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Moon to Mars
AN EFFICIENT PROCEDURE FOR LUNAR ICE EXPLOITATION. D. Sapkota¹, P. Metzger¹, J. Fox², N. Bennett³, ¹University of Central Florida, ²Fox Technical Associates, ³UNSW Australian Centre for Space Engineering Research, Australia. (dhaka.sapkota@ucf.edu).

Introduction: It is crucial for any sustainable exploration to be both cost and energy efficient. A way of minimizing cost is to include in situ resource utilization. For a lunar expedition, solar power, oxygen and metals are the most abundant resources. Another most useful resource, water ice, is also known to be trapped in the Permanently Shadowed Regions (PSRs) which is seen as a feedstock for rocket propellant. We are developing a patent-pending technology for regolith beneficiation to concentrate ice, minimizing energy requirements for a starting architecture of ice extraction. We have also studied the orbital dynamics of commercial lunar propellant usage [1]. Results from these studies will be presented.

Innovation: Beneficiation is common in terrestrial mining. It improves the physical or chemical state of the resource. We performed beneficiation methods of winnowing, magnetic separation, and electrostatic separation with lunar simulants. We simulated ice with plastic due to similar density and magnetic response, and we tested their mixture with lunar simulants of concentrations from 0-5% by weight. The beneficiation can also be extended to other useful minerals.

Architecture and Orbital Dynamics: The excavated resource is lightly ground to help separate ice from lithic fragments prior to the beneficiation processes. A combination of pneumatic, magnetic, and electrostatic and/or vibrational separation is theoretically capable of fulling isolating the ice particles. The concentrated resource is hauled out of the PSR. This way we can keep the power system out of the PSRs, creating a simpler, low-cost architecture. Cleaning the water followed by the electrolysis produces the propellant, which is then liquified and stored, Figure 1.

Figure 1. Flow chat of the extraction and beneficiation processes.

The goal is to make a business case in the lunar propellant manufacture with low enough startup cost that it can be started immediately using commercial investment. Enough fuel needs to be produced for a round trip of the thruster which boosts a communication satellite from initial orbit to a final orbit on a budget. Figure 1 shows the basic architecture: (1) a lander with a tug is fueled on the surface; (2) the lander loiters in LLO; (3) the tug proceeds to GTO where it rendezvous with a commercial satellite; (4) the tug boosts the satellite to GEO; (5) the tug returns to LLO; (6) the tug rendezvous with the lander; (7) lander and tug return to the lunar surface for refueling. Variants of orbital boosts were compared with the different combination of Tug-Thrust mass and oxidizer to fuel ratio with strategies on aerobraking and ion propulsion to identify he minimal viable case. This analysis indicated the mass of propellant that must be mined per satellite boosted to GEO. A subset of the orbital scenarios we considered are shown in Fig. 2.

Figure 2. Comparison of Propellant Requirements for different scenarios of GTO-GEO Boosts. Orange: scenarios leaving the Tug in orbit (orbital Tug = OT). “OT all” includes OT stoichiometric (different mixture ratio that utilizes extra available oxygen for lower ISP but overall, more economic operation) and OT Aerobrake which includes aerobraking to drop into GTO from the Moon. Blue: scenarios landing the Tug on the lunar surface. In these scenarios, the lander will bring a resupply tank to LLO to refill the Tug. The baseline scenario is labeled “Landed Tug”. “All” includes stoichiometric, ion, and ZBO (“zero boiloff” technology required to enable very slow aerobraking without the mass penalty of a heat shield). Percentages on the bars are the propellant requirement reductions relative to the baseline case.
Approach: In addition to the analysis of orbital dynamics, we analyzed the beneficiation process through each stage to predict what fraction of grains, based on their size and mineralogy, would be separated. We also performed experiments to validate the beneficiation concepts, including magnetic, electrostatic, and vibrational separation (see Figs. 3 and 4). Finally, we performed an architectural analysis of the overall mining system including surface and orbital segments to determine mass, power, throughput, and cost.

![Figure 3](image1.png) Magnetic (left) and electrostatic (right) experimental apparatuses.

![Figure 4](image2.png) A: Regolith+plastic (ice) mixture. B/C. After magnetic beneficiation. B: regolith with little plastic (ice). C: regolith with enhanced ice concentration.

Results:
- Experiments show that ice beneficiation is a game changer in lunar propellant manufacture. It rejects more than 80% of the regolith while retaining almost all plastic (ice).
- A dramatic 98% reduction in power estimated in comparison with thermal extraction.
- Architectural analysis shows 2,500 kg of assets and a start-up cost of €175M or $213M to begin operations which are $\frac{1}{12}$ in size and $\frac{1}{19}$ in budget as compared to a recent study on commercial lunar propellant architecture study [2].
- The propellant from the Moon allows fast boosting (within one day) of satellites between orbits that save in millions as compared to the electric thrusters that take 6-12 months.

References:
**SATellite, spacecraft and Lander Refueling via ISRU-produced Hydrazine.**

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**Introduction:** Hundreds of communication and other satellites in Earth orbit use hydrazine propellant for final orbital positioning and station-keeping. As these satellites near the exhaustion of their propellant, they are normally boosted to higher parking orbits and stop being revenue or data producers for their owners. Replacement costs as high as hundreds of millions of dollars create an economic reward for refueling, and thus recovery of satellite operations. Satellite servicing missions are currently underway that could demonstrate active refueling using hydrazine produced on Earth to restore functionality. The discovery of ammonia (NH₃) in lunar polar cryogenic soils by the LCROSS mission in 2010 could enable hydrazine production through multiple chemical synthesis pathways. Solving the complex chemical engineering problem of hydrazine synthesis from lunar resources could enable a straightforward business model of producing and selling the most common satellite propellant known to man. Our strategy is to adapt and leverage recent breakthroughs in chemical reactor technology and unit operations. Key challenges include power budget, radiation tolerance, thermal and vacuum-related constraints, hypogravity conditions, and miniaturization.

**Current Technologies and Market Summary:**

Two missions are currently underway using spacecraft that will attach to two retired GEO satellites and take over attitude control [1] and NASA is developing a spacecraft that will refuel (notably with hydrazine) and repair a legacy satellite to extend its lifetime. [2] These developments would be synergetic with the manufacturing of hydrazine in microgravity or on the lunar surface, provided a simple, robust method of chemical synthesis can be developed and proven. The system would utilize ammonia derived from lunar polar volatile resources. The value of hydrazine in GEO for refueling life extension of commercial and military satellites has been independently estimated to be as high as $350,000/kg. [3] Future customers could include near-term lunar landers and deep space missions that could be refueled before leaving cis-lunar space. Specific current and future customers include owners and operators of communication satellites, the U.S. military, NASA, allied militaries and space agencies, and commercial spaceflight companies, such as SpaceX, Blue Origin, and Boeing. Lunar landers could also be refueled with lunar ammonia-derived hydrazine if the engines and/or thrusters are compatible.

Our patent-pending innovations are also anticipated to be adaptable for use at terrestrial worksites, providing a path to near-term economic returns. NASA and most terrestrial companies that utilize hydrazine have to ship it in but do not use it in large enough quantities to justify their own facility. Technology that could negate the need for shipping hydrazine fits the lean manufacturing technique of supply on-demand, minimizing safety hazards due to exposure.

Industrial analogs for individual hydrazine unit cell processes provide an incremental design path leading to an emergent space resource refining capability. Our goal is to build and test a stand-alone, integrated microreactor system that will utilize input power, water and ammonia to produce hydrazine and hydrogen gas for space propulsion customers anywhere ammonia and water are available in space. An additional application would be refueling of spacecraft designed to rendezvous with and deorbit space debris, then separate and reboost themselves to their next target. Such spacecraft could maneuver itself to a hydrazine depot in Earth orbit rather than requiring a tanker to rendezvous with it.

Our approach may also allow the salvaging of satellites presently in graveyard orbits or adrift. Since the beginning of the space age in 1957 with the launch of Sputnik, there have been over 5,000 rocket launches placing one or more satellites in orbit. It is estimated that there are also over 3,000 dead satellites in orbit with over 1,000 satellites in the GEO graveyard orbit. Many of these graveyard orbit satellites cost hundreds of millions of dollars to manufacture and launch into space. A restoration or recycling of even a small percentage of these legacy space assets could create tremendous value. The metals and electronics in these satellites could then provide additional space resource feedstocks.

One of the largest, most obvious and frequently discussed applications for refueling is satellite life extension in GEO. Recently, Northrop Grumman demonstrated its Mission Extension Vehicle by docking with an Intelsat satellite and taking over the station-keeping role. [1] There are several other companies planning similar life extension capabilities. Satellites have generally been launched with enough station-keeping fuel for a 15-year mission life. Without an ability to keep a satellite in its licensed GEO orbital slot, revenue potential can be reduced by 80% to 100%. Giving a satellite owner/operator additional years of revenue potential can mean $50 million to $500 million per year of incremental revenue...
depending on the size and type of satellite and the markets it serves. As these satellites would typically be fully depreciated and operating margins can be 80% to 95%, most of this incremental revenue becomes operating cash flow and net income, greatly increasing the market value of the company and potentially allowing for significant expansion of satellite capacity and services to end users at reduced pricing.

We envision OrbChem as acting primarily as the production/refinery segment in the value chain, selling in-space propellants as a merchant supplier. Pricing would be driven by supply and demand with discounts for forward commitments and high-volume purchases. For instance, a strategic space reserve for critical commodities like propellants funded by the U.S. government would likely benefit significantly from such discounts. In general, however, pricing would be set to provide customers a clear incentive to buy propellant produced in space rather than launch it from the Earth’s surface. This would include enabling such practices as launching space systems “dry” (unfueled) to save on launch costs which can run up to $10,000 per kilogram and to avoid the health hazards of handling hydrazine on Earth. Initially, as our feedstocks would be sourced primarily from the Earth’s surface, the primary cost and health benefits would be in avoiding the expensive and dangerous handling of hydrazine during production, storage and fueling. Once feedstocks shift to ISRU sourcing, the much lower delta-Vs required to obtain the raw materials versus launching from the Earth’s gravity well should result in substantial cost savings and pricing flexibility even as launch costs continue to decline from the use of reusable systems.

**Potential Issues:** There has been a recent move to green propellants as a hydrazine replacement to minimize serious health risks during initial fuel loading operations on the ground. However, this effort has focused on creating hardware that is backward compatible with hydrazine. Thus, after launch into orbit, space systems designed to burn green propellants would also be refuellable by the automated loading of heritage fuels such as hydrazine produced in space.

Also, likely due to recurring hurricane damage at the only production site in Lake Charles, Louisiana, commercial hydrazine is no longer synthesized in the United States, instead being imported as hydrazine hydrate and converted to pure hydrazine. However, the synthesis process differs the prior method and introduces traces of organic compounds whose effects on long-term storage and thrusters is unknown. Fortunately, NASA is developing analytical techniques to identify them and test their effects. [4] We intend to use the same peroxide process and expect this issue to be resolved by the time we would be in the prototype testing phase.

**Current Technology:** A short summary of the peroxide process is presented. This method is one of simplest paths currently used to chemically synthesize hydrazine, and serves as a point of departure for our patent-pending concept: Ammonia is reacted with methyl ethyl ketone to produce imine and water. Then acetamide is reacted with hydrogen peroxide to produce iminoperacetic acid and water. Iminoperacetic acid is reacted with imine to produce an oxaziridine and reform the acetamide. The oxaziridine is reacted with ammonia to produce a hydrazone. The hydrazone reacts with methyl ethyl ketone to produce an azine. The azine is then hydrolyzed to produce hydrazine and regenerate the methyl ethyl ketone. Acetamide is used as a peroxide activator in the first reaction. EDTA is typically used as a peroxide stabilizer. Other activators and stabilizers may be used. The hydrogen peroxide required can be synthesized using the anthraquinone process. The net hydrazine synthesis reaction is:

\[ 2\text{NH}_3 + \text{H}_2\text{O} \rightarrow \text{N}_2\text{H}_5\text{ONNH}_2 + 2\text{H}_2\text{O} \]

**ISRU Technology Requirements:** Devices will be required for unit operations that include chemical reactions, phase separations, product separation and storage. We have identified candidates for miniaturized reactor technology and are examining them using figures of merit including thermal and electrical power needs, efficiency, scalability, reaction rates, safety, reliability, and controllability in order to identify improvements on traditional industrial methods. These criteria will also determine the feasibility conditions and systems requirements for lunar and asteroidal plant design as a function of scale and throughput.

**Feed Materials:** Recycled astronaut urine from the International Space Station (ISS) could provide an early source of ammonia for a demonstration system that would emulate the microgravity conditions required to make hydrazine from asteroidal and cometary ammonia. Our estimates indicate that a demo near ISS could produce up to 30 kg hydrazine/y. Lunar production rates would depend on availability of ammonia and whether it is a primary ore or a byproduct in the design of a polar mining plant. Our first approximations were based on a NASA study for the production of 1000 kg O\textsubscript{2}/y from a permanently shadowed regions (PSRs) near the lunar south pole, [5] where we show that about 64 kg hydrazine/y could be produced as a byproduct or 640 kg/y in parallel with a 10,000 kg O\textsubscript{2}/y plant [6]. Extracting the ammonia as the primary product could increase production rates to higher values and would eliminate the extreme power required for water electrolysis assumed in [5] and [6].

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ASCEND 2020, 4042.
Designing a Lunar Safe Haven for Sustained Lunar Surface Missions. Melanie L. Grande¹ and Robert W. Moses². ¹NASA Langley Research Center, Hampton, VA, melanie.l.grande@nasa.gov, ²NASA Langley Research Center, Hampton, VA, robert.w.moses@nasa.gov.

Introduction: NASA’s Artemis program will send astronauts to the lunar surface for extended mission durations throughout the 2030s, with a focus on sustainability and extensibility for Mars exploration, as described in NASA’s Artemis Plan [1]. However, NASA must place more emphasis on protecting both the crew and the exploration surface systems if they hope to achieve long-duration sustainability. For example, NASA’s current habitation development does not go far enough to protect astronauts from background radiation, especially if the crew is simulating longer mission durations in preparation for Mars [2]. Development of a “safe haven” shelter on the surface is therefore paramount to continuously protect Artemis astronauts and exploration systems from radiation, thermal extremes, micrometeoroids, and other hazards of the lunar environment during the “sustained” phase of exploration. This “safe haven” need not be pressurized, though traditional use of this term suggests a type of pressurized storm shelter, but it must provide adequate protection for the crew and systems during long-duration crewed surface missions.

The Lunar Safe Haven (LSH) Seedling Study is a one-year effort by NASA to perform a comprehensive trade study for identifying the best approaches for implementing a safe haven shelter. The LSH Study team is therefore examining NASA activities in site preparation, excavation, regolith transfer, surface construction, assembly, deployment, surface mobility, advanced manufacturing, and in situ resource utilization (ISRU). To date, the study has defined high-level requirements, which emphasize synergy with NASA’s Artemis program. Guided by these Level Zero Requirements, the Artemis Plan [1], and NASA exploration goals, and exploration mission design principles, the Study baseline the decision analysis structure by defining objectives and attributes. The study has defined numerous concept alternatives for the design of the LSH shelter, establishment systems (for excavation, construction, assembly, and/or deployment), and sustained operations systems (for maintenance of the shelter during the Artemis “sustained” phase). The concept alternatives will be evaluated against the decision attributes in order to inform downselect and ultimately provide a consensus on the best path forward for designing, establishing, and maintaining a Lunar Safe Haven shelter.

Level Zero Requirements: The Level Zero Requirements were the first focus of the LSH Study. They were developed based on the Artemis Plan, NASA Human Exploration and Operations Mission Direc-torate (HEOMD) ground rules and assumptions for future lunar exploration, known lunar surface hazards, and an emphasis on in situ resource utilization (ISRU). These requirements guide the definition of the LSH Ground Rules and Assumptions and bound the trade space. They include:

1. The Lunar Safe Haven Concept (LSHC) shall shield crew, electronics (such as computers providing command and control of autonomous systems), and other exploration and habitation systems that require radiation shielding as defined by HEOMD for at least 10 (TBR) years without exceeding the proxy dose limits for crew and electronics.
2. The LSHC shall protect crew, electronics, and other exploration and habitation systems that require protection as defined by HEOMD from the hazards of the lunar environment—including but not limited to micrometeoroid impacts, thermal loads, seismic activity, electrical charging, dust, vacuum, and the sun—for at least 10 (TBR) years.
3. The LSHC shall protect crew, electronics, and other exploration and habitation systems that require protection as defined by HEOMD from the impacts and damage from other external assets that could cause collisions or ejecta for at least 10 (TBR) years.
4. The LSHC shall not negatively impact the crew performance, habitability, and safety requirements derived from NASA-3001 for crew—as defined in Human Systems Integration (HSI) requirements documents of the lunar exploration systems to be used by HEOMD—and for proximal Extravehicular Activity (EVA).
5. The LSHC shall not negatively impact functionality nor negatively impact deployment and placement of heritage exploration habitation systems selected by HEOMD that require protection and shielding.
6. The LSH concept shall utilize in situ resources— Including both natural and repurposed resources.
7. The LSH concept shall identify and define the surface equipment concepts necessary to emplace, assemble, and/or construct the safe haven shelter.
8. The technologies included in the LSH concept shall be ready to be deployed and operational on the lunar surface by 2026 (TBR), according to HEOMD.
9. The Lunar Safe Haven shall be compatible with NASA’s lunar lander systems to be selected by HEOMD.

**Decision Objectives and Attributes:** The purpose of decision analysis is to identify and characterize alternatives that will best achieve a decision maker’s priorities, given a set of needs, goals, objectives, and constraints [2]. For the LSH Study, the decision analysis needs to answer the question: What system(s) should be manifested in the Artemis campaign as part of a continuous mitigation strategy that will protect crew and exploration systems on the lunar surface from the hazards of the lunar environment (e.g., radiation, thermal extremes, and micrometeoroids) during sustained missions? Therefore, the LSH Study baselined a decision analysis structure which included first decomposing the need into specific objectives, which must be specific, measurable, attainable, and results-oriented (i.e., based on the desired outcome and not the method) [3]. Although many objectives could be considered, ultimately only ten were selected for the Study, encompassing benefit, cost, and risk.

While the objectives define what the stakeholders value, the attributes are a measure of how well the objectives can be achieved. After design alternatives are assessed for all attributes, the data will communicate the trade-offs between achieving relatively more or less on each objective. The LSH study defined one or more attributes for each of the objectives; examples are shown in Fig. 1.

**Figure 1.** Examples of the LSH Objectives and associated Attributes.

- **Objective:** Minimize radiation exposure to crew
- **Attribute:** Effective dose to crew from background radiation

- **Objective:** Maximize evolvability of the LSH establishment and operations concept
- **Attribute:** Acute dose to crew during SPEs

- **Objective:** Balance resiliency and robustness of the LSH concept as a whole
- **Attribute:** Mean Time Between Failures

**Concept Generation and Evaluation:** To complete the trade study, the LSH Study team performed several rounds of brainstorming to generate alternatives. The brainstorming was guided by three morphological matrices. A morphological matrix was created for the shelter design based on parameters for the physical architecture. The collected ideas therefore included alternatives for the shelter protection material, processing of the protection material, shelter structure material, shelter shape, and other parameters. Next, two morphological matrices were created for the establishment systems and sustained operations systems, respectively, based on the functional decomposition. Ideas collected therefore included alternative means to achieve functions including, but not limited to:
- Transport LSH systems from lander off-loading site to establishment site
- Prepare the site for installment of the LSHC shelter
- Emplace, assemble, and/or construct the LSHC shelter
- Maintain successful operation of the LSHC
- Monitor the lunar environment to provide information on space weather conditions, radiation, seismic activity, and other conditions relevant to protection of crew and surface systems

Based on the alternatives generated, several “complete” alternatives could be defined for the LSH concept, including a combination of shelter design parameters and means to achieve each function for the establishment and sustained operations systems. Based on the high quantity of possible complete alternatives, the Study used an iterative approach to refine the designs. This approach started with a selected number of alternatives, performed assessment of the attributes for each alternative, and identified areas for improvement based on the assessment. This led to a subsequent list of concept alternatives to move forward with and further iterate on. The attributes data at the end of the process outlined the key trade-offs that must be made between concepts and informed down-selection for future design efforts.

**Conclusion:** The Lunar Safe Haven Seedling Study developed Level Zero Requirements, baselined a decision analysis structure, and identified numerous alternatives for implementing a safe haven shelter on the lunar surface. Further, the Study assessed the concepts to illuminate the trade-offs between design choices and communicate how well decision objectives can be achieved. This presentation will review the Study process, the concept alternatives studied, and the results of the decision analysis.

**References:**
NOW MAKING OXYGEN ON MARS: MOXIE AND THE PERSEVERANCE MISSION. M. H. Hecht, J. McClean, J. A. Hoffman and the MOXIE Team, 1MIT Haystack Observatory, 99 Millstone Rd., Westford, MA 01886, mhecht@mit.edu, 2MIT Haystack Observatory, 99 Millstone Rd., Westford, MA 01886, mccleanj@mit.edu, 3MIT Department of Aeronautics and Astronautics; Cambridge, MA, jhoffma1@mit.edu

Introduction: Currently on Mars aboard the Perseverance rover and anticipating its first opportunity to operate, the Mars Oxygen ISRU Experiment (MOXIE) will be the first live demonstration of oxygen production on the surface of another planet (see Figure 1). MOXIE is a prototype of a system that will someday provide many tons of oxygen as the major component of the propellant for a Mars Ascent Vehicle that will return astronauts from the Red Planet.

How MOXIE Works: Designed and integrated at NASA’s Jet Propulsion Laboratory for MIT, MOXIE first collects, filters, and compresses the thin martian air, which consists of 95% CO\textsubscript{2} and small amounts of nitrogen and argon at a pressure of <10 mbar (Figure 2) using a custom scroll pump developed by Air Squared, Inc. It then pre-heats the gas to ~800°C and injects it into a stack of 10 solid oxide electrolysis cells (SOXE), developed by Ceramatec, Inc. (now OxEon Energy). CO\textsubscript{2} is thermally and catalytically decomposed according to the reaction CO\textsubscript{2} \rightarrow CO + O\textsubscript{2} at the cathode of the electrolysis cells, then the oxygen ions are selectively drawn through the yttrium-stabilized zirconia electrolyte where they recombine at the anode into O\textsubscript{2} molecules. The transfer of 4 electrons from anode to cathode completes the circuit and provides the motive force for the reaction. The pure oxygen product is characterized, then released through a precision aperture (labelled VFCD is Figure 2), while CO fuel and unused CO\textsubscript{2} are similarly characterized and discharged through an exhaust port.

MOXIE expects to produce 6-10 grams of 98% pure O\textsubscript{2} per hour, a factor of ~200 less than will eventually be needed on a full-scale system. Limited power availability on Perseverance is the primary constraint on production – a human mission is expected to be supported by a 25-30 kW power plant, while Perseverance generates 110W overall. The eventual full-scale system is expected to take up about a cubic meter and to weigh about 1 ton while generating in excess of 25 tons of O\textsubscript{2} for the ascent vehicle over the course of an Earth year.

MOXIE is expected to operate at least ten times during the primary Perseverance mission of one martian year, distributed across seasons and time of day.

Success criteria: Instrument development for flight projects is driven by capability requirements, which for MOXIE demanded production of 6 g/hr O\textsubscript{2} with at least 98% purity at nominal end-of-life (10 cycles on Mars). Once at their destination, these requirements are superceded by success criteria. For MOXIE, the team has proposed the following criteria:

- Demonstrate that MOXIE can meet its development requirements on Mars by operating for 10 cycles while still achieving >6 g/hr oxygen production at >98% purity on the final cycle.
- Demonstrate reliability of MOXIE by consistent operation without significant degradation through at least 10 cycles of operation.
- Demonstrate robustness of MOXIE by producing oxygen near the beginning and end of the primary mission.
- Demonstrate ruggedness of MOXIE by producing oxygen at the extremes of atmospheric density, throughout the full range of atmospheric density, during day and night in all seasons, and during a dust storm if the opportunity presents itself.
- Inform future designs by learning how MOXIE responds to the range of conditions described above.

With MOXIE’s protected location in the rover belly, the effect of seasons is mostly restricted to the variation in atmospheric density. Moreover, a future human
mission is unlikely to land at a high altitude location like Jezero, so the specific density values aren’t as important as demonstrating that we can accommodate a wide range — the combination of temperature and pressure variations over the martian year amount to nearly a factor of two difference between the maximum and minimum values and diurnal variations are typically 20%.

**Results to date:** As of this writing, MOXIE has completed check-outs of all key systems, including the compressor, the applied SOXE voltage, and the ability to heat the SOXE to 800°C.

A final checkout, a “compressor sweep,” was conducted on April 15th in preparation for the first oxygen production, anticipated in the next few days. The sweep allowed to calibrate the relationship between mass flow rate and compressor speed under these particular atmospheric conditions. All was found to be nominal except for two minor anomalies.

The first anomaly, referred to as a “cross-over leak,” had been seen in the laboratory prior to launch and was essentially unchanged on Mars. As seen in Figure 3, cathode overpressure relative to the anode causes a small amount of the cathode gas to leak into the anode, mixing with the O₂ product. The flow resistance of the leak at low temperature is found to be 206 klohms, compared to 4 klohms for the cathode exhaust and 34 klohms for the anode exhaust. Leak resistance has been confirmed in the laboratory to be an order of magnitude higher at SOXE operating temperature due to increased gas viscosity. Also, flow through the leak will be proportional to the pressure differential ΔPₐn between anode and cathode, which is determined by the compressor speed and will always be far lower than in the compressor sweep. As a result, under nominal operating conditions, CO₂ contamination of the O₂ stream will be <<1%, well within expectations, and can be eliminated entirely by further reducing the inlet flow if desired.

The second anomaly occurred while attempting concurrent operation of a system microphone to record the sound of the compressor as a baseline for future diagnostics of compressor performance. The microphone failed to record, for reasons currently being investigated. Note that even though the Mars atmosphere is sufficient to transmit sound, most of the signal is expected to be via body transmission through the rover.

**Next steps:** MOXIE’s first oxygen production is expected to occur in mid-April, depending on progress of the Perseverance helicopter campaign. It will be conservatively scheduled in the early morning hours, when the atmospheric density is as much as 20% higher than at the early afternoon minimum. Since the MOXIE compressor is a volumetric device, higher atmospheric density offers a wider range of possible mass flow within the control range of the compressor.

![OCE: Crossover leak](image)

Figure 3: A small crossover leak is indicated by the rise in pressure in the anode chamber (P₅, red) when gas is pumped into the cathode (P₄, blue) while the SOXE is at ambient temperature and not producing oxygen.

Following the first oxygen production, MOXIE will schedule regularly spaced operations separated by ~2 Earth months to satisfy the objective of demonstrating all-season operation. Time of sol will be also varied to specifically test the dependence on the thermal environment. All runs will begin with a standard “current-voltage (I-V) profile in order to determine the area-specific resistance (ASR) and track any degradation over time.

Determining the variation of performance with SOXE temperature is a particularly important objective, as it is the only identified way to distinguish the resistance across the membrane, which is a strong function of temperature, from series resistances, which are dominated by the Inconel lead wires but may also include internal voltage drops such as across the contacts between the interconnect plates and the anodes. Improved knowledge of these resistances allows more accurate determination of the Nernst potential for carbon formation, the voltage threshold for coking.

Subsequent runs will evaluate operation at different inlet flows and SOXE temperature, and will test alternative control configurations such as voltage-feedback control instead of current-feedback control or cathode pressure feedback control of compressor speed. In general, a number of potential improvements to the process monitoring and control system have been identified as Lessons Learned from the MOXIE experiment, and these will be explored in the laboratory during the MOXIE campaign.

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RedWater: Extraction of Water from Mars' Ice Deposits. B. Mellerowicz1, K. Zacny1, J. Palmowski1, B. Bradley1, L. Stolov1, B. Yen1, D. Sabahi3, L. Ware1, A. Ridilla1, H. Nguyen1, D. Faris1, P. van Susante2, George Johnson2, N. E. Putzig1, M. Hecht1, 1Honeybee Robotics (kazacny@honeybeerobotics.com), 2Michigan Technological University (pjvansus@mtu.edu), 3Planetary Science Institute (nathaniel@putzig.com), 4Haystack Observatory, Massachusetts Institute of Technology (mhecht@haystack.mit.edu)

Introduction: In the past decade orbital measurements revealed that a third of the Martian surface contains shallow ground ice. MRO’s SHARAD sounder has revealed the presence of ice-rich materials in several non-polar terrains, including debris-covered glaciers and ground ices extending down to latitudes of 37° [1]. These deposits are up to several 100 m thick and many appear to consist of nearly pure water ice. The ability of the radar to resolve shallow layering is limited to ~20 m. Thus, to reach ice and extract water, a system would need to penetrate through at most 20 m of regolith. The discoveries of nearly pure ice deposits in mid latitudes on Mars enable implementing two proven terrestrial technologies: Coiled Tubing (CT) for drilling and Rodriguez Well (RodWell) for water extraction.

CT rigs use a continuous length of tubing (metal or composite) that is flexible enough to be wound on a reel and rigid enough to withstand drilling forces and torques. The tube is pushed downhole using so-called injectors (for example, a set of actuated rollers that pinch the tube and advance it downward). The end of the tube has a Bottom Hole Assembly (BHA) – a motor and a drill bit for drilling into the subsurface. To remove drill cuttings, compressed air (or other drilling fluid) is pumped down the tube. A hole is drilled by advancing coiled tubing deeper into the subsurface while blowing cuttings out of the way. A commercial CT rig, such as RoXplorer, weighs 15 tons and drills to 500 m at 1 m/min in hard rock.

RodWell is a technology where a hole is drilled in ice, which is melted and pumped to the surface. It has been developed and tested in Antarctica in the 1960s and used at the South Pole station since 2002 [2].

RedWater: The RedWater system combines the two technologies into one (Figure 1, Figure 2). It uses the CT approach to create a drill hole. Once the hole is made, the coiled tubing is left in the hole and used as conduit for water extraction. The BHA contains a rotary percussive drill subsystem (similar to the one used in Honeybee Robotics’ Deep Drill [3]), heaters and pneumatic and hydraulic tubes that run along the outside of the housing. The coiled tubing houses insulated and heated hoses as well as wires for downhole motors and heaters. During drilling, compressed gas is sent downhole through the hoses. The gas escapes through the annular space between the tube and borehole wall and removes cuttings that can be collected and analyzed for science. Upon reaching an ice layer, the drill continues for another ~3 m and then stops advancing forward, but the bit continues to spin, and packer is inflated to seal the borehole. Heaters in the auger are

Figure 1. RedWater with all the subsystems.
turned on to melt the surrounding ice. Once ice starts
to melt, the hoses are used to pressurize the borehole
and at the same time pump a fraction of the melted
water up into a storage tank on the surface via a three-
way heated valve, which switches between the gas tank
and the water tank. Using the auger to “stir” the melted
water speeds up the melting process. After melting a
section of ice, the CT is reactivated to drill further into
the underlying ice and the melting process continues.

**Figure 2. Bottom Hole Assembly.**

**Fabrication and Testing:** The RedWater subsys-
tems (Coiled Tubing, Injector, BHA) were fabricated
and assembled. The system ended up weighing 66 kg
with Injector being the heaviest at 54 kg, followed by
the BHA at 10 kg, and Coiled Tubing at 2 kg.

Several tests have been conducted at subsystem
level to evaluate performance of the RedWater subsys-
tems and debug controls and mechanical systems.

The final test of the end to end system was done in-
side 5.5 m tall freezer (Figure 3). During this test,
RedWater demonstrated drilling, blowing cuttings out
of the hole, borehole pressurization and melting.
Pumping was semi-successful since the ice-blocks
were not properly sealed and water leaked out. How-
ever prior pumping tests showed successful pumping.
The data was extrapolated to meet goals of ISRU mis-
sion [4].

Table 1 shows design specifications as well as
test data. It can be seen that the performance data is
within the design specifications of the system confirm-
ing the validity of the subsystem level testing and de-
sign margins. The next step are tests in 3.5 m Mars
chamber.

**Figure 3. Test setup in a 5 m freezer.**

**Table 1. RedWater Test data vs Specifications**

<table>
<thead>
<tr>
<th></th>
<th>Test data</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill Depth (m)</td>
<td>1 – 2</td>
<td>3.4</td>
</tr>
<tr>
<td>Nominal Auger Speed (RPM)</td>
<td>120</td>
<td>134</td>
</tr>
<tr>
<td>WOB (N)</td>
<td>300</td>
<td>500</td>
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<tr>
<td>Torque Output (Nm)</td>
<td>1.3</td>
<td>6</td>
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<tr>
<td>Percuss Speed (BPR) @ 2.5 J/B</td>
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<td>1080</td>
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<tr>
<td>Rate of Penetration (m/hr)</td>
<td>2.1</td>
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<tr>
<td>Drilling Power (W)</td>
<td>172</td>
<td>300</td>
</tr>
<tr>
<td>Heating Power (kW)</td>
<td>1.6</td>
<td>5.8</td>
</tr>
<tr>
<td>Drilling Energy (Whr)</td>
<td>90</td>
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<tr>
<td>Heating Energy (kWhr)</td>
<td>24</td>
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</tr>
<tr>
<td>Well Size (-60°C ice) (L)</td>
<td>100</td>
<td>n/a</td>
</tr>
</tbody>
</table>

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Resource Utilization (ISRU) Technology.
Introduction: EasyMineXR software enables high resolution geologically mapping at the rock face on Mars through 3-D virtual reality environments. Modern geological sciences in the mining and exploration industry are rapidly embracing high accuracy remote sensing technologies to provide fully three-dimensional, high resolution imagery as a practical solution for data gathering in inaccessible or unsafe locations. We have developed a customized application for virtual geological mapping in the mining industry. Using augmented reality (Microsoft HoloLens), or virtual reality, or computer desktop screen (Figure 1), EasyMineXR allows a geologist to easily explore the rock face freely and collect observational data (Onsel et al., 2020). The geologist can examine and trace the lithological contacts or structural patterns as if painting the true rock, and can take orientation measurements faster than using a compass.

Planetary Surface Data: Fully three-dimensional adequate-resolution textured mesh surfaces (Figure 1) can now be rapidly constructed from photographs derived from any kind of source such as drones, cell phones, satellite images, etc. (Onsel et al., 2019) The increasing high-resolution digital imagery from each subsequent Mars exploration rovers, namely Sojourner, Opportunity, Spirit, Curiosity and now the powerful, high-resolution ones from Perseverance, provides all that would be necessary to allow any trained geologist to begin a virtual mapping program on Mars. Only an appropriate software platform is required.

Constructed wireframe meshes of the rock outcrop are imported with the associated image texture files into EasyMineXR. The software tools are then used to navigate around the three-dimensional environment and map at the resolution provided by the images. The images used for mapping can include extra layers such as hyperspectral or thermal imagery to enhance the visual information used for interpretation. A range of image enhancement tools have been developed to allow the user to more easily find discontinuity trends or patterns in the images.

Scientific Collaboration: EasyMineXR can also be a platform for scientific community to interact at the “rockface”. There is likely much we can learn from detailed study of the surface of Mars. Any person with the same outcrop models on their computer can interact in real-time, with audio, with other persons on their computer or virtual reality headset. Each person that joins the “meeting” will see the avatar location of each other attendee and will see the data captured and polyline interpretations created by them. This enables open discussion and subject experts to provide their opinion on the observations. All captured orientation measurements and interpretive traces of the geology are automatically stored in text files, and simple software tools are available to manage the importing, hiding or showing of any digital image, line or point data.

Conclusion: Software tools like EasyMineXR, developed in the mining and exploration industry, can be used for collaborative, geological exploration of planets like Mars where images are available.

Figure 1: Example of the three-dimensional image of Mars, with mapped traces of faults (red), fractures (green) and bedding (blue). Orientation measurements shown as red disks.

References:
Mars Water Well Performance: Experimental Heat Transfer Results Supporting Simulations. Stephen J. Hoffman¹, James H. Lever², Alida D. Andrews³, and Kevin D. Watts⁴. ¹The Aerospace Corporation, 2525 Bay Area Blvd., Houston, Texas 77059; stephen.j.hoffman@nasa.gov. ²U.S. Army Cold Regions Research and Engineering Laboratory, 72 Lyme Rd, Hanover, NH, 03755; james.lever@erdc.dren.mil. ³The Aerospace Corporation, 2525 Bay Area Blvd., Houston, Texas 77059; alida.andrews-1@nasa.gov. ⁴NASA Johnson Space Center, 2101 E NASA Pkwy, Houston, TX 77058; kevin.d.watts@nasa.gov.

Introduction: Current theory holds that Mars once had abundant water flowing on its surface, but now there is a general perception that this surface is completely dry [1]. Several lines of research have shown that there are sources of potentially large quantities of water ice at many locations, including regions considered as candidates for future human missions [2]. Recent discovery of exposed water ice scarps in Martian mid-latitudes [3] has bolstered the evidence for massive amounts of almost pure water ice in some of these regions.

These favorable indications of massive quantities of water have initiated studies of potential changes to human Mars missions if a means can be devised to make this water available to these crews [4]. One such approach relies on mechanical drills to access the water ice through overlying debris and then using a technique known as a Rodriguez Well to melt the ice, store the resulting water in a subsurface ice cavity until needed, and then pump the water to the surface for use [5]. The Rodriguez Well technique has been used in terrestrial polar regions since the early 1960’s and has been supplying fresh water to the Amundsen-Scott South Pole Station since 1995.

![Figure 1. 1960's era Rodriguez Well [5].](image)

Previous planning work in this area utilized a computer simulation to predict the performance of the Rodriguez Well [5]. While the basic approach used in this model is appropriate for a similar well on Mars, several parameters must be changed to correctly model the Martian environment. Parameters used in this model that are related to heat transfer between water and the atmosphere as well as between ice and the atmosphere are empirically derived. Consequently, experiments simulating a pool of water in the Martian environment are required to determine appropriate heat transfer values if this simulation is to be used in support of future Mars missions.

Simulated Mars Environment: An experiment was set up at the NASA Johnson Space Center, with the assistance of the U.S. Army’s Cold Regions Research and Engineering Laboratory, to measure these heat transfer coefficients under Mars surface environmental conditions. These tests were carried out in a small bell jar, with a chamber measuring roughly 2 feet (61 cm) in diameter and 2 feet (61 cm) tall. An internal cooling shroud connected to a Julabo™ chiller allowed gas temperatures as low as -40 C.

![Figure 2: NASA JSC Two-Foot Bell Jar [NASA]](image)

The experiment used a pool of deionized water in an insulated dewar, ensuring that heat loss would only be from the top of the water pool. A resistance heater was held in the water pool and was connected to a resistance temperature detector (RTD), also in the water pool, in a feedback loop to maintain a specified water temperature: either 1° C or 2° C. The power used by the heater was a measure of the heat transferred from the water to the gas. A load cell under the dewar measured the mass loss of water due to evaporation. The
interior of the chamber was instrumented with RTDs and thermocouples at various locations, heat flux sensors at the chamber wall, a pressure transducer for gas pressure, and a relative humidity sensor. A camera and LED light source were used to monitor for ice formation on or in the dewar.

**Figure 3. Experiment Setup**

**Experiment Test Points:** Natural convection, driven by evaporation and heat flow from the pool, governs the flow regime inside a Rodriguez Well. The experiment was operated at several test points to gather data from which heat transfer coefficients and water evaporation rates could be derived. For all tests, the chamber was filled with essentially pure CO₂. Two insulated hemispherical dewars, one 11.4 cm (4.5 in) in diameter and the other 15.2 cm (6.0 in) in diameter, were used to hold the water pool, allowing tests at two different water-pool surface areas. Two gas temperature points (-20° C and -40° C) and several gas pressures, ranging from 1000 mbar (750 torr) to 8 mbar (6 torr) were used to gather these data. Test conditions were chosen to learn whether the experimental work of Bower and Saylor [6] that related natural-convection flow properties to evaporation rates in terrestrial conditions, via dimensionless Rayleigh and Sherwood numbers, could be extended to Mars surface conditions. In all, 12 combinations of pressure, temperature, and water pool diameter were used in this experiment.

**Initial results:** Tests at all 12 test points have been completed and data are being evaluated. One clear outcome is that a water pool representative of a Rodriguez Well can be created and maintained at 1°C to 2°C under Mars surface pressure and temperature conditions. Quantitative results for convective mass transfer correlate well with Bower and Saylor even at Mars surface conditions, as shown in Figure 4. Results for convective heat transfer are higher than expected and are still under analysis to explain this outcome.

**Conclusion:** Favorable indications of massive quantities of water on Mars have initiated studies of potential changes to human Mars missions. Using a technique known as a Rodriguez Well to melt the ice, store the resulting water in a subsurface ice cavity until needed, and then pump water to the surface for use is one potential means to effect these changes. A computer simulation of the Rodriguez Well in a terrestrial environment is one of the engineering tools being used to characterize the performance of this type of well on Mars. An experiment at the NASA Johnson Space Center is gathering data for convective heat transfer and evaporation rates at Mars surface conditions so that this computer simulation can be properly modified to predict performance on Mars. While quantitative results await processing, tests have indicated that a pool of water can be maintained at 1°C to 2°C while at Mars surface temperatures and pressures.

**Figure 4. Current Results Plotted With Bower and Saylor Results.**