

LUNAR SOLAR SOIL REDUCTION EXPERIMENT. D. C. Barker¹, K. Mueller², M. R. Martinez², D. Luna², A. Shipman^{2,3}, D. Nyarwaya², J. K. Meen^{2,3}, ¹MAXD, Inc. P.O. Box 58915, Houston, TX, 77258 (donald.c.barker@att.net), ²Texas Center for Superconductivity, University of Houston, Houston Science Center, 3201 Cullen Blvd, Rm. 202, Houston, Texas 77204 USA, ³Department of Chemistry, University of Houston, Lamar Fleming Building, 3201 Cullen Blvd, Rm. 202, Houston, Texas 77204 USA (jmeen@uh.edu).

Introduction: In order to ensure sustainable, long duration human habitation of the lunar surface, a thorough understanding regarding the mechanics of lunar soil reduction in hard vacuum conditions is required, supporting knowledge gaps from resource extraction to thermochemistry, from fabrication to materials processing and construction [1,2,3]. We present a notional design for a Lunar Solar Soil Reduction (LSSR) experiment that could be deployed by crews on the surface of the Moon to address such questions.

Design and Operating Environments: The experimental apparatus (see Fig. 1) would be designed to operate independent of crew interaction except during surface deployment, sample priming and data recovery. The apparatus is contained in a 0.5-m³ box, and consists of battery power, processor & data storage, sensors and sample thermal reduction systems. EVA crewmembers will collect a single scoop (approximately 50 g) of near surface lunar soil in a sieved container which feeds into the experiment hopper and tungsten sample crucible.

Solar power will provide the energy required to reduce lunar soil samples via step or continuous heating using a programmable Fresnel lens and mirror-optical waveguide fiber optic system [5,6]. Lunar south pole lighting conditions, being the most constrained, at potential sights of interest [7] will provide continuous mission lighting at approximately 1.5° above the summer horizon while translating westward at roughly 0.5° per hour. This will provide the necessary insolation for an estimated experimental operating life of ~2.5 hours. Heating of the soil within the sample crucible will proceed through a series of predefined steps as derived through laboratory simulant reduction experiments during LSSR design and testing to a maximum temperature of 2400 °C. Once predefined temperatures steps are achieved (as measured using a radiation pyrometer), a release mechanism will drain separation products into individual sample containers, located on a carousel, for ambient cooling. During heating, volatilized products will be monitored and measured using infrared spectral and chemical analysis on-a-chip technologies (i.e. miniaturized low-power micro-gas chromatography system (μGC)) [8].

Data collection and storage, mechanical and battery power control will reside in a removable avionics box that will be retrieved, along with the chilled sample

carousel, at the end of the mission by crewmembers and returned to Earth for further analysis.

Experimental Goals and Techniques: Experimental reduction of planetary materials can support many scientific, engineering and user needs and goals. The proposed experiment examines lunar samples collected and processed in an ambient lunar environment. The volatility of metals on heating lunar rocks has been known since the work of Gibson and Hubbard [9] who heated lunar materials at 10⁻⁹ bars total pressure. They showed that Rb was lost at ≤950 °C (subsolidus), K at 950 °C, and Na at ≥1050 °C. They modeled constituent loss on relative volatility of the oxides. Kreuzberger *et al.* [10] looked at loss of alkali metals from doped haplobasalt at 1400 °C for various times in static air, in flowing Ar90:H₂10, and in continuous pumped vacuum <10⁻⁶ bars. In each case, the loss of alkali metals was Cs>Rb>K>Na. More recently [11], the loss of alkali metals was shown to be consistent with the reduction of the oxides and volatilization of the metals. At sufficiently high temperatures, each metal oxide will be reduced in the lunar environment where the metal is freed as solid, liquid, or gas. The thermochemical processes at each reduction step will be employed here and the freed metals collected for analysis.

In situ samples, once heated, will be introduced into the tungsten crucible through a covered hole in the base. The first heating step will release volatiles below 1000 °C, and as the volatiles leave the crucible they will be funneled into a tungsten metal tube allowing them to cool before they being introduced into the μGC. Alkali metals and sulfur will sublime/precipitate onto the walls of the collection unit where whiteness plates can be recovered for later analysis.

The bulk soil will begin to melt at about 1000 °C. Above that temperature the gases that leave the system will be oxygen and metals generated by the reduction of the silicates and oxides in the liquid. Na and K are released at temperatures of 1000-1400 °C. They will plate out on the cooler walls of the collection unit.

Oxygen will be intermittently generated as reduction reactions are encountered and analyzed in the μGC system. The soil will be totally liquid at about 1500 °C which is near the temperature at which FeO will be reduced. [9] This will be accompanied by a large volume of oxygen entering the μGC system. Fe

(and some other transition metals in minor amounts) will form a very dense immiscible liquid with a silicate liquid. The metal liquid will collect in the base of the tungsten crucible and can be collected in the first recovery step.

The next major oxide to be reduced is SiO_2 with the generation of essentially half the oxygen in the soil. The Si will form a liquid, leaving a Ca-MgO-TiO₂-Al₂O₃ liquid. The relative densities of the two liquids remain to be determined. Si liquid has a density of 2.57 g/cm³ and is probably less dense than the oxide liquid (this will be determined experimentally on simulants). The relative amounts of the two liquids will be calculated as the average composition of the soil has a limited range. The potential exists to skim this less dense Si liquid from the crucible by adding a lip-axis ladle.

TiO₂ is reduced next and, if Ti is to be collected, it could again be drained from the crucible. Ca and Mg are released as gases and, although Al₂O₃, in theory, is reduced to Al liquid and O₂, it is expected that the vapor pressure of Al liquid at the required temperature is so high that the Al will be released as a gas. It is, therefore, suggested that, rather than producing metal vapors at >2000 °C in the box, the Ca-Mg-Al-O liquid be retained in the crucible and returned to Earth for analysis with the previous separation products and data.

Forward Work: Technology demonstration and scientific returns for this experiment include addressing the thermochemical understanding of reducing lunar soil (i.e. regolith) in situ, quantifying the amounts of each metal and volatile generated and the form in which they are produced, and provide an enhanced understanding of the associated thermal conditions and physical constraints and interactions for the reduction reactions under ambient lunar conditions. Assessing the scalability will lead to design requirements for the realistic production of resources and ISRU on the lunar surface. Ongoing laboratory investigations regarding lunar material reduction will address aspects of chemistry, petrology and operational viability while providing inputs to future engineering designs for resource acquisition.

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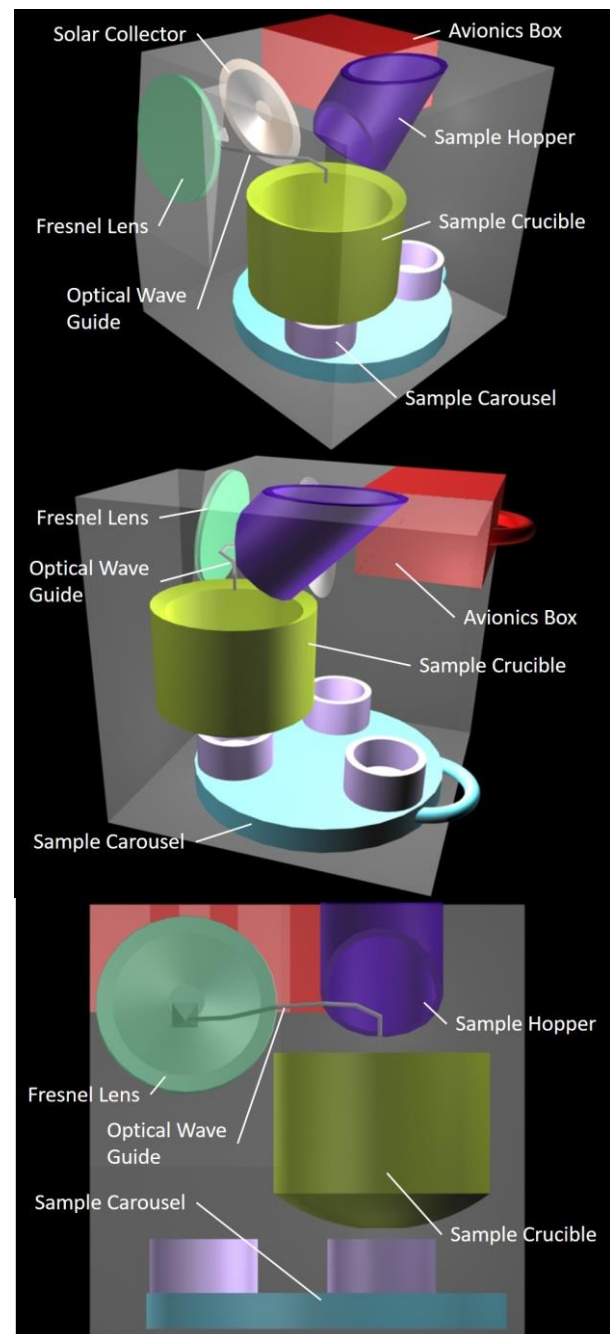


Figure 1. Notional schematics of the LSSR experiment. Two oblique and one side view of the 0.5 x 0.5 meter LSSR experimental apparatus. Major components are labeled. Note that the “avionics box” and “sample carousel” are removable and would be returned for analysis.