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Extraction and Processing

HIGH-TEST PEROXIDE PRODUCTION SYSTEM FOR IN-SITU PROPELLANT MANUFACTURE FROM EXTRATERRESTRIALLY MINED WATER

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The need for in-situ propellant production: Systems which can produce propellant on the surface of the Moon or an asteroid will be integral to the development of the space economy. This fact is evidenced by the increasing number of companies developing technologies for in-situ resource utilization, and by NASA's focus on establishing a permanent presence on the Moon. Extraterrestrial propellant production will enable exploration throughout the solar system at a lower cost.

In order to facilitate ISRU propellant use, propellants that can be produced from readily available in-situ resources must be identified. Storability and high impulse density are both key characteristics of the ideal in-situ propellant.

High-test peroxide for ISRU: High-test peroxide (HTP) has been identified as a propellant that shows promise for interplanetary and small-body exploration [1]. Hydrogen peroxide is nontoxic and requires only hydrogen and oxygen to produce, both of which can be collected from lunar ice. Unlike hydrolox, the cryogenic bipropellant of hydrogen and oxygen, it is easy to store. The specific impulse for 98% HTP monopropellant is approximately 192 s and HTP is a high density-specific impulse fuel, at 17140 lbf-s/ft^3 [2]. For comparison hydrazine, which cannot be made from lunar resources, has a slightly higher specific impulse of 245 s, but a lower density-specific impulse of 15295 lbf-s/ft^3 [3, 4]. Because HTP is storable, can be manufactured from commonly available hydrogen and oxygen, and has a high density-specific impulse, HTP is one of the best candidate propellants for in-situ production on the Moon in the near future.

In-situ HTP production methods: Most peroxide today is produced using the anthraquinone process [5], in which 2-alkyl-9,10-anthraquinones react with hydrogen in the presence of a catalyst such as palladium or Raney nickel, producing hydroquinones. The hydroquinones are oxidized, producing quinones and hydrogen peroxide. This peroxide is concentrated into HTP by fractional distillation or fractional crystallization [6]. Because the anthraquinone process requires many intermediate steps and additives it is a process not well suited for adaptation to ISRU. A new approach is needed if HTP is to be produced from mined lunar water.

An ideal ISRU solution should take inputs of only water and energy, and produce HTP with little to no waste. If it is to be deployed in a location off Earth, the system must be small-form factor in order to reduce costs.

A more compact alternative to the anthraquinone mehod is a proton-exchange membrane (PEM) fuel cell. The reactions occurring within a hydrogen peroxide PEM cell are as follows in Equations 1–3.

Cathode oxygen reduction reaction:

$$H_2 \rightarrow 2H^+ + 2e^- \#(1)$$

Anode hydrogen oxidation reaction:

$$O_2 + H_2O + 2e^- \rightarrow HO_2{}^- + OH^- \#(2)$$

Overal PEM cell reaction:

$$HO_2{}^- + H^+ \rightarrow H_2O_2 \#(3)$$

In order to facilitate ion exchange most PEM cells require the water passing through to be conductive, which may be accomplished by the addition of an electrolyte. The electrolyte must be added to incoming water and removed from the peroxide product. Due to the added complexity, such a process is not ideal for in-situ peroxide production.

The Wang Group at Rice University have developed a solid electrolyte PEM cell that does not require an electrolyte to be added to the input water, instead using a stationary solid electrolyte matrix for ion conduction [7]. A simplified schematic of this PEM cell is compared to a conventional fuel cell in Figure 1.

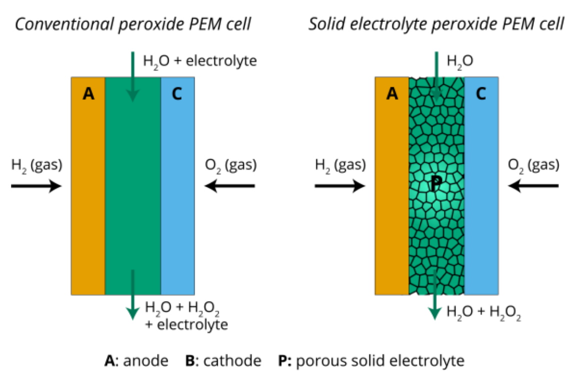

Figure 1: Comparison of conventional electrolyte and porous solid electrolyte hydrogen peroxide PEM cell shows improved configuration of solid electrolyte cell

The Wang Group PEM cell, which is licensed to Orbit Fab, can produce peroxide in concentrations up to 20%, from inputs of water, oxygen, and hydrogen. The peroxide from the PEM cell output is concentrated into 90–98% HTP. There are several feasible concentration methods for peroxide, such as membrane concentration and fractional distillation. Future work will report detailed analysis of the available concentration methods.

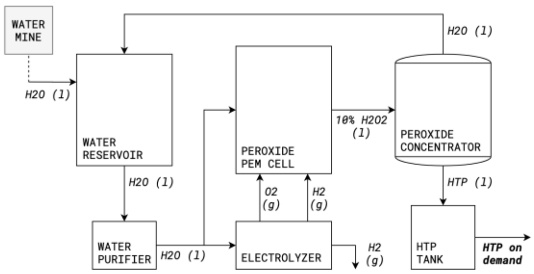

Figure 2: Notional block diagram showing PEM cell and peroxide concentrator integrated into compact water-to-HTP system

The HTP production system: The PEM cell and concentrator are integrated into a system as shown in Figure 2. This system includes water and HTP tanks, a water purifier, and an electrolyzer which provides the hydrogen and oxygen gas to the PEM cell. Excess hydrogen is created, which may be vented or stored for use elsewhere. This self contained system requires only water and energy as inputs, and produces HTP on demand.

This HTP production system is currently at TRL 3, and could be raised to TRL 6 in a one-year development program. Subcomponents have been developed individually, such as the Wang Group PEM cell (Figure 3), and will be integrated into a compact self contained system by Orbit Fab.

Not only can the system operate autonomously on the surface of a moon or asteroid, it also functions in microgravity. PEM cells have been operated in microgravity on orbit and both concentration methods mentioned are microgravity compatible [8].

The cell can produce 130 L of 1% peroxide per hour per square meter of membrane, meaning that only a 0.69 m^2 is needed to produce 1 L/hr of 90% HTP.

Conclusion: HTP is a promising propellant for in-situ production for upcoming lunar missions due to its storability, low toxicity, and ability to be produced from the readily available elements hydrogen and oxygen. However, no system yet exists to produce HTP from the water harvested on the Moon or an asteroid. Popular hydrogen peroxide generation methods are unsuitable for a compact extraterrestrial HTP production system, but the solid electrolyte PEM cell developed by the Wang Group enables a much more compact system. Orbit Fab is building a full HTP production system by integrating this PEM cell with a peroxide concentrator, water purifier, and electrolyzer. The system is currently at TRL 3 and could be developed and flown by 2023. The deployment of the Orbit Fab HTP system enables increased mobility for spacecraft operators, lowers costs, and catalyzes development of the extraterrestrial mining and exploration economy.

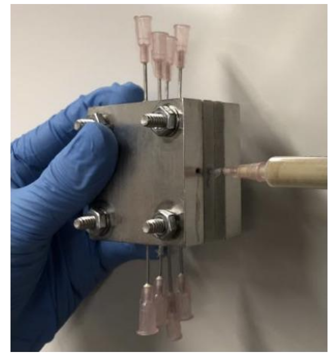

Figure 3: Prototype solid electrolyte PEM cell developed by the Wang Group at Rice University

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LUNAR AUGER DRYER ISRU (LADI) BREADBOARD TESTING AND MODEL VALIDATION.

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In 2009, the Lunar Reconnaissance Orbiter (LRO) and Lunar Crater Observation and Sensing Satellite (LCROSS) provided definitive proof of water in the Lunar's southern permanently shadowed region (PSR)[1]. Both the 2020 NASA Technology Taxonomy[2] and the Lunar Surface Innovation Initiative (LSII) team identified capability gaps in icy regolith transfer and reactor processing in Permanently Shadowed Region (PSR) environmental conditions. A screw conveyor dryer system operating from inside the PSR can continuously process water (and volatiles) for both breathable air and propellant. NASA's Johnson Space Center (JSC) began development of a similar subsystem for Mars operation in 2017 and fabricated a unique breadboard test stand for validating the feasibility of this concept. This testing was postponed with the redirection of NASA's mission from Mars to Moon. A JSC led trade study[3] in FY20 formulated a plan to leverage existing hardware to test concept feasibility, developed a lunar auger dryer sizing tool, and identified that both a physical flow and thermal model is required to develop an Engineering Development Unit (EDU) for environmental testing. Beginning in FY21, the Game Changing Development Program (GCDP) funded a three-year technology development project to increase the Technology Readiness Level (TRL) of the Lunar Auger Dryer ISRU (LADI) subsystem to TRL 5.

The major subsystems of a lunar water processing plant include the upstream Excavation rover and Hopper/Size-sorter subsystems, the Screw Conveyor Dryer (SCD), and a downstream Cold trap subsystem used to de-sublimate water vapor to ice. The top-level concept of operations begins with the excavator digging up icy regolith and delivering it to a stationary ISRU processing plant (inside PSR), size sorting the feed to remove large rocks, and then discharging into a hopper. The hopper feeds the regolith to an auger-dryer (LADI) which extracts water from the soil and then sends it to a cold trap subsystem. The dried regolith is collected, dumped (potentially processed for waste heat), and the excavator repeats the process. The cold trap de-sublimates the vapor into ice, removes impurities, and then stores the product on a tanker. This tanker will either travel out of the PSR to a stationary electrolyzing processing plant located on the crater ridge or the tank will be pressurized and liquid water pumped to the plant via flex hose. At the crater ridge, the water is cleaned, electrolyzed into oxygen and hydrogen, liquefied, and finally stored.

The key design features of the auger dryer design is operating below the triple point of water and using a variable pitch auger to create a 100% full regolith plug-seal at the inlet and outlet of the auger but spread out and mix the regolith in the 15% full heated section as shown in Figure 1.

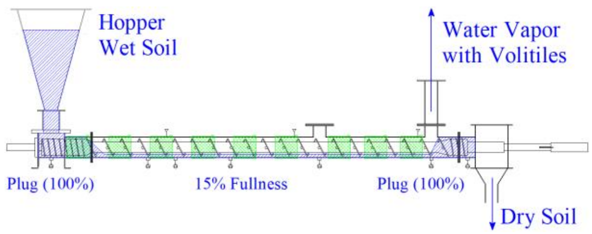

Figure 1 – Breadboard Auger Dryer with heaters (green) and 100% full inlet/outlet plug soil seal (blue)

These features maintain low internal pressure (easier to sustain regolith plug), prevent liquid water from forming (alters torque required from motor and allows equilibrium chemistry with impurities), and eliminate the need for isolation valves. Isolation valves significantly increase system height, mass, complexity, and reduces reliability.

The TRL 3 breadboard auger dryer, shown in Figure 2, will be tested in a laboratory environment using Exolith Lab's Lunar Highlands Simulant (LHS-1). The breadboard test stand has the unique capability to operate with either a clear or stainless steel casing.

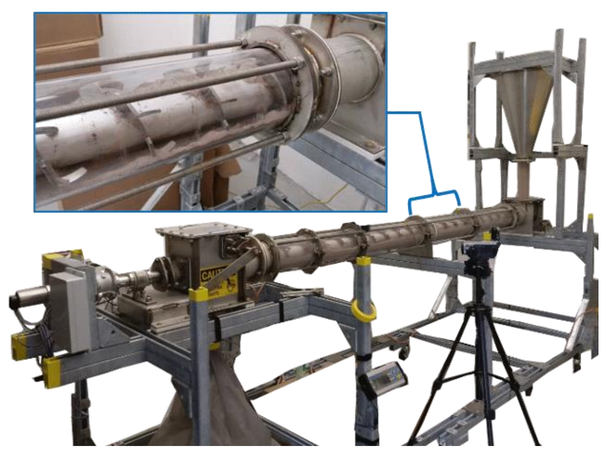

Figure 2 – Existing Mars Screw Conveyer Dryer Breadboard System (clear casing installed)

Mechanical testing at 100% and 50% production rates will be performed using the clear casing. This allows flow to be observed while measuring torque, RPM, mass flow rate, and power. The max regolith seal pressure will be determined and high-density cryogenic blasting dry ice will be mixed with the lunar simulant to observe sublimation at room temperature.

Thermal testing requires the stainless steel casing and resistance band heaters. These heaters can be reconfigured into either a long or short configuration as shown in Figure 3 and operate with three independent zones to manipulate the residence time.

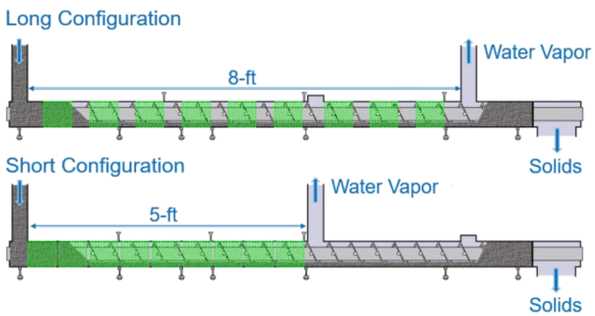

Figure 3 – Alternate Heater Configurations

The simulant will be prepared with a 5% to 8.5% water ice (weight %) mixture and heated until vaporization. A Commercial Off-The-Shelf (COTS) condenser will be used to liquefy the vapor and calculate the yield. The laboratory test data will be analyzed and compared with both a thermal and physics based model.

A Thermal Desktop thermal model will predict the residence time to sublimate ice, verify the feasibility of operation below the triple point of water (by estimating temperature and sublimated water's partial pressure), and predict heat transfer between bulk particle motion and the heated casing. This model will be run at both laboratory and lunar environmental conditions for a pilot plant and full-scale plant scenario. The preliminary Thermal Desktop model is shown in Figure 4 (without heaters and insulation).

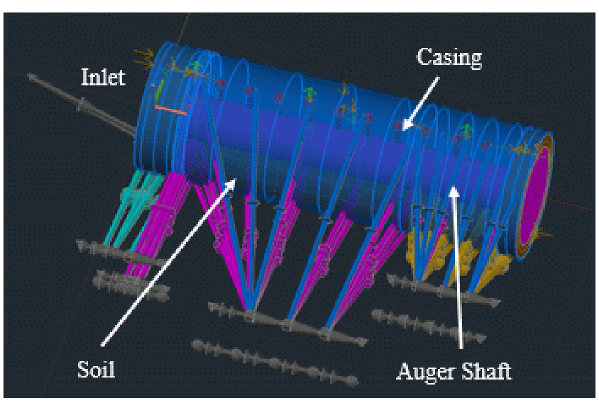

Figure 4 – Thermal Desktop Model

The paths are set to ice, ice/vapor, or liquid/vapor based on the temperature of the sub-models.

A Discrete Element Method (DEM) simulation will compare test observations performed with the clear casing with particle-scale numerical modeling. Figure 5 demonstrates the (as-built) breadboard test stand geometry and a 4-sphere tetrahedral cluster (not to scale).

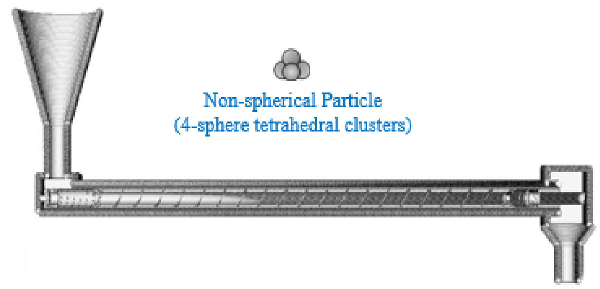

Figure 5 – DEM Model Geometry

The cluster adds fidelity by simulating a non-spherical particle while cohesion, particle size, and particle count will be varied until the model mimics the test results. After the model is validated, optimizations to the regolith plug seal, auger flight geometry, and flow rate can be performed. Moreover, the gravity can be reduced to lunar conditions to predict lunar performance.

The modelling, testing, and analysis performed in FY21 will be used to design an EDU for future environmental testing in JSC's 15-foot thermal vacuum chamber. The knowledge obtained on this project can be used as a stepping stone to develop a future Mars auger dryer (combined with a Sabatier reactor) to produce oxygen and methane.

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Beneficiation of Lunar Regolith: Progress and Challenges.

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Introduction: Many chemical processes have been proposed to extract oxygen from lunar regolith, such as hydrogen reduction and molten salt electrolysis. Once in operation, these ISRU reactors will require feedstock with very specific chemical properties and physical characteristics to produce oxygen reliably and efficiently. This may require controlling the feedstock particle size into a narrow range by removing coarse and fine particles from the mined regolith, concentrating specific minerals, or rejecting valueless particle types.

These physical processing stages, *beneficiation*, lies between the mine and the chemical reactor. Beneficiation reduces the effects of feedstock variability on downstream operations and improves the operation of reactors treating naturally variable materials.

The challenges of handling and manipulating lunar regolith in situ are numerous. For example, on Earth, separating mineral particles by size at 50 microns without water is challenging. On the Moon, the environmental conditions and particle characteristics increase significantly the complexity of this simple processing requirement.

At Imperial College London, we are designing lunar regolith beneficiation methods by combining our terrestrial mineral processing expertise with the specific needs and restrictions of ISRU. We are focussing on fluid-free separation of regolith particles by size, and exploiting the differences in electrostatic properties of mineral types in the lunar environment.

Examples of research projects are:

- Measurement of particle saturation charges under terrestrial and lunar conditions
- Design of tribo-chargers for electrostatic separators
- Novel vibratory particle size classification systems
- Modelling of charged particle transport in dynamic electric fields.

The research presented in this talk will showcase the progress being made in the beneficiation of lunar regolith, but will also highlight the gaps in knowledge that must be addressed in order to constrain further this often overlooked stage of the ISRU value chain.

MOON TO MARS OXYGEN AND STEEL TECHNOLOGY. M. Berggren and R. Zubrin, Pioneer Astronautics, 11111 W. 8th Ave, Unit A; Lakewood, CO 80215; mberggren@pioneerastro.com; zubrin@aol.com

Introduction: Moon to Mars Oxygen and Steel Technology (MMOST) is an integrated system that can enable the production of metallic iron or steel as well as 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 motion controls and production of metallic iron via hydrogen reduction.

The MMOST employs physical particle size sorting, electromagnetic regolith beneficiation, materials handling, hydrogen reduction, electrolysis, and melt-refining to produce metallic iron and oxygen products. The best lunar MMOST sites include those with naturally high ilmenite or FeO concentration. However, beneficiation to further enrich the overall iron oxide concentration of the regolith is important to enable efficient hydrogen reduction and subsequent melt refining. By minimizing the amount of impurities, the iron oxide reduction and melt refining hardware is much smaller and requires less energy. In addition, iron enrichment facilitates the coalescence and separation of molten metal from oxide slag impurities. Concentrations of up to 70 percent ilmenite with total FeO grade of 30 to 40 percent to iron oxide reduction are targeted for MMOST beneficiation of lunar regolith.

Iron produced from beneficiated regolith can be used as-is or can be alloyed to manufacture steel components in support of human exploration and commercial development using additive manufacturing, machining, or casting technologies. The proposed full-scale MMOST will produce about 35 kilograms per day of iron while co-producing 10 kg per day of oxygen.

Pioneer Astronautics has partnered with Colorado School of Mines (Mines) and Honeybee Robotics to provide the breadth and depth of expertise and facilities to demonstrate MMOST. Mines will evaluate additive manufacturing methods to fabricate test articles from metal generated from reduced lunar regolith simulant. Following development and extensive component testing of the lunar manufacturing and *in-situ* resource utilization hardware by the Pioneer/Mines team in Colorado, the MMOST will be demonstrated as an integrated system in Honeybee Robotics vacuum chamber, bringing the technology to TRL6. At the conclusion of the two-year NASA SBIR Phase II Sequential program, the MMOST hardware will be delivered to NASA, allowing further testing in conjunction with other technologies to continue.

Description: Although the MMOST is centered on manufacturing to produce metallic components, oxygen is an important co-product. The proposed system complements in-situ resource utilization (ISRU) activities directed toward lunar polar ice by providing an alternative lunar oxygen source (regolith) that is available over nearly the entire lunar surface. The MMOST therefore provides key habitat and infrastructure capabilities for human exploration over vast areas of the Moon. Furthermore, the MMOST iron/steel production technology demonstrated on the Moon will be fully extensible to Mars, where its capability for enabling the production of spare parts will be even more valuable.

The MMOST system produces a metallic iron or steel product and demonstrates key unit operations that will be critical for future *in-situ* resource utilization (ISRU) supporting exploration and development of the Moon and Mars. Designed as a modular system, the MMOST is capable of phased implementation, allowing independent operation of the upstream regolith preparation and reduction followed by independent melt refining and metals component manufacturing. By decoupling reduction and melt operations in this way, the MMOST power budget can be optimized. The proposed end-to-end MMOST demonstration unit will operate at a rate of production of 12.6 metric tons of iron and 3.6 metric tons of oxygen annually, which is a relevant scale for Artemis program human exploration mission requirements.

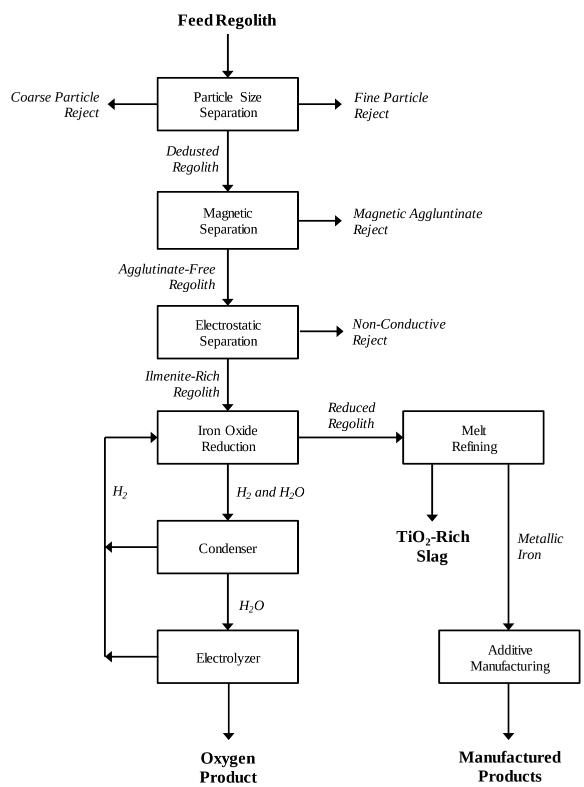
The target metallic iron/steel production rate would initially support additive manufacturing methods for production of replacement parts, piping, tools, and habitat components. As manufacturing capabilities are further developed for larger-scale items, the production of solar thermal power systems, propellant tanks, and even habitation modules could be enabled. The co-produced oxygen would have use for life support, fuel cell powered vehicles, and ascent vehicle propellant. The MMOST scale is relevant to lunar mission operations in that the 3.6 metric tons per year of oxygen produced by a single module would be capable of supporting the equivalent of two annual missions having oxidizer requirements for a vehicle similar to the Apollo Lunar Module for ascent from the lunar surface to lunar orbit. Alternatively, based on current projections, this could supply the oxygen for roughly one ascent vehicle return from the surface to lunar Gateway orbit annually.

Approach: The Phase II Sequential MMOST technology is being developed initially at a scale of about 3.5 kg/day iron (1 kg/day oxygen). This subscale unit will provide the data to finalize the design of the full-scale 35 kg/day iron (10 kg/day oxygen) unit. Each key unit operation is being developed independently and in parallel to support full-scale hardware design. Materials handling and transfer requirements are being established through significant hands-on experiments to determine motion controls and automation requirements for the larger system. The full-scale system will then be designed, built, and tested as separate modules in vacuum chambers at Pioneer Astronautics and Mines. The final product from the proposed Moon to Mars Oxygen and Steel Technology system will be a remotely operated, automated demonstration system along with a design and work plan from which a flight-ready system can be developed. Following unit operations testing and optimization at Pioneer and Mines, the full-scale MMOST demonstration system will be shipped to Honeybee Robotics for operation as an integrated system in vacuum. The hardware will then be delivered to NASA for further testing and evaluation.

The MMOST experimental system will be automated and remotely operated, facilitating vacuum chamber demonstrations. In addition, the MMOST design will be based on operation using expected regolith compositions at FeO-enriched mare-type basalt outcrop sites that may be found near the lunar south pole (within driving range of potential Artemis mission sites) as well as ilmenite-rich deposits which are known to exist in lower-latitude mare regions and may potentially be found in mare-type outcrops near the south pole as well. Simulants for the proposed effort were selected to match lunar regolith physical and chemical characteristics to the maximum extent possible during development. Important parameters for MMOST simulants include particle size distribution, particle shape, mineral composition, space weathering effects, and expected iron oxide concentrations (whether as ilmenite-rich or FeO-rich basaltic minerals).

Previous mineral processing work that was carried out in conjunction with the selection of suitable lunar simulants will provide additional beneficial data for the preparation of targeted MMOST simulants containing a representative range of iron oxide concentrations. In this manner, the MMOST will be developed in consideration of potential, realistic future mission plans, with robust capability for dealing with a range of potential material feedstocks.

Flow Sheet: Flow sheets for processing of ilmenite-enriched regolith as well as for FeO-rich basalts were prepared as a basis for process development. The flow sheet for the ilmenite case is shown below. The flow sheet for the FeO case is similar except that additional magnetic separation is anticipated for recovery of FeO-rich minerals rather than the electrostatic separation employed for ilmenite beneficiation.



Acknowledgements: The Moon to Mars Oxygen and Steel Technology program is being carried out under a NASA SBIR Phase II Sequential award. Aaron Paz is the Technical Monitor at NASA. The team at Colorado School of Mines is providing important support related to simulant selection, MMOST product properties and additive manufacturing, and vacuum chamber testing. Honeybee Robotics will host final MMOST system testing in their large vacuum chamber. The team at Pioneer Astronautics is conducting design, fabrication, testing, and scale-up for each MMOST unit operation.

A CONTINUOUS HYDROGEN REDUCTION PROCESS FOR ISRU ON THE MOON.

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Introduction: Several manned lunar exploration and development have been planned recently. In-situ resource utilization (ISRU) technology is necessary for sustainable missions on the moon because the transportation from the earth requires much cost, time and labor.

Oxygen and water are the most essential products that are available through ISRU. Oxygen extraction from lunar regolith by hydrogen reduction is one of the simplest and the best methods. The hydrogen reduction system of lunar regolith is described in Figure 1. Two main steps are involved to obtain oxygen. Reaction 1 is the reduction of oxides in lunar regolith with hydrogen producing water. The main target of the reduction is ilmenite. Oxygen is produced by electrolysis of the water. Hydrogen produced in reaction 2 can be recycled in reaction 1.

$$FeTiO_3 + H_2 \rightarrow Fe + TiO_2 + H_2O \quad (1)$$

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \quad (2)$$

Many kinds of batch processes for hydrogen reduction such as fixed bed reactors and fluidized bed reactors have been investigated, however much less work has done with continuous process. Continuous processes are strongly required to produce large amount of water and oxygen on the moon. This research suggests a continuous hydrogen reduction system for extracting oxygen from lunar soil.

The purpose of this study is to investigate the oxygen production mechanism with the continuous hydrogen reduction system.

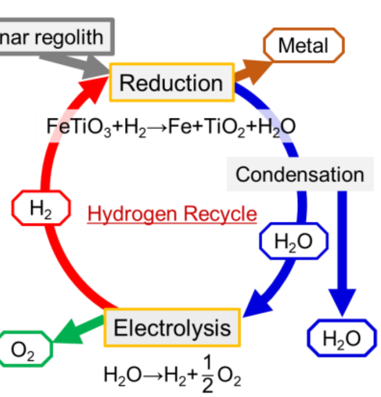

Figure 1 Schematic of hydrogen reduction system.

Experiments: A continuous screw reactor was assembled in this work. Figure 2 shows the schematic diagram of the experimental apparatus. The setup mainly consists of a hopper, a screw to carry the samples, a reactor, an electric furnace for heating the reactor, and a measurement line including a moisture meter. The screw transports the sample from the hopper to the reactor. Hydrogen reduction proceeds in the heated region. The pressure is kept at 200 kPa by controlling the pressure valve at the exit. Argon, hydrogen and produced water vapor is transported to the moisture meter to measure the water production rate.

The sample used in this work is lunar simulant FJS-1. The components of FJS-1 are similar to that of lunar mare regolith [1]. The reduced samples are analyzed by XRD, SEM, and EDX.

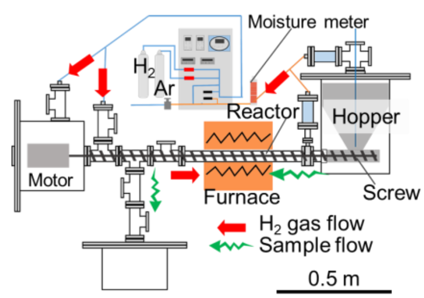

Figure. 2 Schematic diagram of the continuous screw reactor for hydrogen reduction system.

Results and discussions: The effect of reduction time on water production rate during continuous hydrogen reduction was investigated. Figure 3 shows the water production rate with different reduction times at 1273 K. The reduction times were set as 7, 10 and 15 min. The time 0 in the figure represents the time when the valve in hydrogen flow line is opened. Water is not detected at the beginning in all conditions. This is because the amount of untreated sample in the reactor is insufficient to produce the water at higher humidity than the detection limit. The water production rate increases slowly during untreated sample is increasing. After the reactor is filled with sample, the water production rate becomes constant.

The water production rate is highest with the reduction time of 15 min.

The XRD spectra of raw FJS-1 and reduced products with different reduction times are demonstrated in Figure 4. Diffraction peak associated with α-Fe phase at 2θ = 44.68 is observed only in the reduced samples. This indicates the appearance of pure Fe due to the reduction of iron oxides such as FeO, Fe_2O_3, and $FeTiO_3$ in FJS-1. Moreover the relative intensity of α-Fe becomes larger with longer reduction time. It represents more reduction yield with longer reduction time.

The cross-sections of the samples were observed to investigate the morphological change of the samples during hydrogen reduction. The SEM images and the EDS results of untreated and reduced FJS-1 are shown in figure 5. The cross-sections of both initial and reduced samples have ununiformed morphology. The brightest regions contain Fe and Ti according to the EDS results. Therefore these regions are recognized as ilmenite. The ilmenite regions on the reduced sample have numerous halls, while the halls are not observed in the initial sample. Moreover, the decrease of O atoms in the porous regions is observed by EDS result. The results indicate that the extraction of oxygen by the hydrogen reduction produces the pores. Also, the reduction proceeds even on the inside of the particles, as explained by the halls on the middle of the particles.

Conclusion: A continuous hydrogen reduction system with a screw reactor for the extraction of oxygen from the lunar regolith was established. Lunar soil simulant was successfully reduced by hydrogen in continuous process. The effects of reduction time on the hydrogen reduction were revealed.

This work suggests the continuous hydrogen reduction system with a screw reactor as a promising process to acquire oxygen on the moon.

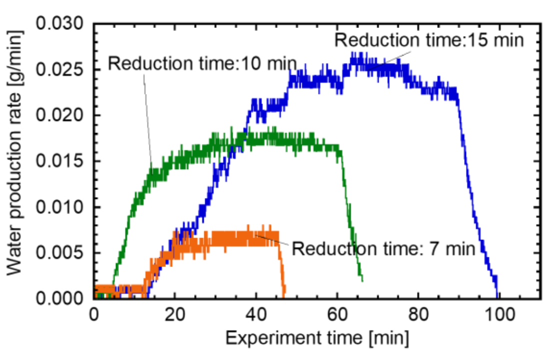

Fig. 3 Effect of reduction time on water production rate in 3vol% hydrogen at 1273 K.

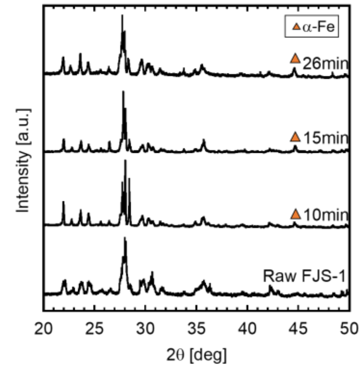

Fig. 4 XRD chart of lunar simulant after hydrogen reduction in different reduction times in 3% hydrogen at 1273 K.

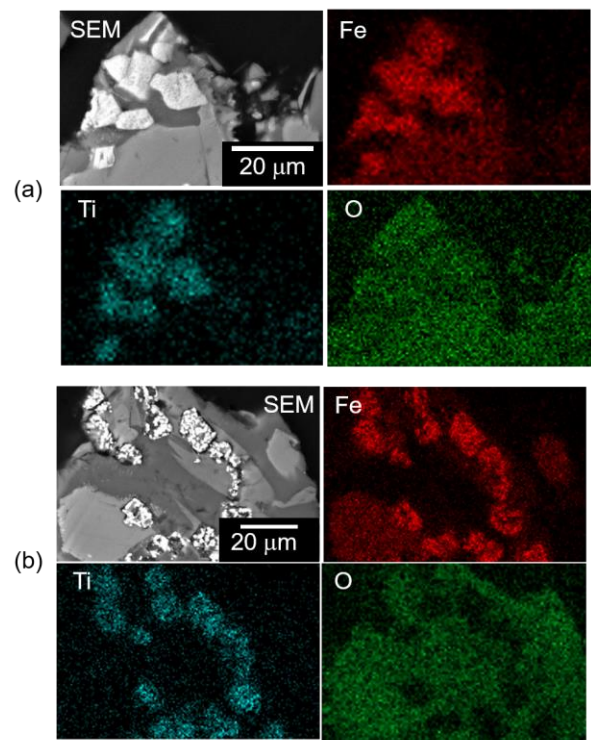

Fig. 5 EDS results of (a) Raw FJS-1 and (b) products reduced for 26 minutes in 3% hydrogen at 1273 K.

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[1] H. Kanamori, et al., Development of new lunar soil simulants in Japan, Space Resources Roundtable Ⅷ (2006), p.35.

Acknowledgements: This research was carried out as a part of the JAXA Space Exploration Innovation Hub Center (TANSAX) based on the JST Innovation Hub Construction Support Project.

Environmental Testing of the OVEN System for Lunar Water Extraction and Prospecting. A. Paz[1] [1] NASA Johnson Space Center Houston, TX 77058

Introduction: The presence of water ice in permanently shadowed regions on the lunar surface [1] may enable a sustained human presence on the Moon with minimal need for consumables. However, in order to develop a long term utilization plan that includes the usage of in-situ water we must first understand the abundance, stratigraphy and distribution of this resource. Multiple space agencies currently have plans for lunar water prospecting missions. The Optimized Volatile Extraction Node (OVEN) was designed for water prospecting missions that require samples to be weighed, sealed, and heated as the means of determining water concentration. This method of water quantification necessitates a fair amount of automation, so a rigorous environmental test program was performed in order to build confidence in the performance of the OVEN design. The work presented here describes the OVEN environmental test program as well as ongoing efforts to improve on the design.

Vibration: The OVEN participated in two rounds of random vibration tests. The first test was a standalone test performed at the Energy Systems Test Area of the Johnson Space Center. The second test was an integrated test with the mobile platform developed for the Resource Prospector project. The OVEN survived both tests without damage, but the tests did provide valuable lessons learned with regards to specific operations.

Thermal Vacuum: The OVEN was successfully demonstrated at a temperature range of -50 to 75 C in a thermal vacuum chamber. The need to heat motor gearboxes at lower temperatures was predetermined so this test program was completed by implementing a method of gearbox heating that used the existing circuitry within the motors.

Dust: A custom dynamometer was built in order to determine the torque required to move the various mechanisms within the OVEN at a range of temperatures. The OVEN system was coated with lunar dust simulant in order to determine mechanism torques under a worst-case operating condition.

Sublimation: Sublimation losses within the OVEN were quantified through a series of test configurations, including an integrated test in a thermal vacuum chamber at Glenn Research Center [2].

Current Work: The OVEN subsystem is currently not a component of any existing prospecting missions, but work continues that will take the lessons learned from previous environmental tests and improve on the design in order to be considered for future prospecting opportunities.

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[2] Kleinhenz, J., Smith, J., Roush, T., Colaprete, A., Zacny, K., Paulsen, G., ... & Paz, A. (2018). Volatiles Loss from water bearing regolith simulant at Lunar Environments. In *Earth and Space 2018: Engineering for Extreme Environments* (pp. 454-466). Reston, VA: American Society of Civil Engineers.

THE REGOLITH AND ICE DRILL FOR EXPLORING NEW TERRAINS (TRIDENT) ON NASA'S VOLATILES INVESTIGATING POLAR EXPLORATION ROVER (VIPER) AND POLAR RESOURCES ICE MINING EXPERIMENT (PRIME-1). K. Zacny[1], P. Chu[1], V. Vendiola[1], E. P. Seto[1], J. Quinn[2], A. Eichenbaum[2], J. Captain[2], J. Kleinhenz[3], A. Colaprete[4], R. Elphic[4] and TRIDENT/VIPER team, [1]Honeybee Robotics, Altadena, CA, KAZacny@HoneybeeRobotics.com, [2]NASA Kennedy Space Center, FL, [3]NASA Johnson Space Center, TX, [4]NASA Ames Research Center, CA.

Introduction: The Regolith and Ice Drill for Exploration of New Terrains (TRIDENT) is an ice mining drill under development for two exploration/ISRU missions to the Moon: Volatiles Investigating Polar Exploration Rover (VIPER) – see Figure 1, and PRIME1 (Polar Resources Ice Mining Experiment) – see Figure 2 [1]. PRIME1 is scheduled to fly to the Moon in 2022 while VIPER is targeting 2023 launch year. Both missions are targeting South Pole's volatile rich deposits.

The primary goal of TRIDENT is to deliver volatile-rich samples from up 1 m depth to the lunar surface [2]. Once on surface, the material would be analyzed by Mass Spectrometer Observing Lunar Operations (MSolo) and the Near InfraRed Volatiles Spectrometer System (NIRVSS) to determine volatile composition and mineralogy of the material. MSolo will fly on both missions while NIRVSS will fly on VIPER.

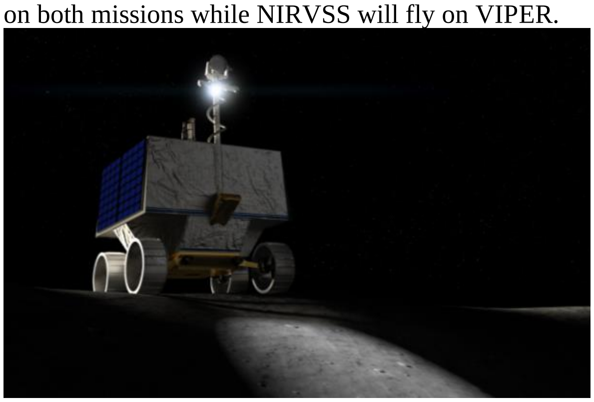

Figure 1. VIPER mission. TRIDENT is placed in vertical position in the middle of the rover.

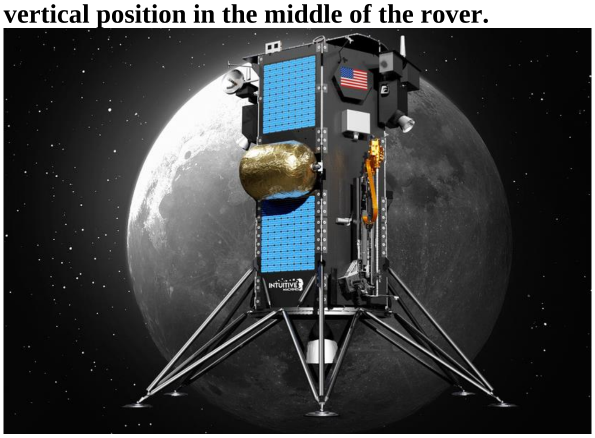

Figure 2. PRIME1 mission. TRIDENT is vertically mounted on the right hand side of the Intuitive Machines (IM) lander.

TRIDENT is a rotary-percussive drill which enables it to cut into icy material that could be as hard as rock. The drill consists of several major subsystems: rotary-percussive drill head for providing percussion and rotation to the drill string, deployment stage for deploying the drill to the ground, feed stage for advancing the drill string 1 m into subsurface, drill string for drilling and sampling, brushing station for depositing material onto the surface (Figure 3).

Percussive energy is set to 2 J/blow and maximum frequency is 972 blow per minute. The rotation speed is 120 revolutions per minute and the stall torque is 16 Nm. The mass of the drill is 20 kg without harness and the mass of avionics 5.4 kg. The stowed volume of the drill is 20.6 cm x 33.3 cm x 168 cm.

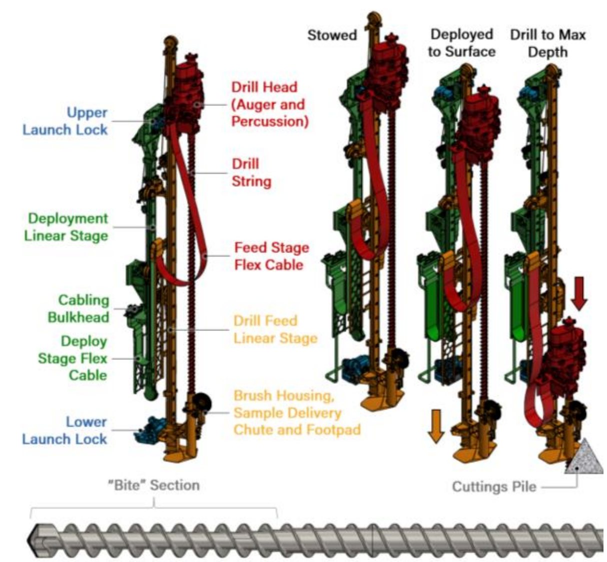

Figure 3. TRIDENT subsystems. The sampling auger is pictured at the bottom.

To reduce thermal risks, risk of getting stuck, reduce drilling power, and provide stratigraphic information, the drill will capture samples in so-called 10 cm bites (Figure 4). That is the drill will drill 10 cm at a time and bring up 10 cm worth of material to the surface. For this reason, the auger is split into two sections (Figure 3 and Figure 4). The lower section has flutes designed for sample retention: the flutes are deep and have low pitch. The upper section is designed for efficient conveyance of material to the surface: the flutes are shallow and the pitch is steep. This combination allows efficient sampling but inefficient conveyance – the drill should not be used to drill to 1 m depth in a single run as this will lead to increase in drilling power and ultimately heat input into formation.

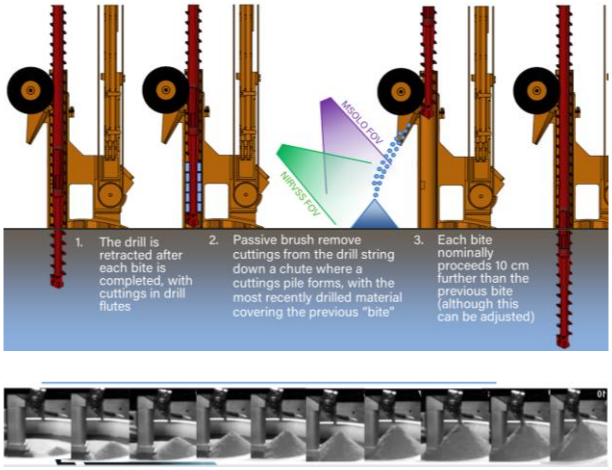

Figure 4. Bite sampling approach. Shown below are cuttings cones every 10 cm bite.

In addition to being tool for providing samples, TRIDENT is also an instrument. TRIDENT drilling power and penetration rate is used to determine regolith strength. Measuring the strength in combination with input from MSolo, NIRVSS and Neutron Spectrometer System (NSS), will enable determination of the physical state of ice – whether it's mixed with regolith or cemented with regolith grains. The former will lead to low drilling power and the latter to high drilling power – while the water-ice concentration could be the same.

TRIDENT's integrated 40 Watt heater and RTD temperature sensors will measure downhole temperature and could provide thermal conductivity. These two measurements, temperature and thermal conductivity, are needed to determine heat flow properties of the Moon. The first RTD is located in the drill bit and the second RTD is co-located with the heater, some 20 cm above the bit.

TRIDENT will also be able to provide bearing capacity of the top lunar surface from measuring of the sinkage of its footpad into the surface, as well as angle of repose from measuring the angle of the cuttings pile.

It needs to be emphasized that drilling in 10 cm bites enables more accurate measurement of subsurface temperature and material strength. Every time the drill is lowered into the borehole, it will be pre-loaded onto the bottom of the borehole and cold soaked without drilling (i.e. no heat input). This cold soaking with be used to extrapolate the subsurface temperature. In addition, when the drilling starts, the drilling power will be initially attributed to penetrating/breaking the icy-formation. As the drill continuous drilling deeper, the power would start increasing due to the cuttings removal (i.e. auger) contribution to the total power budget (the drill can only measure the total drilling power – contribution of drilling and cuttings removal). As such knowing the initial drilling power and the power once the drill penetrated 10 cm will allow determination of the auger-contribution to the total power budget.

TRIDENT's downhole heater and temperature sensors pave the way for more advanced downhole technologies that could be developed for future missions. For example, neutron spectrometer and near infrared spectrometer could be integrated into the auger. This advancement would change the paradigm of planetary exploration: instead of bringing a sample to an instrument we would be bringing an instrument to a sample.

TRIDENT drill has undergone several end to end tests at NASA Glenn Research Center (Figure 5). These tests were conducted with NIRVSS and MSolo instruments and in the NU-LHT-3M lunar soil simulant doped with various water-ice concentrations. In all cases, the vacuum was maintained in the 10^-5 torr range (or lower) while the temperature of the chamber and the sample was mainatined at around 100K or higher.

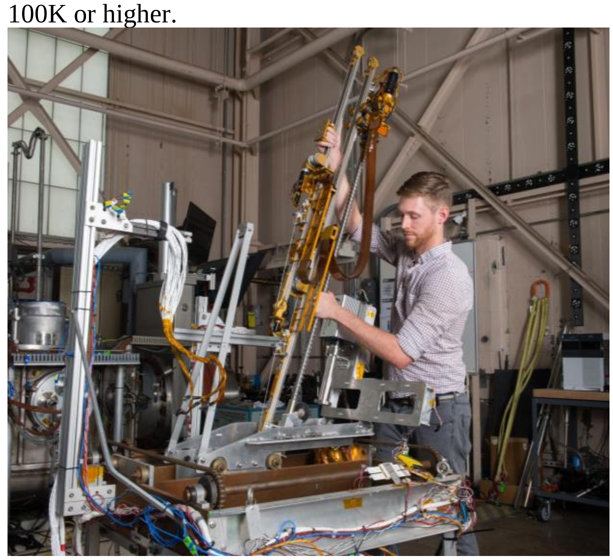

Figure 5. TRIDENR drill undergoing TVAC tests at NASA GRC.

The drill has passed Crititcal Desig Review (CDR) in 2020 and is currently being fabricated and assembled. The flight drill is scheduled to be delivered to NASA in March of 2022.

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Acknowledgments: This work is being supported by NASA SMD. TRIDENT drill has been developed thanks to funding from various NASA programs including (but not limited to) SBIR, ASTID, and ASTEP.

A Lunar Water ISRU System Study for Human-Scale Propellant Production. J. E. Kleinhenz[1], A. Paz[2], and G. Sanders[2] [1]NASA Glenn Research Center, 21000 Brookpark Rd. Cleveland, OH 44135, [2]NASA Johnson Space Center Houston, TX 77058.

Introduction: Current NASA direction is to achieve a sustainable presence on the lunar surface by 2028 [1]. Implementation of ISRU systems to produce consumables, namely propellants and life support, is key to sustainable operations. On the Moon there are two potential resources available for these consumables; bound oxygen in the regolith minerals and water ice (which would provide both oxygen and hydrogen propellants) in discrete locations near at poles. The extended periods of solar illumination near the poles make it an attractive target for missions, thus opening up the possibility of utilizing the water available there.

The study presented here was initiated to assess what it would take, in terms of mass, power, and infrastructure, to produce propellants (hydrogen and oxygen) from lunar water. This study covers an end-to-end ISRU production system including water retrieval (excavation and water extraction), propellant production (water clean-up and electrolysis), propellant liquefaction and storage, and the mobility platforms needed to support these efforts. Whenever possible, existing technologies and hardware were baselined to leverage empirical data regarding performance, mass, and power. However, we recognize that the technologies selected may not be the optimized choice.

A comparable oxygen-only production system targeting the mineral oxides was examined in [2] and compared against the water production system. The trade is whether the additional systems and hardware required to retrieve the water balances with the benefit of producing fuel as well as oxidizer.

Full details of this study, including a sensitivity study, were published in [3]. Since then, there have been some updates to the Artemis campaign, specifically to site planning for the ISRU water system. These will be addressed broadly, focusing on assumptions regarding operational time and solar availability, and how this impacts the ISRU baseline system.

System breakdown: The water based ISRU system was divided into three primary subsystems for this study, as shown graphically in Fig. 1. The water mining system includes excavation and water extraction hardware, which are permanently emplaced at the mine site. Therefore this hardware must be able operate in the shadowed regions where water is stable.

The second system is the production plant; the hardware that converts water into usable propellant and stores it. Since this involves high energy processes (e.g. electrolysis, liquefaction), this portion of the system is located in an area of extended illumination to leverage the possibility of solar power, though no explicit power solutions were specified in this study. This also positions the end product (propellant) in a more accessible location for the ascent vehicles and habitat.

The final system is the water transport system which moves water from the mine to the production plant. There are two identical water tankers in this architecture, and they swap between the two locations. At the mine site, the tanker is also the water storage unit; extracted water is frozen directly in the tanker's water tank. At the production site the water is thawed with the available solar flux, and transferred into a holding tank.

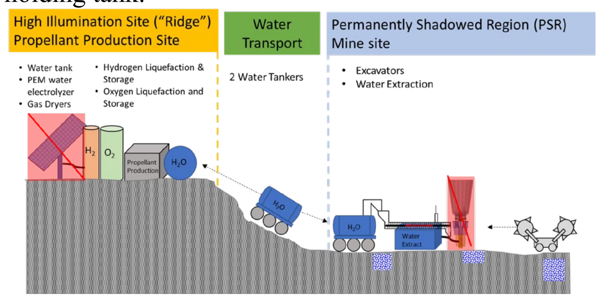

Figure 1: The ISRU architecture used for the model. Tentative power systems are shown for completeness, but were not included.

Baseline ISRU system assumptions: The baseline ISRU system targets the production of 10 mT of oxygen, with enough hydrogen to support the mixture ratio of 6, over the course of 225 days. The production target is NASA's approximation for human vehicle needs [4]. The 225 day target was based the complimentary study that looked at oxygen extraction from minerals [2]. The water content of the soil was a key study parameter, but the baseline was 5wt%, based on [5], but with an extraction efficiency of 75% (so a usable concentration of 3.75wt%). Other details including margins (20% for growth on both mass and power, plus 15% for structure for mass) are listed in [3].

It is important to note that power sources were not part of this study and were not included in the mass estimates. ISRU power needs were calculated so that an appropriate power solution can be identified. Transport of propellant to the use location is also not included in this study.

Results: The tabular results for mass and power for the baseline system are shown in Table 1. The primary power drivers for power were the electrolyzer and the hydrogen liquefaction at the production plant, and water extraction at the mine site (~20 kW each). Note the water extraction power is primarily thermal. In terms of mass drivers, the water tankers are significant, though more transport trips could be traded to reduce tank size (baseline was transport every 10 days). Hydrogen liquefaction is a mass driver as well at 1.7 mT.

A sensitivity study on key variables was performed in [3] including production rate, regolith water content and depth, and water transport timeline. Water concentrations below 1wt% are not a viable solution, 2wt% or greater is recommended. The depth to the water (the amount of dry overburden that must be removed) had a stepwise impact on mass and power, where greater than 1 m depths was a break point.

These results were compared with the system targeting oxygen from regolith minerals [2] and shown in Table 1. The production assumptions were the same, but the oxygen study included a lander bus and solar arrays to support electrical needs. Both of these masses were subtracted out for better comparison to the water case. The oxygen case also uses direct solar heating for regolith extraction, but this is included in the stated power to make it comparable to the water case, which does not separate thermal and electrical requirements. Since the water case includes production of both oxygen and hydrogen propellants, the mass of a filled hydrogen tank was added to the oxygen from regolith system.

Table 1: Mass and power results for the water system model (left) and the oxygen model from [4] (right).

Water Ice ISRU System		O_2 from Regolith ISRU System	
Total Mass	**4.9 mT**	**2.7 mT**	
Ridge System	2.6 mT	*ISRU system*	0.429 mT
Mine system	0.49 mT	*H_2 from earth*	2.3 mT
2 water Tankers	1.8 mT		
Total power	**68 kW**	**45 kW**	
Ridge Power	*46 kW*	*Electrical*	*11.8 kW_e*
Mine Power	*22 kW*	*Direct thermal*	*33.3 kW_t*

While additional studies need to be conducted to ensure equivalent assumptions/assessment between the two options are being made, the comparison clearly reveals that an oxygen from regolith system is a lower mass and power option at this scale. Even with more optimized assumptions, it would be difficult for the water system to match the oxygen system, especially when you consider power systems and the higher complexity of emplacement of hardware and access of the resource. That being said, the value of producing fuel with the water system will increase over multiple missions; the hydrogen up-mass of 2 mT per mission will accrue against the oxygen system.

Site planning: The baseline scenario that has been discussed to this point included the identification of notional lunar sites. This was necessary to baseline parameters such as traverse distances and other environmental conditions for the model. The map in Fig. 2 indicates the baseline locations used. However, the location of Processing Site 1 was not fully validated against the 225 day assumption. A more detailed analysis, which includes terrain feature considerations, shows this site to have periodic sunlight periods on the order of 20 days. Processing site 4 was identified in [6] and is projected to have contiguous sunlight for on the order of 130 days. With all other assumptions the same, reducing production time to 130 days would result in an ISRU system power and mass increase on the order of 50%.

There are only a few locations on the lunar surface that offer this level of continuous sun [6], on the order of 100s of days, and most are concentrated at regions targeted for human operations, like the circled area in Fig. 2. Restricting ISRU production operations to any of these sites would potentially complicate infusion and operation of an ISRU system. Conversely, for less illuminated sites, flexibility in the use of non-solar power options is limited because the power levels projected for propellant production would require significant infrastructure. Therefore revisions are currently underway to the ISRU system model to consider the effects of power dormancy, where a lower level of power would be required while the propellant production operations are reduced or suspended.

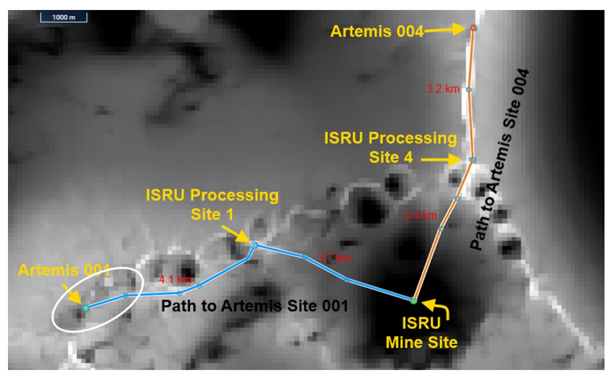

Figure 2: Notional lunar sites and traverse paths used in the model.

References: [1] NASA'S Plan For Sustained Lunar Exploration and Development (2020). https://www.nasa.gov/sites/default/files/atoms/files/a_sustained_lunar_presence_nspc_report4220final.pdf [2] Linne, D.L., et. al. (2021). Journal of Aerospace Engineering. Publication Pending. [3] Kleinhenz, J.E. and Paz, A. (2020), AIAA ASCEND, AIAA-2020-4042 [4] Sanders, G. (2020) http://lsic.jhuapl.edu/Focus-Areas/files/Presentation%20from%20ISRU%20Monthly%20Meeting%20-%202020% 2007%20July.pdf [5] Colaprete, A. et. al. (2010) Science 330, 463 [6] Mazarico, E., et. al. (2011), Icarus. 211, 1066 1081.