Innovating Lunar ISRU Technologies for Long-Term Exploration and Habitation. A. D. Whizin[1], P. Metzger[2], C. Dreyer[3], C. Phillips-Lander[1], C. Asquith[1], R. Focia[1], and K. Retherford[1]. [1]Southwest Research Institute (6220 Culebra Rd., San Antonio, TX, 78238), [2]University of Central Florida, [3]Colorado School of Mines. (author contact: awhizin@swri.edu)

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 construciton (AC) 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. AC could revolutionize the robotic construction of lunar bases (see Figure 1), create landing pads, roads, and other structures to increase mobility, accessibility, and enable exploration of caves and other potentially useful or resource rich sites on the lunar surface. This project involves studying MI AC of lunar soils by making regolith products 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 Resources – It is now known that 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 [1, 2]. Water has been detected in the LCROSS impact-induced plume in Cabeus crater [3, 4, 5, 6], and over much of the lunar surface at levels of hundreds of ppm [7, 8, 9]. The lunar regolith, comprised of iron- and titanium-bearing silicates [10], is highly valuable as a construction material for building habitats, roads, berms, walls, and other support structures, including astronaut habitats, which could be built in or in close association with cave-like features which offer stable temperatures of ~-13ºC at Tranquililitatis pit [11].

Figure 1: Concept of Autonomous AM on the Moon.

Lunar Geologic Features – There is a great deal of speculation about the possibility of lunar caves, pit craters, and exposed bedrock providing not only valuable resource deposits, but scientific insight into the geologic past of the Moon, including volatile budgets and transport, the timing of magmatic events, faulting, weathering, and the relationship to between the transition from regolith to bedrock [11].

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 ([12, 13, 14, 15, 16, 17, 18]; and many references therein). MI heating and sintering has never been applied to additive manufacturing of lunar regolith and has the potential to address some of the shortfalls of the other methods. 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: A steel crucible containing lunar regolith simulant heated to 1500ºC.

MI heating and sintering works by applying an alternating current 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. MI printing is fast, simple, can function in a vacuum, and low-cost, and potentially a game-changing technology for lunar base-construction.

Different types of induction sintering are possible with this methodology. Our goal is to apply it in three ways to the building and paving on the lunar surface: 1) 3D printing through extrusion, 2) brick making, and 3) contact-less sintering/paving of the surface.

Experimental Approach: The basic operating procedures and thermal responses to lunar regolith are being characterized by placing regolith into a crucible that is surrounded by copper tubing (Figure 2). As a controlled A/C 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 induction prototype shown in Figure 3).

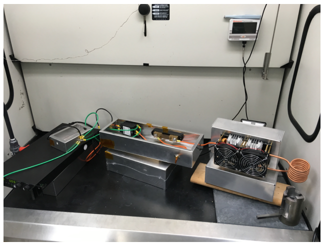
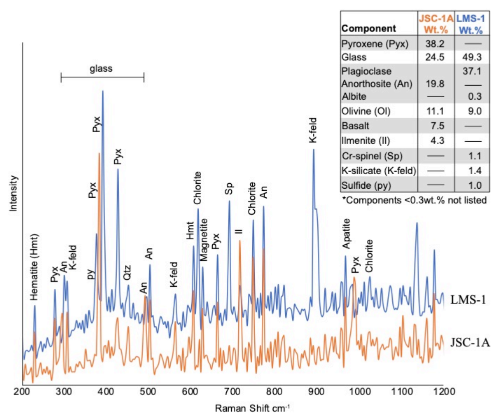


Figure 3: Breadboard level prototyping of the 30-amp magnetic induction heating circuit.

Advancing Lunar Volatile Capture Technology – The magnetic induction printing technology is also able to incorporate volatile capture of released gases from the heating of the soil. We are working to study the integration of this advantageous ISRU technology. Based on the types and abundances seen in remote sensing and in the LCROSS impact, there appears to be a strong case for implementing this type of gaseous volatile capture.



Component	JSC-1A Wt.%	LMS-1 Wt.%
Pyroxene (Pyx)	38.2	—
Glass	24.5	49.3
Plagioclase		37.1
Anorthosite (An)	19.8	—
Albite	—	0.3
Olivine (Ol)	11.1	9.0
Basalt	7.5	—
Ilmenite (Il)	4.3	—
Cr-spinel (Sp)	—	1.1
K-silicate (K-feld)	—	1.4
Sulfide (py)	—	1.0

*Components <0.3wt.% not listed

Figure 4: Raman spectra of lunar regolith simulants.

Raman Characterization of Lunar Simulants – We are using a novel cavity raman spectroscopy technique to study the compositions and mineralogy of various lunar simulants we plan to use in the MI printing (Figure 4). By analyzing the differences in composition coupled with the result form the sintering tests, we can better understand which types of regolith are better suited for induction sintering, and better tailor the induction system to handle unknown regolith materials that a rover may encounter while construction an outpost on the Moon.

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