CHARACTERIZING ELECTROMAGNETIC COUPLING WITH LUNAR REGOLITH AND SIMULANTS FOR WIRELESS POWER TRANSFER ON THE LUNAR SURFACE.

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Introduction: Wireless power transfer (WPT) using magnetically coupled resonators (MCR) is being integrated into space vehicles destined for the lunar surface. Recent research into the coupling of electromagnetic (EM) fields with lunar regolith has revealed the importance of metallic iron content and iron particle size in the simulants used. In this work we present experimental results from laboratory testing of a 6.78 MHz MCR-based WPT system in the presence of various standard lunar simulant samples, iron powders, and a custom iron-enriched lunar simulant. Results show that coupling between the 6.78 MHz power transfer field and simulants is related to the particle size of metallic iron in the samples. Results also suggest new opportunities for research into lunar regolith's electromagnetic properties at WPT frequencies, as well as development of simulants which more accurately represent the nanophase iron present in lunar regolith.

Research and Findings: Currently, MCR-based WPT technology is being integrated into space vehicles, such as lunar landers and rovers, where the ability for rovers to charge wirelessly is an important component of lunar surface power infrastructure and dust mitigation [1-3]. To enable wireless charging on the lunar surface, it is important to characterize the EM properties of lunar regolith, specifically at the 6.78 MHz magnetic resonance field frequency. Lunar regolith is known to contain iron in the form of oxides (Fe_xO_y) and metallic iron (Fe^0). While existing terrestrial feedstocks for lunar simulants contain iron oxide, they lack metallic iron. To investigate interactions between the WPT field and metallic iron, we selected pure iron powders at two particle sizes (150μm and 45μm) and also collaborated with Off Planet Research (OPR) to create a custom simulant enriched with 25nm iron, OPRL2NS.

The experimental setup includes a commercially available MCR-based wireless charger which transmits approximately 90 W wirelessly from a 6.78 MHz transmitter (TX) to a receiver (RX) connected to a battery load [4]. Simulant test samples are placed in the power transfer field, adjacent to the TX and RX antenna coils. Samples include four standard lunar simulants (LHS-1, LHS-1D, JSC-1A, and OPRH4W30), as well as the iron-enriched simulant (OPRL2NS) plus two iron powders (FE100 and FE325). Key performance parameters, including wireless power transfer efficiency and resonant frequency, are measured with each sample in place. Results are summarized in Table 1.

Table 1. WPT Performance with Simulants and Iron Powder.

Sample Material (Mass)	WPT Norm. Efficiency η	Frequency Shift (kHz) Δf	Frequency Shift (%) $\lvert\Delta f/f_0\rvert$
LHS-1 (1kg)	0.967	0	0.00
LHS-1D (1kg)	0.967	0	0.00
JSC-1A (350g)	0.967	0	0.00
OPRH4W30 (500g)	0.967	0	0.00
OPRL2NS (400g)	0.965	-14	0.21
FE325 (40g)	0.957	-14	0.21
FE100 (40g)	0.953	-14	0.21
FE325 (80g)	0.951	-28	0.42
FE100 (80g)	0.928	-42	0.63
FE325 (160g)	0.923	-	-
FE100 (160g)	0.918	-	-

Results show negligible effects from the standard lunar simulants, even though these contain iron in the form of iron oxide. However, the presence of the iron-enriched simulant and iron powders causes progressively impacted performance, particularly as the mass of metallic iron increases. Iron oxides have much lower magnetic susceptibility compared to metallic iron, which helps explain these results. Furthermore, the 150μm particle size iron shows a larger degree of coupling than the 45μm particle size iron, as indicated by the decreased power transfer efficiency. Particle size is shown to play a critical role in coupling in this study.

Iron Content of Lunar Regolith and Simulants: Analysis of 79 samples returned during NASA's Apollo missions show lunar regolith contains iron in the form of iron oxide (FeO) and nanophase metallic iron (Fe^0) [5]. Reported values from these lunar soil samples show FeO content ranges from 4.2 wt.% up to 22.0 wt.%, and Fe^0 content ranges from 0.1 wt.% up to 2.0 wt.%. OPR has developed a line of lunar regolith simulants with an increased magnetic response for clients with specialized research, such as magnetic beneficiation to aid extraction of metals for ISRU efforts [6]. The custom OPRL2NS simulant is designed for use with the WPT setup described above and has a total iron content of 20.0 wt.%. The iron content includes both the iron oxide already present in the feedstock materials plus 25nm metallic iron particles added to the feedstocks. Figure 1 shows scanning electron microscopy (SEM) images of OPRL2NS after a focused ion beam (FIB) cut is made to provide a section view of the grain. Energy-dispersive spectroscopy (EDS) analysis shows the 25nm iron particles in purple, highlighting the distribution of the iron nanoparticles across the base feedstock grain. The iron nanoparticles appear to be distributed broadly. However, some clumping does occur, and the coating of iron nanoparticles is less contiguous than the rim of nanophase iron reported for regolith previously [6, 7].

EM Properties of Lunar Regolith Across Frequency: While it is well-established for many materials that EM properties such as relative dielectric permittivity (ε_r) and relative magnetic permeability (μ_r) vary over frequency, scant data exist in the literature for lunar regolith's EM constitutive parameters below microwave frequencies. Published data on the EM properties of lunar regolith include recent *in situ* ground penetrating radar (GPR) measurements from the Chang'E-3 and Chang'E-4 lunar landing sites at 60 MHz and 450 MHz [8-10], as well as previous laboratory measurements of Apollo samples reported at 2 GHz [11] and 3.5 GHz [12]. Data for lunar simulants is reported at various frequencies and indicate field attenuation constants at levels an order of magnitude below those of actual regolith [3].

Conclusions and Future Work: Results reported here demonstrate that iron content and its particle size play an important role in the EM coupling between a MCR-based WPT field and lunar regolith. As additional wireless and EM technologies are launched to the lunar surface, additional data on lunar regolith's EM properties across frequency is needed in order to develop accurate models of EM coupling and other field interactions. Furthermore, given the limited accessibility of Apollo samples, additional development of iron-enriched lunar simulants would be valuable for lab-based experiments and investigations into EM field interactions with lunar regolith. Particle shape and distribution of the metallic iron particles is an additional consideration which should be investigated further. Future research in this area would benefit the broader lunar and planetary research community.

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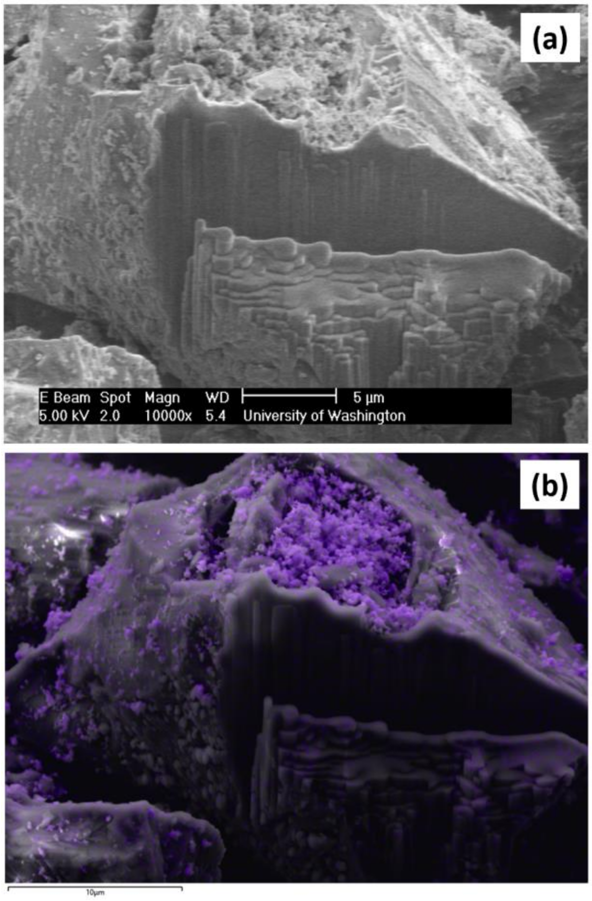

Figure 1. Images of Iron-Enriched Simulant OPRL2NS. (a) SEM image with FIB cut shows broad distribution of 25nm iron particles across feedstock grain. (b) EDS image shows iron nanoparticles in purple. Some clumping is observed.

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