Additive Manufacturing and Resource Extraction Using Lunar Regolith. A. D. Whizin[1], C. Popelar[1], K. Kirkpatrick[2], V. Roux[3], and M. Roth[3]. [1]Southwest Research Institute (6220 Culebra Rd., San Antonio, TX, 78238), [2]RedWorks Construction Technologies, Inc, [2]Off Planet Research Labs, LLC.

Introduction: We are developing an instrument-level architecture for ***magnetic induction additive manufacturing***, which when applied to off-world applications, is a potentially revolutionary technique for the ISRU of lunar feedstocks. Additive manufacturing (AM) is the use of printers or extruders to build up three-dimensional objects layer by layer (e.g. 3D printing). Generally, this is done by heating a feedstock material and producing shapes or layers. In this case, this is accomplished through Magnetic Induction (MI) heating (a common method in industrial metallurgy), where the feedstock is melted in a metal vessel inside an oscillating magnetic field. AM could revolutionize the robotic construction of lunar bases (see Figure 1). This project involves studying MI AM of lunar soils by making regolith proucts and determining their efficiency for lunar surface applications (by measuring power requirements and mechanical strengths) and beginning work on a new resource extraction device integrated into the Mi print head (Figure 2).

Lunar surface materials can provide numerous resources if properly excavated and utilized. Analyses of both Highlands and Mare Apollo samples demonstrated that either type of lunar regolith contains usable volatiles such as OH, H_2O, H_2S, CO_2, NH_3, SO_2, and CO, which are released by heating to 1200°C (Gibson and Johnson, 1971; Holland *et al.*, 1972). Water has been detected in the LCROSS impact-induced plume in Cabeus crater (Colaprete *et al.*, 2010; 2012; Gladstone *et al.*, 2010; Hurley *et al.*, 2012), and over much of the lunar surface at levels of hundreds of ppm (Pieters *et al.*, 2009; Sunshine *et al.*, 2009; Hendrix *et al.*, 2012). The lunar regolith, comprised of iron- and titanium-bearing silicates (*Handbook of Lunar Soils* – Morris *et al.*, 1983), is highly valuable as a construction material for building habitats, roads, berms, walls, and other support structures.

Figure 1: Concept of Autonomous AM on the Moon.

Additive Manufacturing on the Moon: The use of lunar regolith in AM has been an active area of research for many years, focusing on laser/solar heating and sintering, polymer binders, resistive heating, and microwave sintering (Vaniman *et al.*, 1986; Taylor & Meek, 2005; Balla *et al.*, 2012; Montes *et al.*, 2015; Davis *et al.*, 2017; Jakus *et al.*, 2017; Chen *et al.*, 2018; and many references therein). Each method has drawbacks. MI heating and sintering has never been applied to additive manufacturing of lunar regolith and has the potential to address some of these shortfalls. This project aims to advance the MI for ISRU concept by addressing unanswered questions about the operation, engineering, and efficacy of this application to off-world problems.

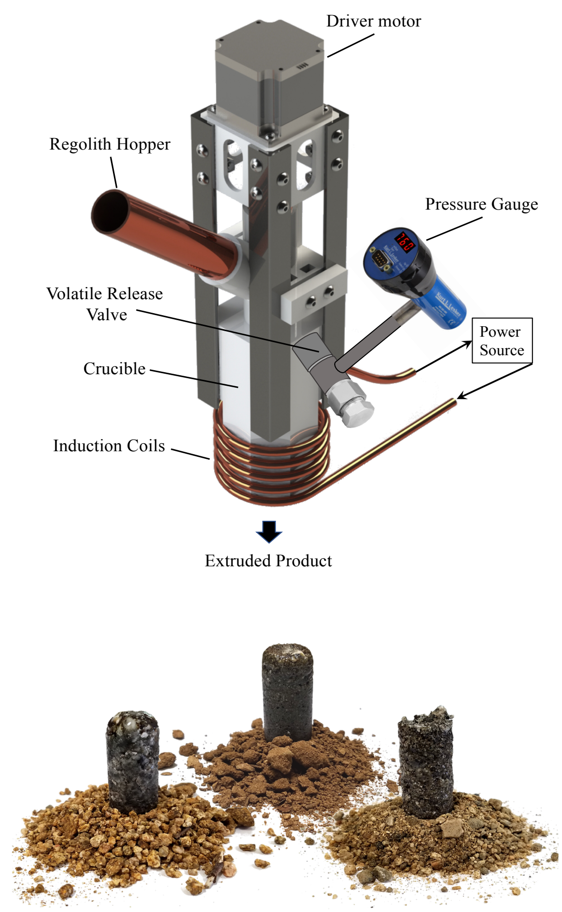

Figure 2: Magnetic Induction print head and extruded sintered cylinders for use in building materials.

MI heating and sintering works by applying an alternating current (AC) through loops of copper coils wrapped around a ferrous metal crucible (i.e., a bored iron cylinder or vessel). The oscillating magnetic field from the coils (solenoid) induces a magnetic field in the crucible, which, based on Lenz's law ($E = -N\partial\Phi B/\partial t$), produces an electromotive force in the opposite direction for N loops resisting each subsequent change in the applied field, producing eddy-currents in the metal. This current-induced "friction" rapidly heats the metal, and the lunar regolith that will be placed inside, which has melting points of ~1200°C (primarily silicates). MI printing is fast, simple, can function in a vacuum, and low-cost.

Collaborator RedWorks Construction Technologies, Inc. has partnered with SwRI to conduct this research, with the lunar simulants being supplied by Off Planet Research Labs, LLC, and UCF Exolith Labs.

Experimental Approach: The basic operating procedures and thermal responses to lunar regolith will be characterized by placing regolith into the RedWorks' print head crucible that is wrapped in copper wires (Figure 2). As a controlled AC current from a power source is passed through the wires, the crucible and regolith heat up due to eddy currents. Conduction between the crucible and regolith heats the sample until molten. The print head then extrudes the desired molten cylindrical product at a rate controlled by the composition of the sample, input power, packing density, and possibly atmospheric pressure (examples of product cylinders shown in Figure 2).

1. Magnetic Induction Printing – We measure the power input and sintering level for the highland and Mare lunar regolith simulants (differences influenced by composition), determine the time and energy required for optimum heating (measured by a thermocouple) of the test cylinder (Figure 2).

2. Mechanical Strength of 3D Printed Lunar Regolith – We study the feasibility of MI printing in space-like conditions using a vacuum chamber, which is a critical requirement for use of the technology on the lunar surface. The compressive and shear strength of these test cylinders will also be tested in §3. The results will be compared to the strengths determined in §3 as an assessment of the AM method for use on the Moon. To estimate the effectiveness of MI printing as a construction solution on the lunar surface using lunar regolith as the feedstock, printed test cylinders that were produced in §1 and §2 will undergo mechanical testing and characterization in load cells to measure the unconfined compressive strength and shear strength.

3. Advancing Lunar Volatile Capture Technology – The mechanical tests will be repeated for the two lunar regolith simulant types and degree of melting performed in vacuum. Comparisons between strengths and melt states and compositions will be published after project completion. The expected strengths of the rock cylinders are in the 2 – 20 MPa range, depending on degree of melting.

The MI print head will be modified to bring the HPRC device from a TRL of ~3 to ~4. A series of vacuum valves to isolate internal pressures due to volatile release from the heated regolith will be incorporated into the MI print head. The integration of pressure valves on the print head will be tested using a pressure gauge and pumping the crucible to <100 mT. Future maturation of the HPRC proposed in the next NASA ROSES call will lead to a brass-board level cold trap and gas feedline attached to the MI print head enclosed in a cryo-cooled high-vacuum chamber at SwRI. Considerations will be made with regard to valve seal temperature rating, the flow of regolith through a seal, the potential corrosive nature of H_2S gas, and the range of expected pressures.

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