the CaRD project, but not implemented. In addition, one of the solar concentrator deployment motors would have to be replaced.

The solar concentrator developed for the CaRD project could be paired with other oxygen extraction technologies in the future. It could also be used for purposes other than oxygen extraction. The first-generation solar concentrator demonstrated the ability to sinter regolith in two dimensions. The CaRD solar concentrator could be used to demonstrate three-dimensional sintering of lunar regolith simulants as a construction material. Concentrated solar energy could also be used to demonstrate melting of metal components into wire or other useful items as a means to recycle lunar landers into beneficial infrastructure.

The CaRD project was initiated in 2020 with a request from the Lunar Surface Innovation Initiative for Oxygen from Regolith technology that could be demonstrated on the lunar surface. From the beginning, the CaRD and COPR projects defined requirements with a lunar demonstration as the eventual goal. The next step for CaRD would be to complete environmental testing. Locking mechanisms and vibration dampeners need to be added to the existing design to complete vibration testing. Heaters and insulation may need to be added to complete thermal vacuum testing.

In addition to environmental testing, the solar-carbothermal process ultimately needs to scale up and demonstrate that the entire process can operate unattended for months at a time and survive the lunar night. Development and testing of the water electrolysis and liquefaction systems can be done in parallel to environmental testing of the CaRD prototype because those downstream components could be anchored to a specific production rate. Development of any larger scale solar concentrator would be dependent on knowing (or at least estimating) the yield of oxygen extracted from real lunar regolith at the location where a large scale system would ultimately be deployed.

The long term goal of this technology is to produce significant quantities of oxygen propellant on the surface of the Moon to reduce the cost of a sustained human campaign. One advantage of this method of extracting oxygen from regolith is that it has commonality with Mars ISRU and ECLSS. In addition to oxygen production, this process makes it possible to produce methane propellant on the Moon. Hydrogen from lunar water is not easily liquefied, but could be fed into a methanation reactor where it reacts with the CO from carbothermal reduction to form methane which is much easier to liquefy and store as a propellant than hydrogen. In this case, carbon would be consumed in the process, but could theoretically be replaced by incinerating trash from a lunar base. The production of propellants on the lunar surface would not only reduce the cost of lunar surface missions, it could enable a space economy beyond low earth orbit. For example, there are currently companies developing asteroid mining technology, but the round-trip time to the asteroid belt could mean a payoff period of more than ten years depending on the target. If the round-trip time could be reduced by supplying spacecraft with propellant that is not sourced from earth, companies may find success in pursuing the high-reward venture of asteroid mining.

VI. Conclusion

The CaRD project had two goals. The first goal was to design, build and demonstrate performance and efficiency of a prototype solar energy delivery system for a carbothermal reactor. The second goal was to integrate a solar concentrator, carbothermal reactor, and mass spectrometer to collect oxygen from regolith performance and efficiency data. Both goals were achieved successfully. The data collected and experience gained from this effort can now be used to prepare for a demonstration on the lunar surface.

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