

Oxygen Production via Carbothermal Reduction of Lunar Regolith

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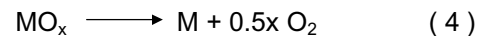
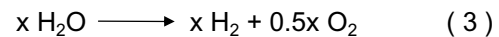
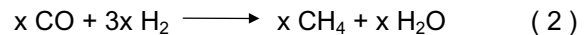
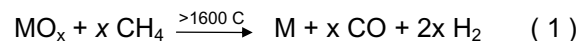
ABSTRACT

The Moon is composed of a variety of oxygen-bearing minerals, providing a virtually unlimited quantity of raw material that can be processed to produce oxygen. One attractive method to extract oxygen from the lunar regolith is the carbothermal reduction process. This paper discusses recent development work conducted through the PILOT project under the NASA OPTIMA program. The OPTIMA test program utilizes a modular technology suite of ISRU excavation, oxygen extraction, oxygen storage, and oxygen distribution hardware sized to be consistent with the draft Constellation requirements for oxygen extraction from the regolith to support the early lunar outpost (1 MT O₂/year).

INTRODUCTION

The utilization of extraterrestrial resources will be a key element in space exploration and permanent human presence on the Moon. The development and operation of ISRU manufacturing plants will enable permanent human bases on the Moon. Oxygen for life support and propulsion applications will likely be the first lunar ISRU product. Fortunately the Moon is composed of a variety of oxygen-bearing minerals, providing a virtually unlimited quantity of raw material that can be processed to produce oxygen. One attractive method to extract oxygen from the lunar regolith is the carbothermal reduction process. The carbothermal reduction process is a mature terrestrial technology for producing high-purity silicon from silicon dioxide (SiO₂). The same process can be used to reduce ilmenite and silicates in the lunar regolith to produce oxygen. The baseline carbothermal reduction for the manufacture of oxygen from lunar regolith has three steps [as shown in Eqs. (1-4) and Fig. 1] where M = metal: (1) reduction of minerals containing metallic oxides (e.g., ferrous, silicon, titanium,

etc.) with a carbonaceous source (e.g., methane) to form carbon monoxide and hydrogen; (2) reduction of carbon monoxide with hydrogen to form methane and water; and (3) electrolysis of water to form oxygen and hydrogen.



The hydrogen formed in Steps 1 and 3 is consumed in Step 2. The methane formed in Step 2 is reused in Step 1. This closed cyclic process does not depend upon the presence of water or water precursors in the lunar materials. It will produce oxygen from ilmenite and silicates in the lunar regolith regardless of their precise mineralogical composition.

While the composition of the Moon is not homogeneous, analyses of the Apollo samples indicate that minerals containing SiO₂ (silicates) comprise 40-50% of the total oxide mixture. Since silicates are so abundant in the lunar regolith, the carbothermal reduction process can be operated at virtually any location on the Moon with approximately the same efficiency (Gustafson et al., 2009).

HISTORY OF CARBOTHERMAL REDUCTION TECHNOLOGY

The original work with carbothermal reduction of lunar regolith was performed by Dr. Sandy Rosenberg and Dr. Gerald Guter at Aerojet in the 1960s. This research used a traditional hot-wall furnace approach to implement the carbothermal reduction process (Rosenberg et al.,

1964). In 1993, Dr. Rosenberg joined ORBITEC as an Associate and worked with Dr. Eric Rice on Phase 1 and 2 SBIR projects to further develop the carbothermal reduction process. Significant problems were encountered when the lunar regolith simulants (MLS-1 and JSC-1) were heated in crucible-type containment vessels in a hot-wall furnace. The molten regolith simulants reacted with the crucible-type containment vessels to varying degrees. The crucible-type containment structures were also prone to failure due to thermal stresses (see Figure 1). In addition, tubes used to inject methane gas into the furnace became plugged with carbon due to unwanted pyrolysis (Rice et al., 1997).

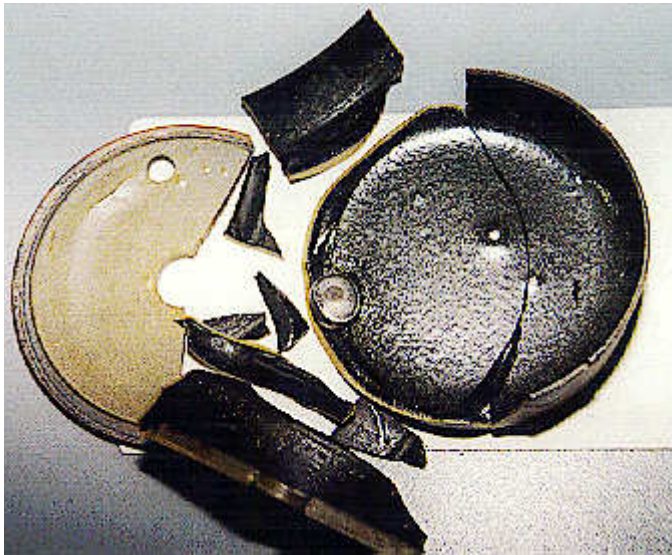


Figure 1. Typical crucible failure after a single carbothermal reduction processing batch in a traditional hot-wall furnace.

ORBITEC developed a direct energy processing approach to solve the problems encountered with hot-wall furnace approach. A direct heating source (such as a laser or concentrated solar energy) melts a localized region of regolith and leaves the surrounding regolith unmelted to serve as an insulative barrier for support structures (see Figure 2). This approach avoids the thermal and chemical compatibility issues observed with crucible-type containers since the unmelted regolith surrounding the melt region acts as its own processing container. Because the lunar regolith has a very low thermal conductivity, it is an excellent material to use with the direct energy processing approach. Another benefit of the direct energy processing approach is that a processing chamber with relatively cold walls can be utilized. The methane gas can be simply injected into the chamber and it will only pyrolyze on and near the surface of the molten regolith. The temperatures of the other locations in the processing chamber are too low for significant pyrolysis of methane (<1000 C). Temperatures required for carbonaceous reduction of silicon oxides (>1625 C) are relatively easy to meet or exceed with direct energy processing approach, while eliminating the need for special insulations and containment structures (Rice et al., 2000).

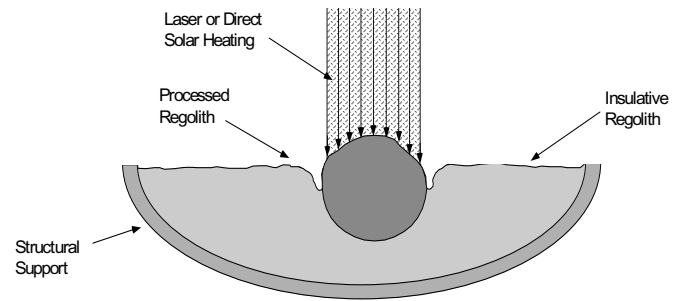


Figure 2. Direct energy processing approach where the regolith becomes its own insulative container.

CARBOTHERMAL LUNAR REGOLITH PROCESSING SYSTEM

Recent development work was conducted under the "Integrated In-Situ Resource Utilization for Human Exploration – Propellant Production for the Moon and Beyond" aka Precursor In-situ Lunar Oxygen Testbed (PILOT) project. Lockheed Martin is prime contractor for the PILOT project and ORBITEC is a major subcontractor. ORBITEC is focusing on the production of oxygen from the carbothermal reduction of lunar regolith while Lockheed Martin is investigating the production of oxygen from hydrogen reduction. The PILOT project is currently being funded by NASA as part of the Outpost Precursor Testbed for ISRU and Modular Architecture (OPTIMA) program. The OPTIMA program is integrating a modular technology suite of In-Situ Resource Utilization (ISRU) excavation, oxygen extraction, oxygen storage, and oxygen distribution hardware for integrated testing. All of the hardware utilized by OPTIMA is sized to be consistent with the Constellation draft requirement for oxygen extraction from regolith to support the early lunar outpost (1 MT O₂/year). The OPTIMA integrated testing will accomplish end-to-end system testing of a variety of different technology options to demonstrate the storage of oxygen created from lunar regolith simulant.

The ISRU technologies to be utilized by OPTIMA are being developed under multiple projects funded by the ISRU Project Office and non-ISRU hardware may be added into the integrated testing by other sources/programs. The ISRU Project Office is funded by the Exploration Technology Development Program (ETDP). Potential additional partners include other ETDP offices, industry or academia developed hardware, and international partners. In order to allow for a modular architecture of the OPTIMA integrated testing, each technology or module uses standard interfaces. This modular approach will allow different technologies to be characterized during integrated testing for roles such as excavation, oxygen extraction, water electrolysis, and oxygen storage. The OPTIMA integrated testing will be an unprecedented demonstration of lunar ISRU and help improve the accuracy of system models and trade studies. The projects providing ISRU hardware to the OPTIMA integrated testing are primarily the PILOT project (Lockheed Martin lead) and the ROxygen project (NASA lead), and the excavation hardware development area of ISRU. Support projects within the ISRU program