MOON TO MARS OXYGEN AND STEEL TECHNOLOGY UPDATE. M. Berggren, R. Zubrin, M. Riley, and S. Carrera, Pioneer Astronautics, 11111 W. 8th Ave, Unit A; Lakewood, CO 80215; mberggren@pioneerastro.com; rzubrin@pioneerastro.com; mriley@pioneerastro.com; scarrrera@pioneerastro.com

Introduction: Moon to Mars Oxygen and Steel Technology (MMOST) is an integrated system for co-production of metallic iron and oxygen from lunar regolith, thereby providing a strong support for the exploration and development of the Moon. The MMOST has extensive heritage, utilizing technology developed and demonstrated by Pioneer Astronautics during a NASA SBIR Phase II program titled "Extraterrestrial Metals Processing" while leveraging supporting technologies established during other previous Pioneer NASA SBIR programs. Relevant previous work at Pioneer includes the "Lunar Soil Particle Separator" for beneficiation and the "Lunar Materials Handling System" for automation and repetitive operations using hydrogen reduction as a demonstration platform.

The MMOST employs physical particle size sorting, magnetic and electrostatic regolith beneficiation, automated materials handling, hydrogen reduction, and melt-refining to produce metallic iron and oxygen products. As a baseline approach, the metallic iron is alloyed as required and then formed into wire for additive manufacturing via robotic vacuum arc deposition. Pioneer Astronautics has partnered with Colorado School of Mines (Mines) to provide the breadth and depth of expertise and facilities to demonstrate production of metal articles derived from lunar regolith simulant.

The best lunar sites for MMOST include those with naturally high ilmenite or FeO concentrations. Beneficiation to further enrich the overall iron oxide concentration of the regolith boosts the efficiency of hydrogen reduction and subsequent melt refining. By minimizing the amount of non-reducible impurities, the iron oxide reduction and melt refining hardware is much smaller and requires less energy. In addition, iron enrichment facilitates the coalescence and subsequent separation of molten metal from oxide slag impurities. The targeted degree of beneficiation is based on the achievable grade and recovery of high-FeO mineral grains with consideration of excavation requirements, beneficiation hardware requirements, reduction/melt refining hardware volume/mass, and energy/power input.

The scale of the MMOST demonstration hardware is based on production of 1 kg per day of oxygen with co-production of iron at a rate of 3.5 kg per day. Beneficiation, iron oxide reduction, and melt refining are being carried out at the design rate. A 10x scaled up design will be prepared using the MMOST operation results.

A subset of the technology targets demonstration of a prototype flight experiment including beneficiation, iron oxide reduction, and electrolysis for oxygen production. These integrated technologies are referred to as the Lunar OXygen In-situ Experiment (LOXIE) designed for a rate of about 20 grams per hour of oxygen with cumulative production of 1 kilogram of oxygen during a single lunar day. The LOXIE is designed around a concept in which flight test hardware, including a rover/excavator/prospector, would be delivered to the surface of the Moon aboard a Commercial Lunar Payload Services (CLPS) lander. The process hardware would remain on board the lander while the excavator identifies and retrieves appropriate feed regolith. A successful demonstration would set the stage for lunar implementation of oxygen production followed by further integration for iron and steel production to support human space exploration.

Work is baselined on a simulant mixture containing magnetic agglutinates, basalt (similar to JSC-1A), and ilmenite. However, mineral separations using Earth analog minerals are also being evaluated to expand the potential range of feeds and site locations suitable for MMOST/LOXIE.

The MMOST/LOXIE hardware is being assembled for testing and demonstration in vacuum to boost the Technology Readiness Level (TRL) as a key step toward a flight experiment. At the conclusion of the two-year NASA SBIR Phase II Sequential program, the MMOST/LOXIE hardware will be delivered to NASA, allowing further testing to continue.

Description: Beneficiation is the first step in processing lunar soil after excavation. Excavated soil is passed over a grizzly screen to remove the coarsest rocks before loading a feed hopper. Regolith is metered from the hopper to the initial separation step, which includes a device to disperse the regolith across the width of a separation ramp while rejecting particles larger than desired for eventual iron oxide reduction. The dispersed particles are fed to a high-strength permanent magnet drum separator to remove magnetic agglutinates as well as a significant fraction of fine basalt. Because the basalt exhibits slightly greater magnetic susceptibility compared to ilmenite, this step also provides some ilmenite beneficiation (as might be expected from properties of related lunar minerals). Remaining regolith cascades to a vibrating, slotted ramp that exploits differences in friction across an engineered surface as a function of particle size to selectively remove dust and fine particles. The slotted ramp avoids sieve blinding that typically occurs as near-size particles gradually become trapped in a screen mesh. The final product from the integrated slotted ramp separator is regolith from which the finest particles have mostly been removed. Because adhesion forces between particles smaller than about 75 microns (200 mesh) are strong, removal of the finest particles facilitates further beneficiation (and also facilitates handling during subsequent iron oxide reduction).

Additional beneficiation of the sized regolith is conducted using electrostatic separation to concentrate ilmenite or high-FeO particles based on differences in mineral particle conductivity and their relative capability to develop surface charges. After a pre-charging step, particles are fed to a separation unit in which charged plates (powered at low current at up to plus or minus 30 kV) selectively attract mineral particles. The degree of upgrading targeted in this step is based on evaluation of the benefits of obtaining higher grade (with lower recovery) versus higher recovery (with lower grade) and the implications on overall system mass, volume, and power.

The beneficiated regolith is next fed to an iron oxide reduction step. Reduction using hydrogen produces water, which is fed to electrolysis for production of oxygen product and hydrogen for recycle. The MMOST/LOXIE reactor is based on a down-flow, fixed-bed design into which a periodic back-pulsing system has been integrated to mix the regolith to aid heat transfer and to break up channels. Internal and reactor shell heaters provide up to 950°C surface temperatures. The reactor design and thermal controls enable the use of a single, stationary, high-temperature elastomer seal. Reduced residue is discharged by inverting the entire reactor assembly (including a heat exchanger, contaminant trap, back-pulse tank, and hydrogen preheater). The MMOST/LOXIE iron oxide reduction module is built within a one-cubic meter frame to facilitate vacuum chamber testing. Automated motion controls via linear and rotary electromechanical actuators provide installation of a seal protection sleeve for reactor filling and discharging, reactor sealing, and inversion for discharge of product. Extensive instrumentation and controls facilitate automation of the process.

An electrolysis system is integrated into the LOXIE iron oxide reduction design. The operations of the iron oxide reduction and electrolysis sytems are coordinated to spread electrolysis energy over the batch reduction cycle while minimizing requirements for hydrogen gas storage.

Hot reduced regolith is transferred to a melt refining step to coalesce and separate metallic iron from oxide slag components. Metal recovered from this step is alloyed as required and poured into a mold to create a rod. The rod is then drawn into wire for additive manufacturing. Induction furnaces are being used for the melt refining and the rod formation steps. Metal products are being provided to Colorado School of Mines for robotic arc-deposition trials.

Status: The MMOST/LOXIE beneficiation hardware continues to be refined to identify the best operating parameters for a range of iron oxide grade and recovery from feed simulant. Beneficiated regolith representing a range of potential feeds for reduction has been subjected to laboratory experiments to guide the selection of larger-scale hydrogen reduction operating conditions. The beneficiation and reduction-electrolysis modules including automated motion controls are being tested in preparation for vacuum chamber demonstration. Reduced residue is being subjected to melt refining for preparation of rods as feed to wire drawing and additive manufacturing. Preliminary evaluation of metal properties and their condition of use are being conducted to establish requirements for alloying agents required for specific applications on the Moon.

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