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Extraction and Processing

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Extraction and Processing

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

Connor Geiman[1*], James Bultitude[*], Daniel Faber[*], Zachary Burkhardt[*]
[1]connor@orbitfab.space, *Orbit Fab, 274 Shotwell St. San Francisco, CA 94110

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.

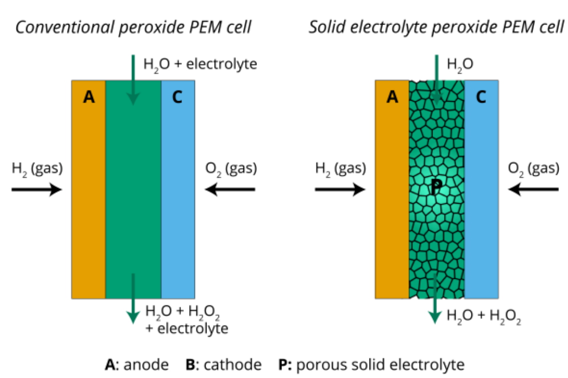

Figure 1: Comparison of conventional electrolyte and porous solid electrolyte hydrogen peroxide PEM cell shows improved configuration of solid electrolyte cell

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

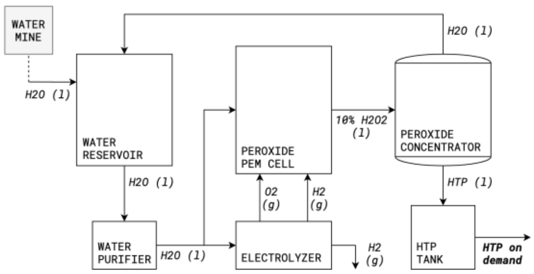

Figure 2: Notional block diagram showing PEM cell and peroxide concentrator integrated into compact water-to-HTP system

methods.

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 produc-

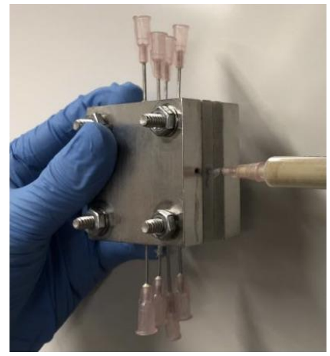

Figure 3: Prototype solid electrolyte PEM cell developed by the Wang Group at Rice University

tion 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.

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LUNAR AUGER DRYER ISRU (LADI) BREADBOARD TESTING AND MODEL VALIDATION.
J. A. Collins[1], L.R. Erickson[2], and O. Walton, [1 & 2]NASA Johnson Space Center (2101 NASA Parkway, Houston, Texas 77058; jacob.collins-1@nasa.gov; lisa.erickson@nasa.gov), [3]Grainflow Dynamics Inc. (1141 Catalina Drive, PMB-270, Livermore, CA 94550; walton@grainflow.com).

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.

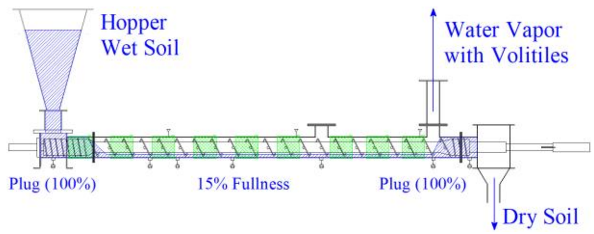

Figure 1 – Breadboard Auger Dryer with heaters (green) and 100% full inlet/outlet plug soil seal (blue)

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.

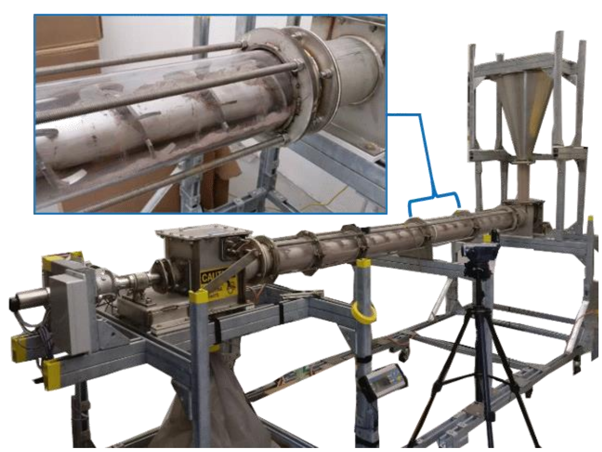

Figure 2 – Existing Mars Screw Conveyer Dryer Breadboard System (clear casing installed)

LUNAR AUGER DRYER ISRU (LADI) BREADBOARD TESTING AND MODEL VALIDATION. J. A. Collins, L.R. Erickson, and O. Walton.

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.

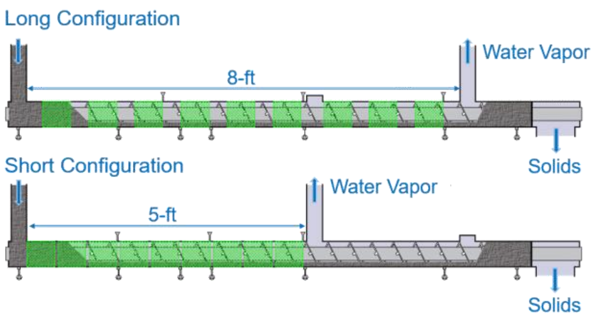

Figure 3 – Alternate Heater Configurations

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).

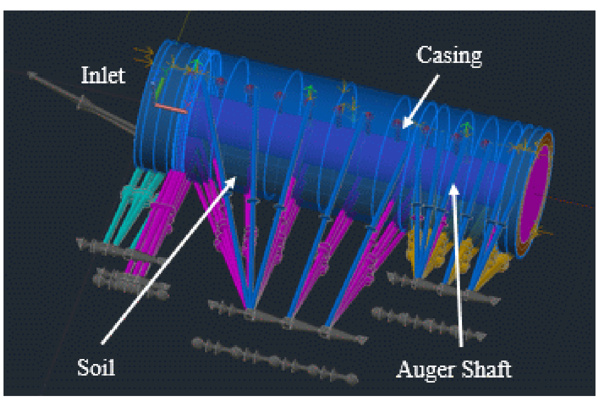

Figure 4 – Thermal Desktop Model

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).

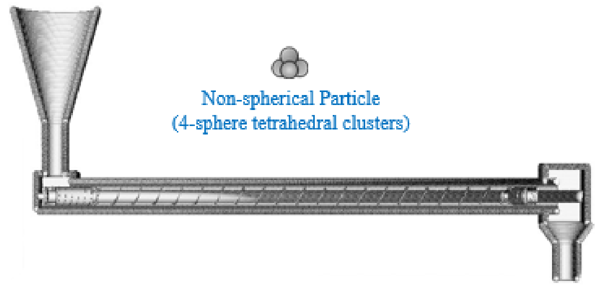

Figure 5 – DEM Model Geometry

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.

K. Hadler (k.hadler@imperial.ac.uk), J. Rasera, R. Cruise, Y. Yu, J. Witchalls, S. Starr, and J. Cilliers, (Department of Earth Science and Engineering, Imperial College London, SW7 2AZ, UK)

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.

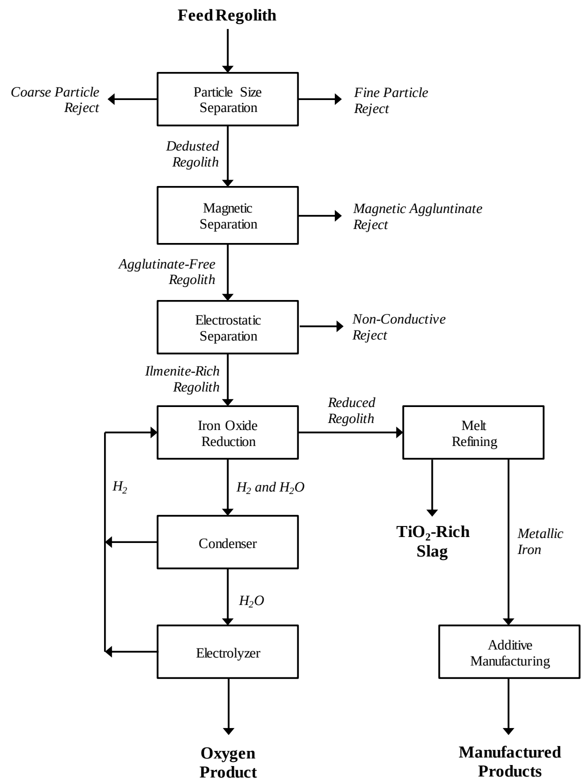
The target metallic iron/steel production rate would initially support additive manufacturing methods for production of replacement parts, piping, tools, and habitat components. As manufacturing capabilities are further developed for larger-scale items, the production of solar thermal power systems, 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.

E. Kumai[1], M. Tanaka[1], T. Watanabe[1], T. Hoshino[2], S. Hosoda[2], and H. Kanamori[2]
[1]Department of Chemical Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan; kumaieri@kyudai.jp, mtanaka@chem-eng.kyushu-u.ac.jp, watanabe@chem-eng.kyushu-u.ac.jp
[2]Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan; hoshino.takeshi@jaxa.jp, hosoda.satoshi@jaxa.jp, kanamori.hiroshi@jaxa.jp

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.

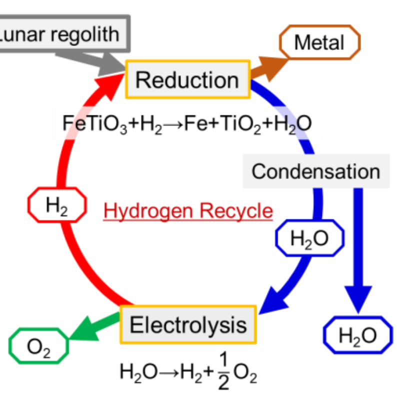


Figure 1 Schematic of hydrogen reduction system.

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.

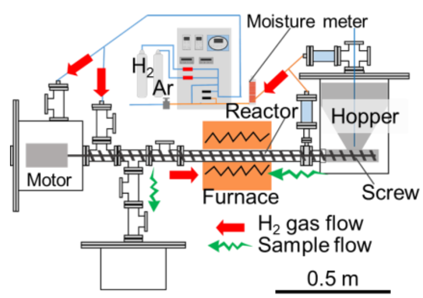


Figure. 2 Schematic diagram of the continuous screw reactor for hydrogen reduction system.

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.

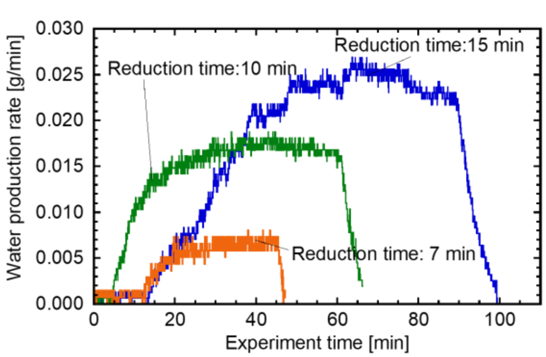


Fig. 3 Effect of reduction time on water production rate in 3vol% hydrogen at 1273 K.

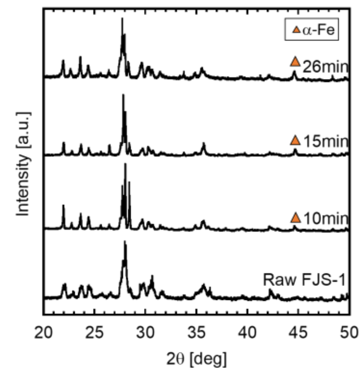


Fig. 4 XRD chart of lunar simulant after hydrogen reduction in different reduction times in 3% hydrogen at 1273 K.

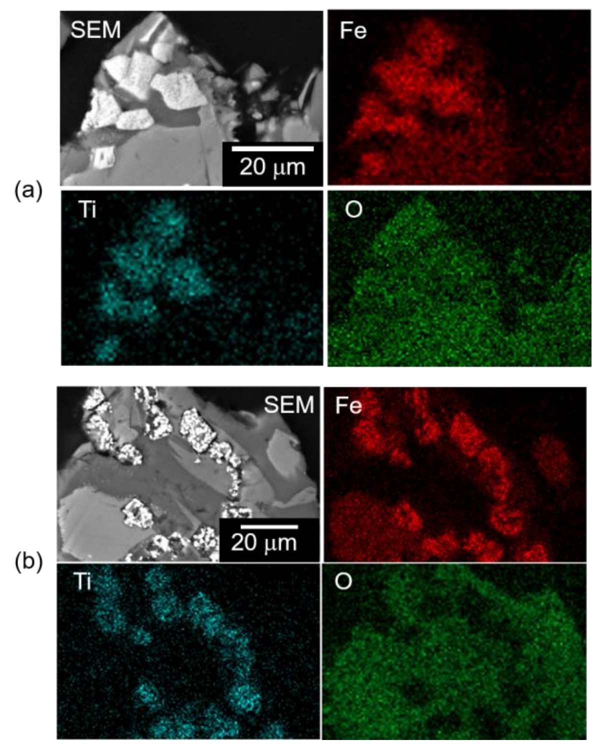


Fig. 5 EDS results of (a) Raw FJS-1 and (b) products reduced for 26 minutes in 3% hydrogen at 1273 K.

References:

[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.

References: [1] Colaprete, A., Schultz, P., Heldmann, J., Wooden, D., Shirley, M., Ennico, K., ... & Sollitt, L. (2010). Detection of water in the LCROSS ejecta plume. *science*, *330*(6003), 463-468.
[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.

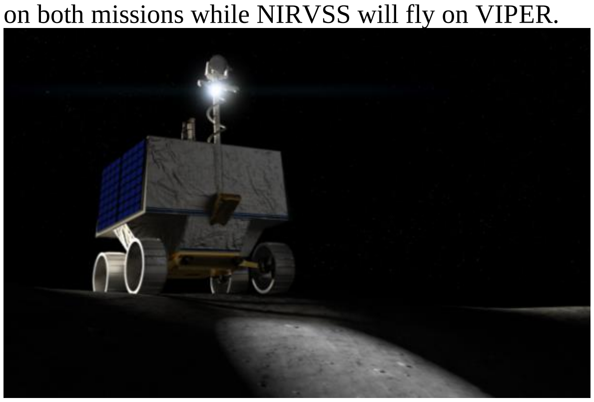


Figure 1. VIPER mission. TRIDENT is placed in vertical position in the middle of the rover.

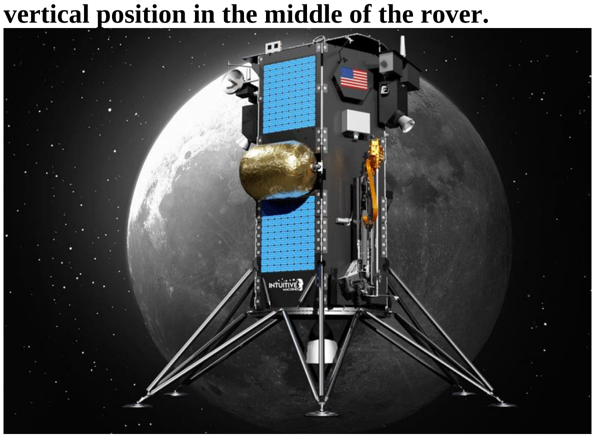


Figure 2. PRIME1 mission. TRIDENT is vertically mounted on the right hand side of the Intuitive Machines (IM) lander.

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.

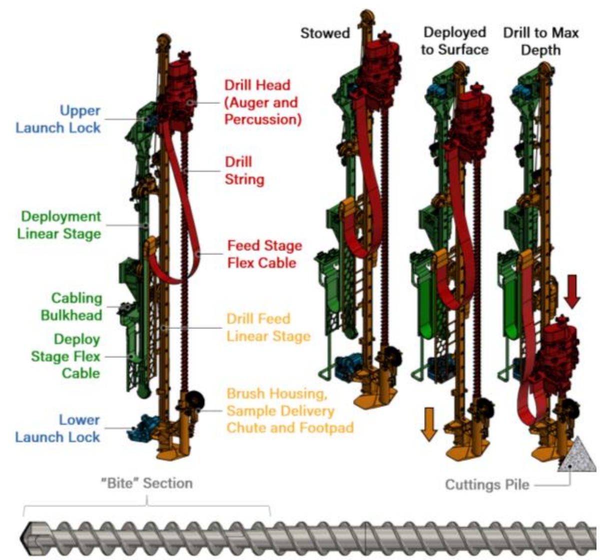


Figure 3. TRIDENT subsystems. The sampling auger is pictured at the bottom.

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.

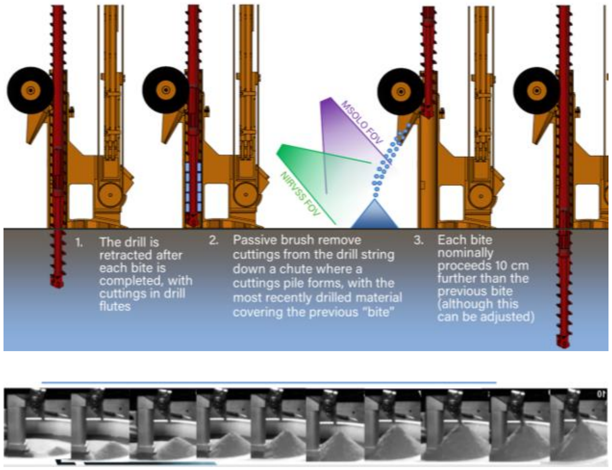


Figure 4. Bite sampling approach. Shown below are cuttings cones every 10 cm bite.

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.

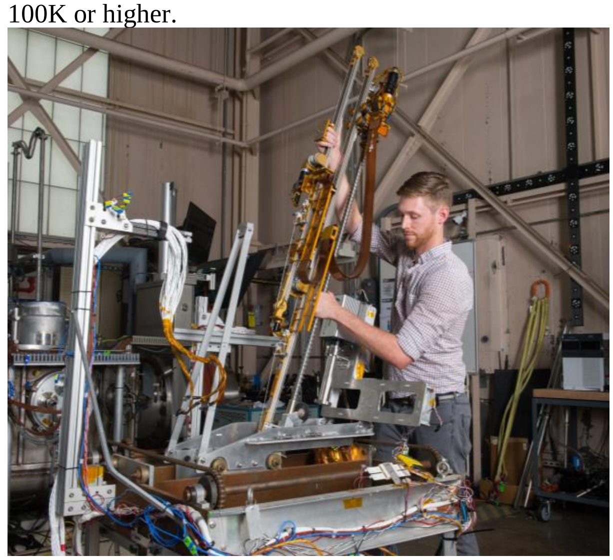


Figure 5. TRIDENR drill undergoing TVAC tests at NASA GRC.

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.

References: [1] Colaprete et al., (2020), LPSC, [2] Zacny et al., (2018), LPSC, [3] Paulsen et al., (2018), Aerospace Mechanisms Symposium.

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.

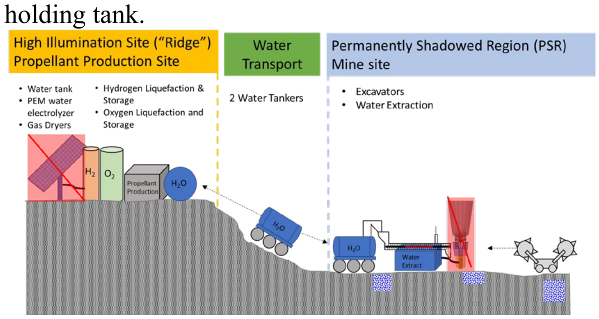


Figure 1: The ISRU architecture used for the model. Tentative power systems are shown for completeness, but were not included.

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.

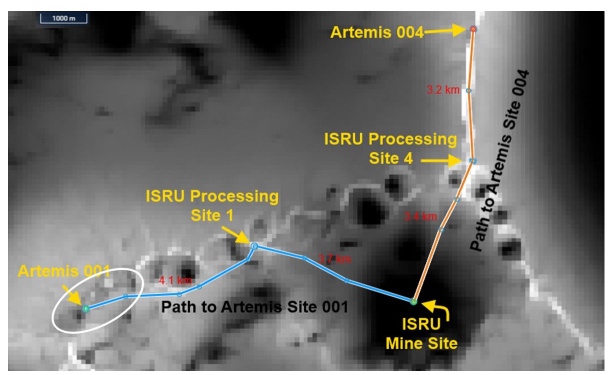


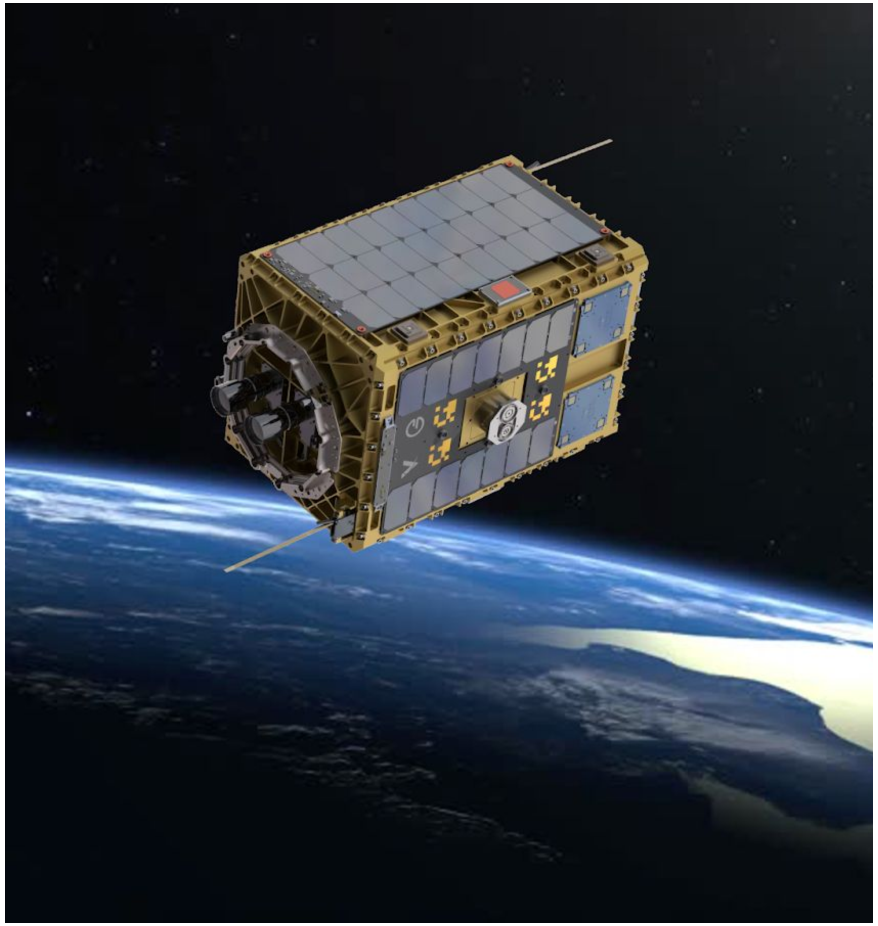
Figure 2: Notional lunar sites and traverse paths used in the model.

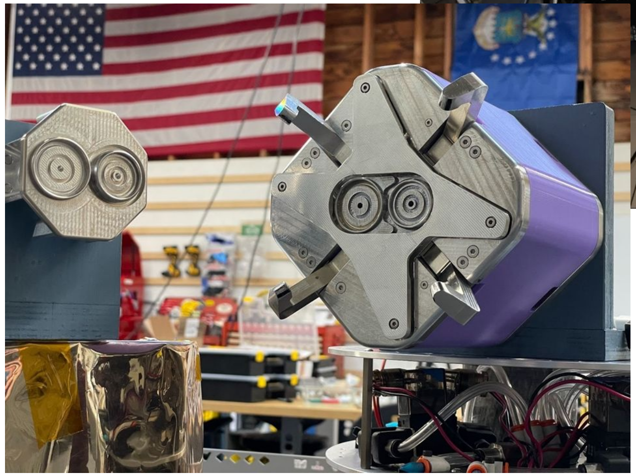
References: [1] NASA'S Plan For Sustained Lunar Exploration and Development (2020). https://www.nasa.gov/sites/default/files/atoms/files/a_sustained_lunar_presence_nspc_report4220final.pdf [2] Linne, D.L., et. al. (2021). Journal of Aerospace Engineering. Publication Pending. [3] Kleinhenz, J.E. and 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.

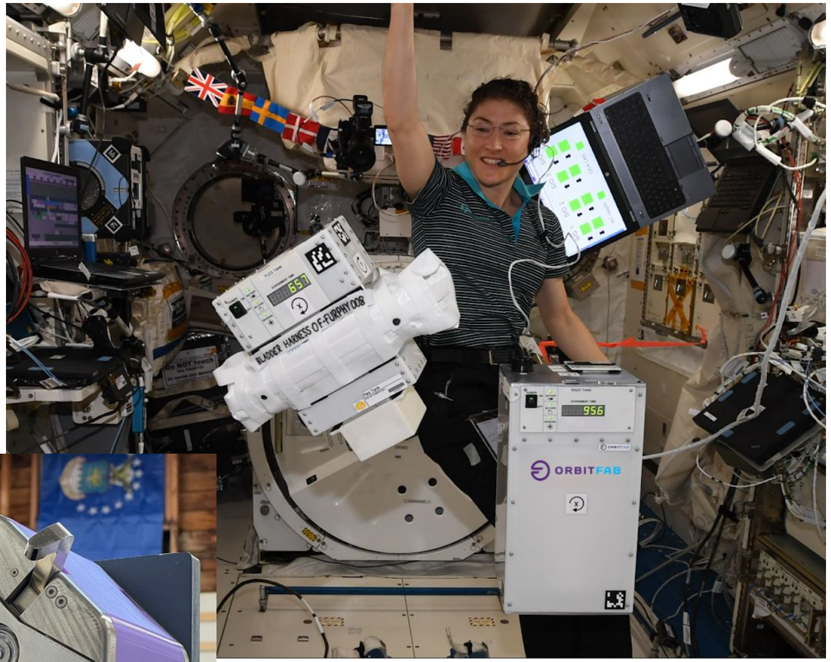
High-Test Peroxide Production System for In-Situ Propellant Manufacture from Extraterrestrially Mined Water

Connor Geiman, Haotian Wang, Alex Deuitch, James Bultitude, Daniel Faber, Zachary Burkhardt

Orbit Fab – Gas Stations in Space





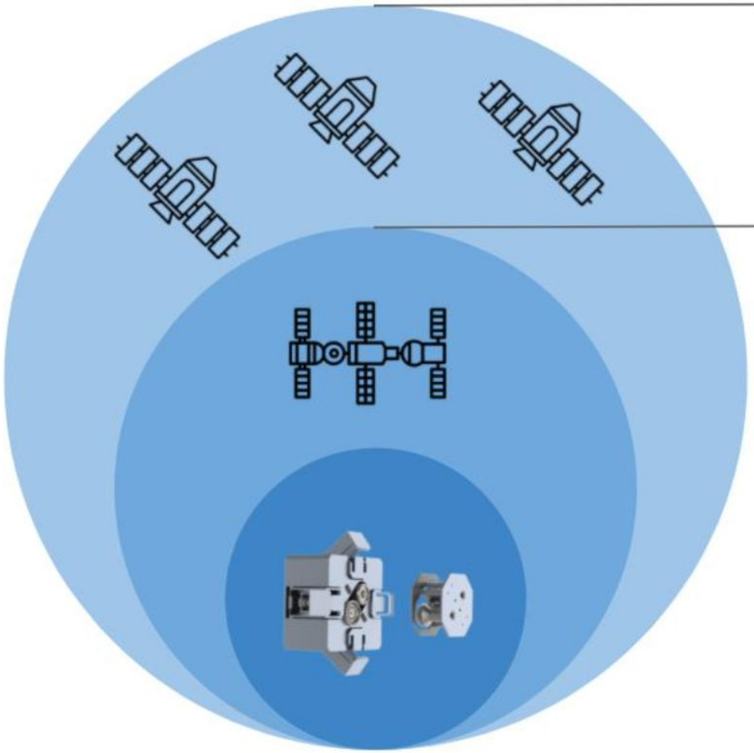


NASA's Artemis Priorities

NASA's Plan for Sustained Lunar Exploration and Development (2020):

"ISRU will enable the production of fuel, water, and/or oxygen from local materials, enabling **sustainable surface operations with decreasing supply needs from Earth**."

The Propellant Market



$3B Total Market

Total in-space value of all propellant launched to space last year

$1.5B Addressable Market

Total in-space value of all propellant launched on potentially refuelable satellites

The Challenge

→ Off-Earth propellant production is critical to the long term success of the bustling in space economy.

→ But, there is no complete system that could be deployed today to produce and store propellant from mined extraterrestrial resources.

What is the most cost- and time-effective pathway to produce a useful propellant on the surface of the Moon?

Lunar Propellant

Figure: Kutter et al. 2008

Lunar ISRU resource availability:

- Ice may comprise up to ~30 wt% of lunar regolith in some areas. (Sanders 2018)
- Oxygen comprises up to 40 wt% of lunar regolith. (Sanders 2018)
- Nitrogen and carbon in lunar samples are present at ppm levels. (Sanders 2006)

In-Situ Propellant Options

Cryogens: high complexity, not yet storable

- Hydrolox: can be produced from water alone. But, despite much funding, cryogens need more time before fluid management and storability technology is ready.

Chemical storable:

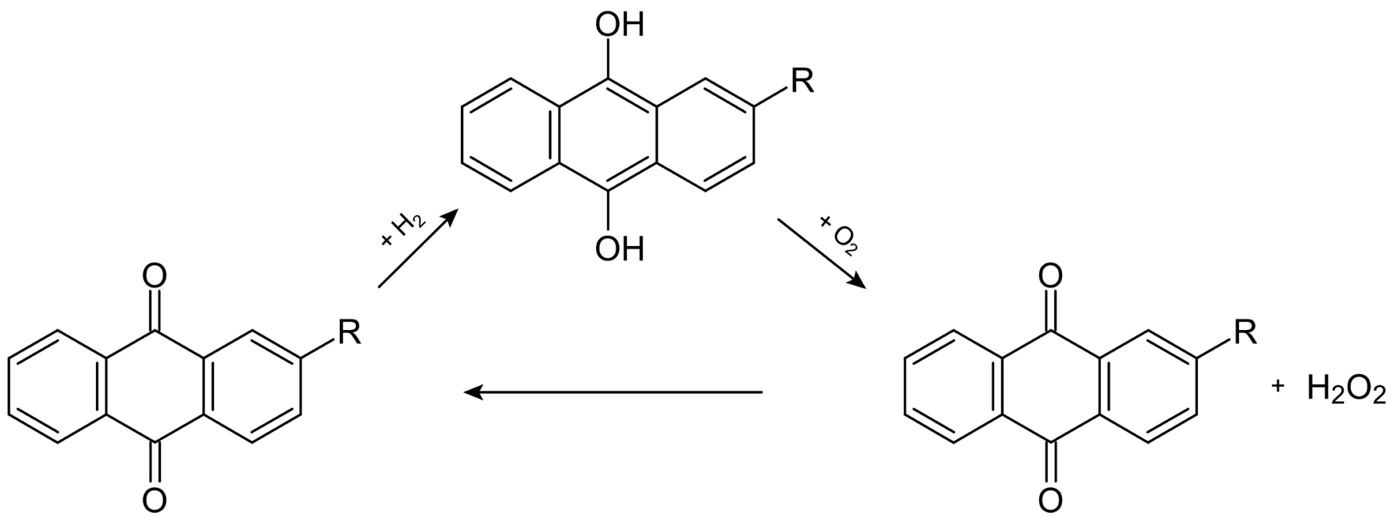
- Hydrazine: widely used but needs nitrogen (non-ISRU). Toxic.
- High-test peroxide (HTP): can be produced from water alone. Storable and nontoxic with enough specific impulse for lunar and small body ascent.

High-Test Peroxide for ISRU

HTP can be stored, but is there a way to produce it in a compact form factor?

Biggest hurdle: turn water into low-concentration hydrogen peroxide.

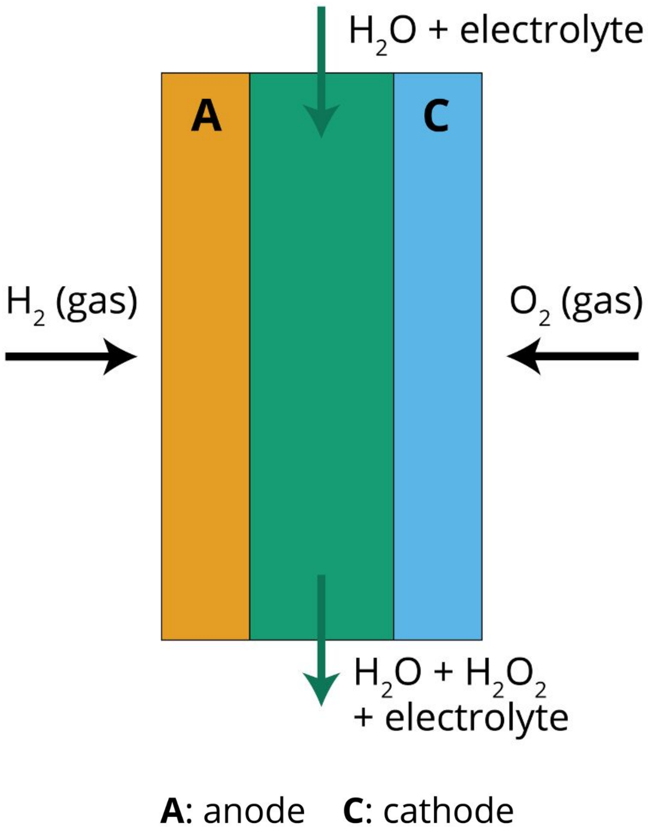
Peroxide: Anthraquinone Process



Most widely used process to produce hydrogen peroxide.

Drawbacks: wasteful, resource intensive, and challenging to scale for ISRU.

Peroxide: Electrosynthesis

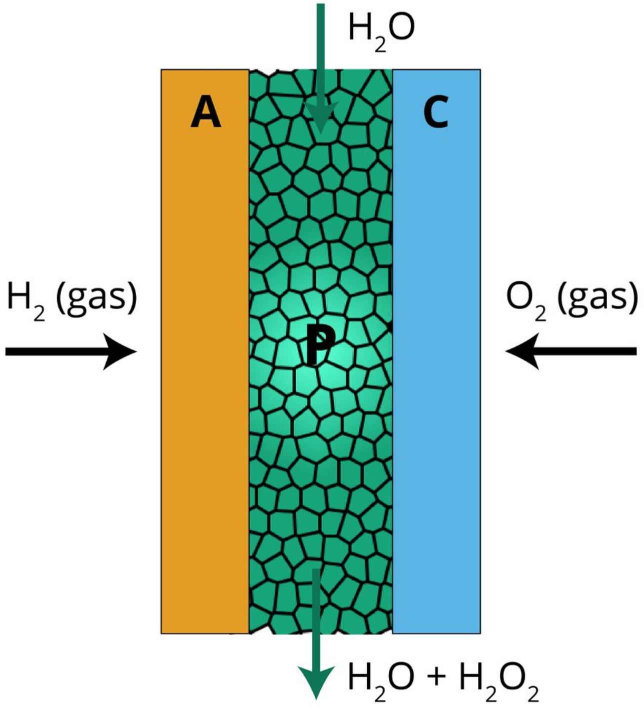


Benefits

- Little to no waste.
- Less energy intensive.
- Scalable form factor.
- Not dependent on gravity to function.

Drawback: step of electrolyte separation required.

Peroxide: Solid Electrolyte Electrosynthesis



A: anode **C**: cathode
P: porous solid electrolyte

Replace liquid electrolyte with a porous solid to get the **benefits of electrosynthesis without the intermediate step** of electrolyte separation.

Thus, water, oxygen, and hydrogen are turned directly into high-purity low-concentration hydrogen peroxide.

Peroxide: Solid Electrolyte Electrosynthesis

PEM cell reaction equations:

Anode hydrogen oxidation reaction:

$$H_2 \rightarrow 2H^+ + 2e^-$$

Cathode oxygen reduction reaction:

$$O_2 + H_2O + 2e^- \rightarrow HO_2^- + OH^-$$

Overal PEM cell reaction:

$$HO_2^- + H^+ \rightarrow H_2O_2$$

Peroxide: Solid Electrolyte Electrosynthesis

- TRL 6 cell produces 130 L of 1% peroxide per hour per square meter of membrane.
- When coupled with a concentrator, only 0.69 m^2 area cell is needed to produce 1 L/hr of 90% HTP.
- Resulting PEM cell energy consumption is about 850 W.

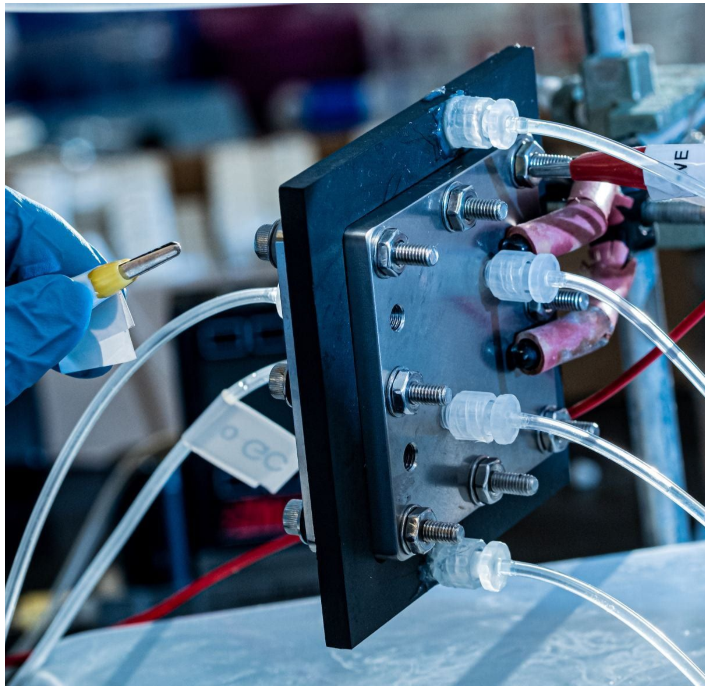


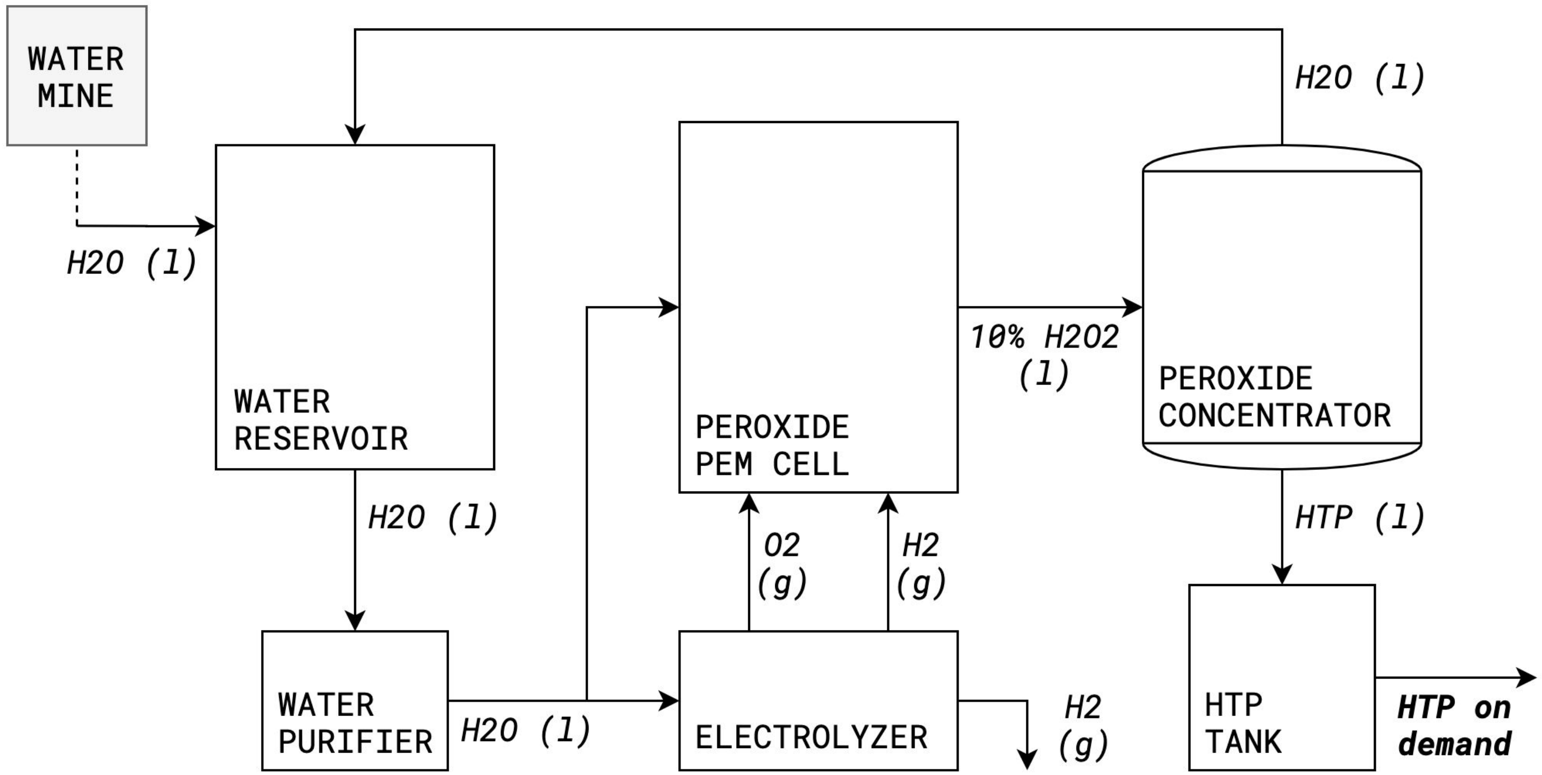
Figure: Haotian Wang

HTP Production System Architecture

The **new solid electrolyte peroxide cell**, coupled with **mature concentration technology**, enables several architectures with inputs of:

1. hydrogen, oxygen, and water
2. oxygen and water
3. air and water
4. water

HTP Production System Architecture



Minimum Viable Product system weighing on the order of 100 kg will output liters per hour.

Conclusions

- A benchtop prototype could be built in a year's time.
- A system could be ready to fly in 2023 and deployed on the lunar surface soon after.
- Capital requirements for fully operational space production system: single digit millions.
- The HTP system will build operational expertise and enable rapid iteration for future propellant diversification.

References

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Xia, Chuan, et al. "Direct Electrosynthesis of Pure Aqueous H_2O_2 Solutions up to 20% by Weight Using a Solid Electrolyte." Science, vol. 366, no. 6462, Oct. 2019, pp. 226–31.

Lunar Auger Dryer ISRU (LADI) Breadboard Testing and Model Validation

11th Joint
Planetary and Terrestrial Mining Sciences Symposium (PTMSS)
and
Space Resources Roundtable (SRR)

June 7th to 11th, 2021

DARE
UNITE
EXPLORE

Jacob Collins

NASA Johnson Space Center (JSC)

Houston TX

Overview

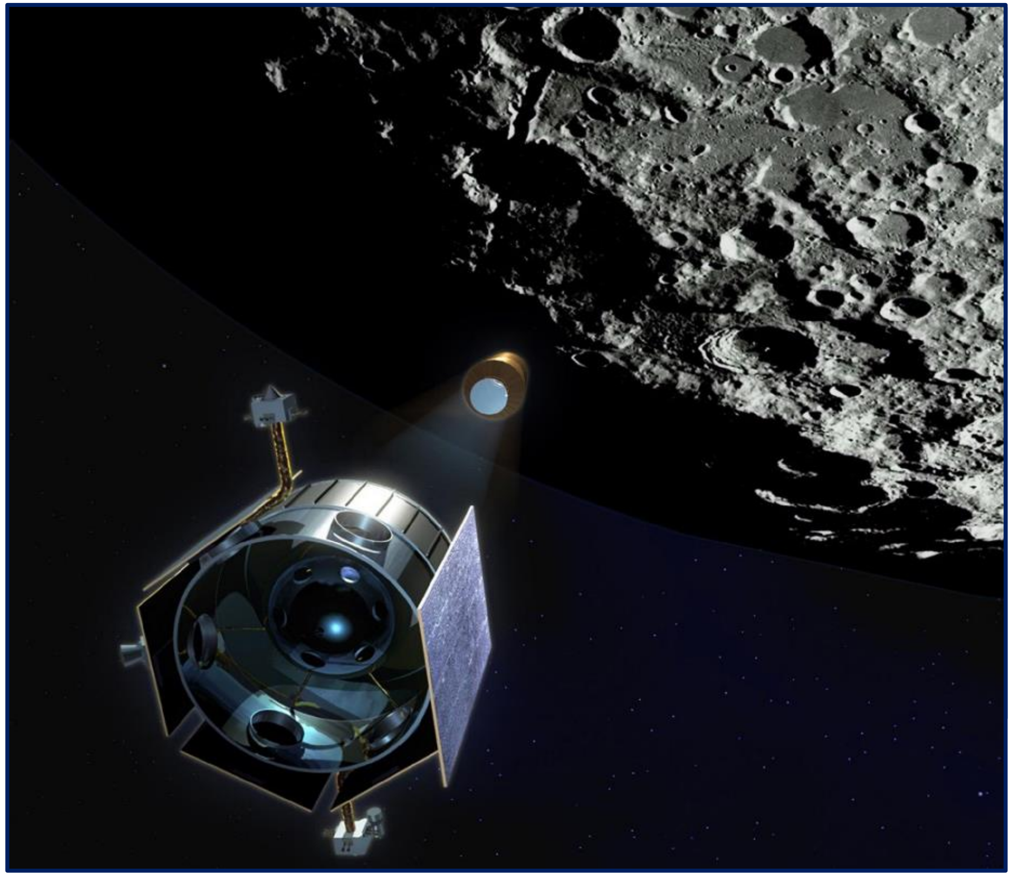
- My Background
- Why Return to the Moon?
- Lunar Water Processing Plant
- LADI Breadboard Capability Video
- LADI Subsystem Breadboard Testing
- LADI Modeling
- Summary

Background Information

- Born and raised in Houston Texas (Space City)
- Married with 3 boys - oldest is a freshman in college and youngest just finished 3rd grade
- Hobbies range from Boy Scouts, guitar, coaching martial arts, video games, to serving in my church
- B.S. in Chemical Engineering and M.S. in Physics
- Been with NASA ~20 years and worked many projects and played many roles

Why Return to the Moon?

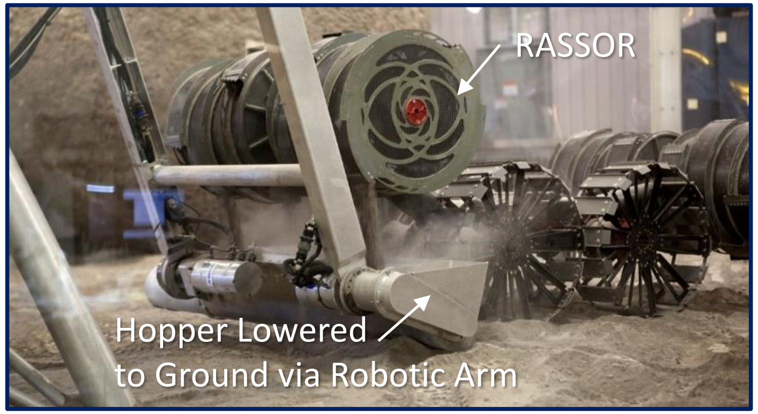
- 1976 Luna-24 sample analysis showed ~0.1% water by mass
- 1994 Clementine spacecraft indicated water ice at poles
- 1998 Lunar Prospector detected H_2 using a neutron spectrometer and estimated 300 million MT water ice
- 2008 Chandrayaan-1 estimates 600 million MT
- 2008 analysis of Apollo samples indicated presence of water
- 2009 LRO and LCROSS provided definitive proof [1]:
  - Slammed centaur upper stage (from LRO) into Cabeus crater
  - Permanently Shadowed Region (PSR) estimated at 5.6 ± 2.9% (mass) water content
- 2020 NASA Technology Taxonomy[2] and Lunar Surface Innovation Initiative (LSII) team identified capability gaps in icy regolith transfer and reactor processing



LCROSS Lunar Impact (artist concept)

Lunar Water Processing

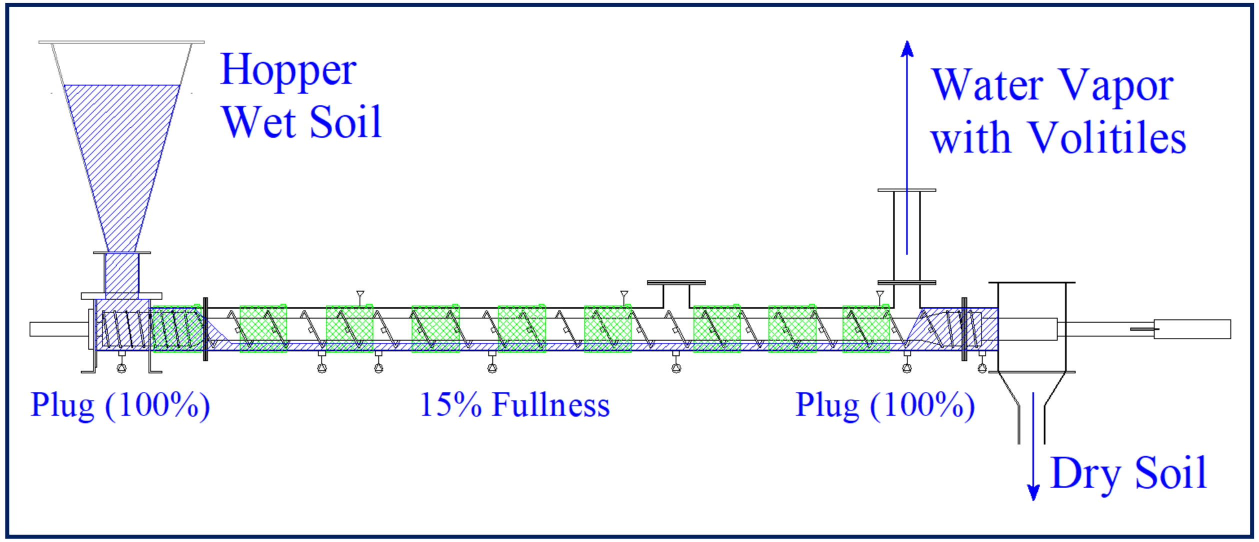
- Major lunar water processing plant subsystems include:
  - Upstream Excavation rover and Hopper / Size-sorter [KSC]
  - Screw Conveyor Dryer (SCD) located in PSR [JSC]
  - Downstream Cold Trap (de-sublimate water vapor to ice) [GRC]
- Top-level concept of operations:
  - Excavate icy regolith, deliver to hopper (remove large rocks), & feeds auger
  - Regolith is heated to sublimation temperature as it traverses through auger
  - Deposition of water vapor into ice occurs in downstream Cold Trap
  - Discharged warm regolith is removed and excavator repeats process
  - Tanker travels out of PSR, or pressurized and $H_2O_{(L)}$ pumped to electrolyzing processing plant at crater ridge
  - At ridge, water is cleaned, electrolyzed into O_2 and H_2, liquefied, and stored



RASSOR Rover delivering Regolith at KSC "Swamp Works" Laboratory

Lunar Water Processing

- Operates below triple point of water:
  - Maintain low internal pressure (sustain regolith plug)
  - Prevent liquid water phase (increased motor torque and equilibrium chemistry with impurities)
- Variable pitch auger creates 100% full regolith plug-seal at inlet & outlet with 15% heated section fullness:
  - Eliminates inlet/outlet isolation valves and batch processing
  - Isolation valves increase system height, mass, complexity, and reduces reliability

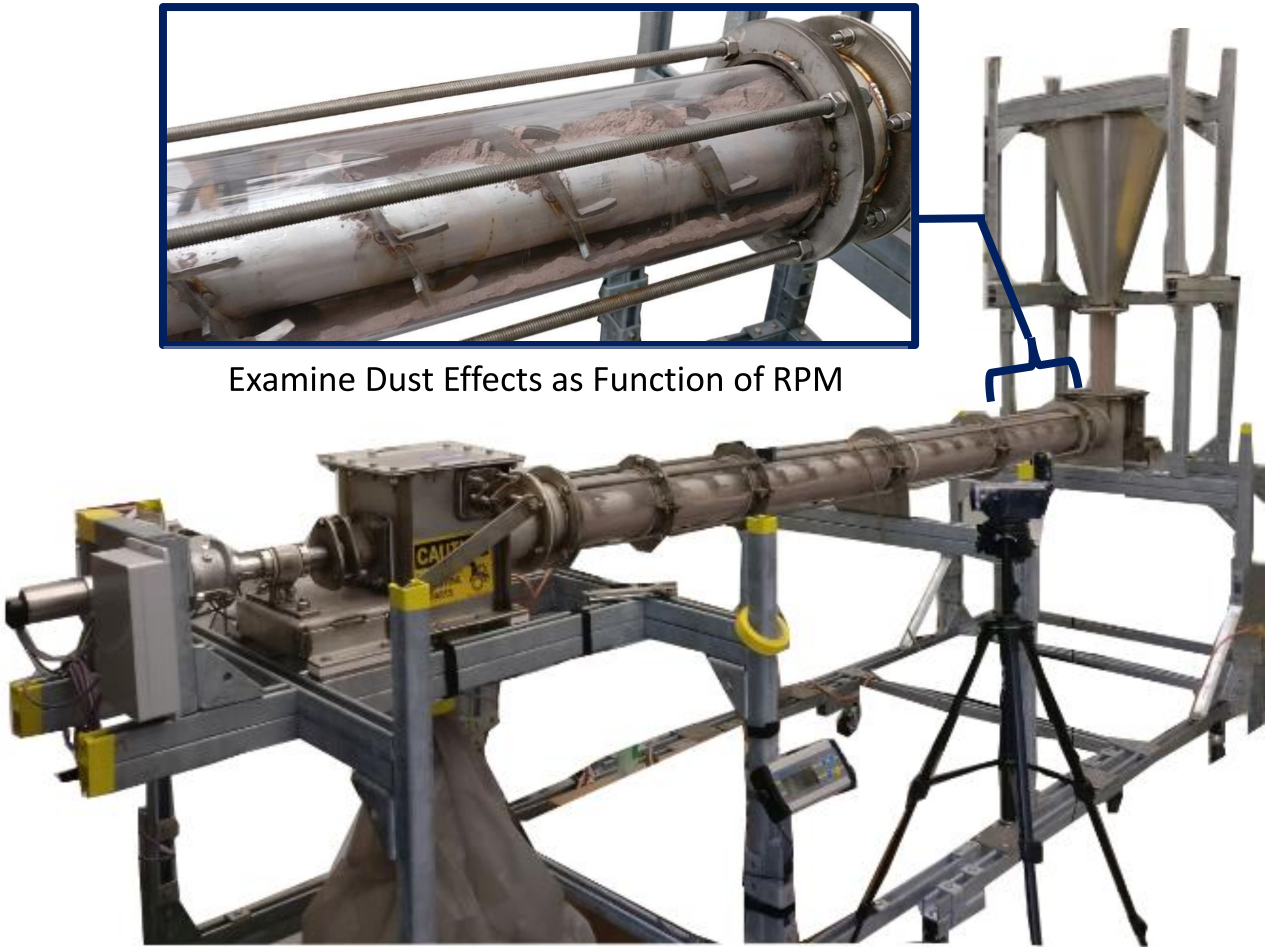


Breadboard Auger Dryer:
Heaters (green) and 100% full inlet/outlet plug soil seal (blue)

LADI Breadboard Capability Video

LADI Subsystem Breadboard Testing

- NASA JSC developed SCD sub-system for Mars operation & fabricated breadboard test stand:
  - Unique capability to operate with either clear or stainless-steel casing
  - Testing postponed with redirection of NASA’s mission from Mars to Moon
- Game Changing Development Program (GCDP) funded tech development project to increase TRL of Lunar Auger Dryer ISRU (LADI) to TRL 5:
  - Near-term goal: Leverage existing hardware to gather physical and thermal data to develop an Engineering Development Unit (EDU)
  - Future goal: Integrate LADI into system and test in a relevant thermal vacuum environment (TRL 6)



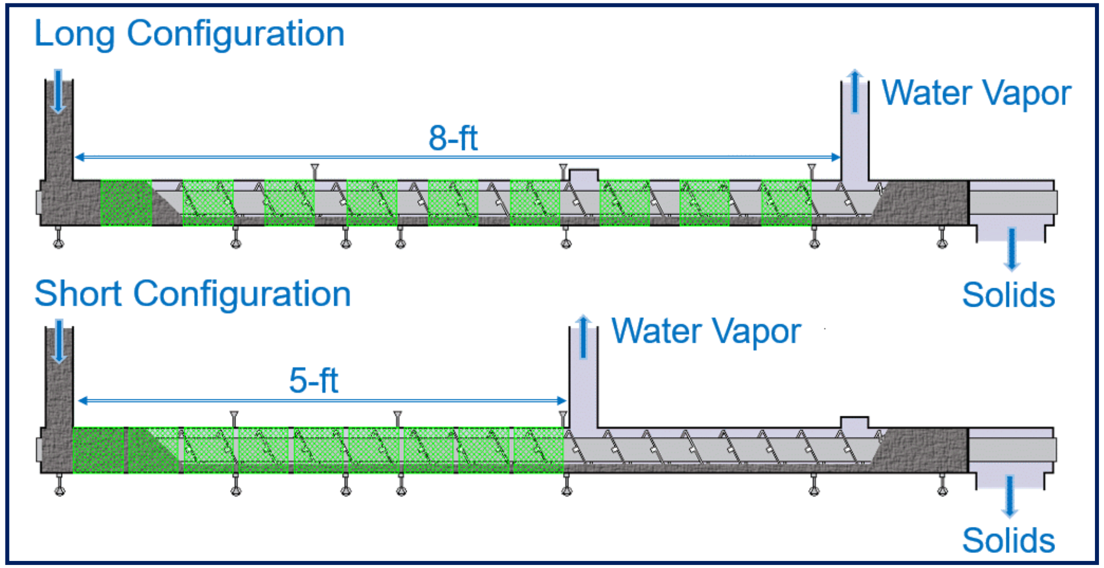
Examine Dust Effects as Function of RPM

Existing Mars Breadboard Screw Conveyer Dryer (clear casing installed)

LADI Subsystem Breadboard Testing

- Mechanical testing performed using the clear casing:
  - Allows flow to be observed while measuring torque, RPM, mass flow rate, gate angel, and power
  - Currently using Lunar Highlands simulant (LHS-1)
  - Max regolith soil-seal pressure will be measured
  - High-density cryogenic blasting dry ice will be mixed with lunar simulant to observe sublimation at lab temp
- Thermal testing requires stainless steel casing and resistance band heaters:
  - Heaters reconfigurable into long or short configuration
  - Operates with three independent zones to manipulate residence time
  - Simulant will be prepared with a 5% to 8.5% water ice (weight %) mixture and heated until vaporization
  - Commercial Off-The-Shelf (COTS) condenser will be used to liquefy vapor and calculate yield

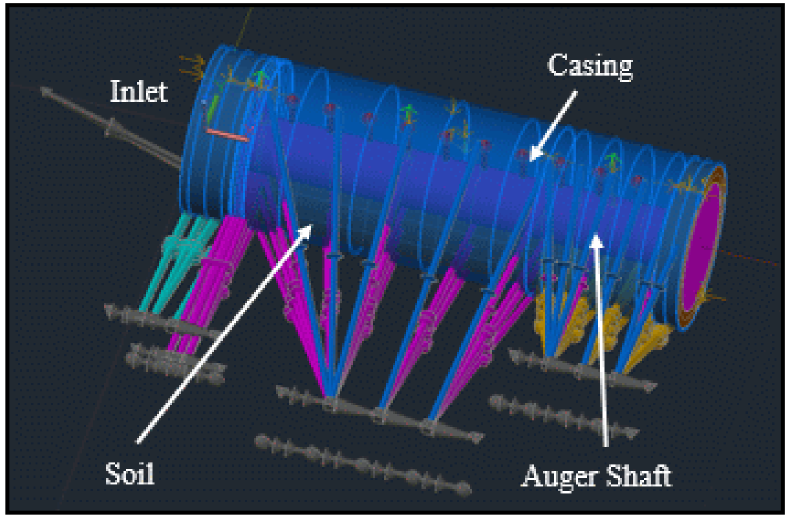
High-Density Cryogenic Dry Ice (~ ⅛")



Alternate Heater Configurations

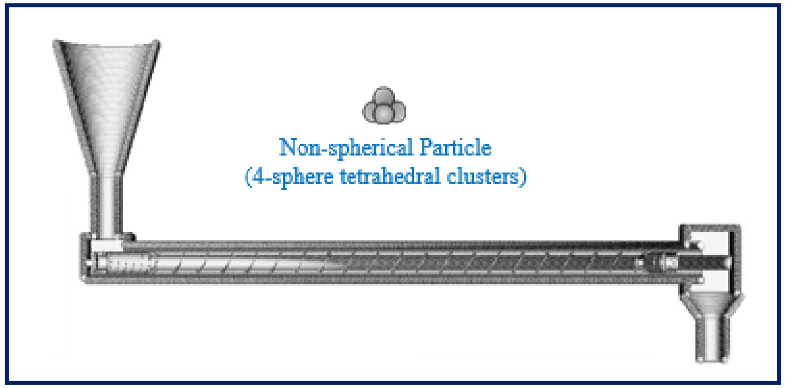
LADI Modeling

- Thermal Desktop Thermal Model:
  - Predict residence time to sublimate ice
  - Verify feasibility of operation below triple point of water (by estimating temperature and sublimated water's partial pressure)
  - Predict heat transfer between bulk particle motion and heated casing
  - Model will be run at laboratory and lunar environment conditions for a pilot plant and full-scale plant scenario
  - Paths set to ice, ice/vapor, or liquid/vapor based on temp of sub-model



Thermal Desktop Model (no heaters or insulation)

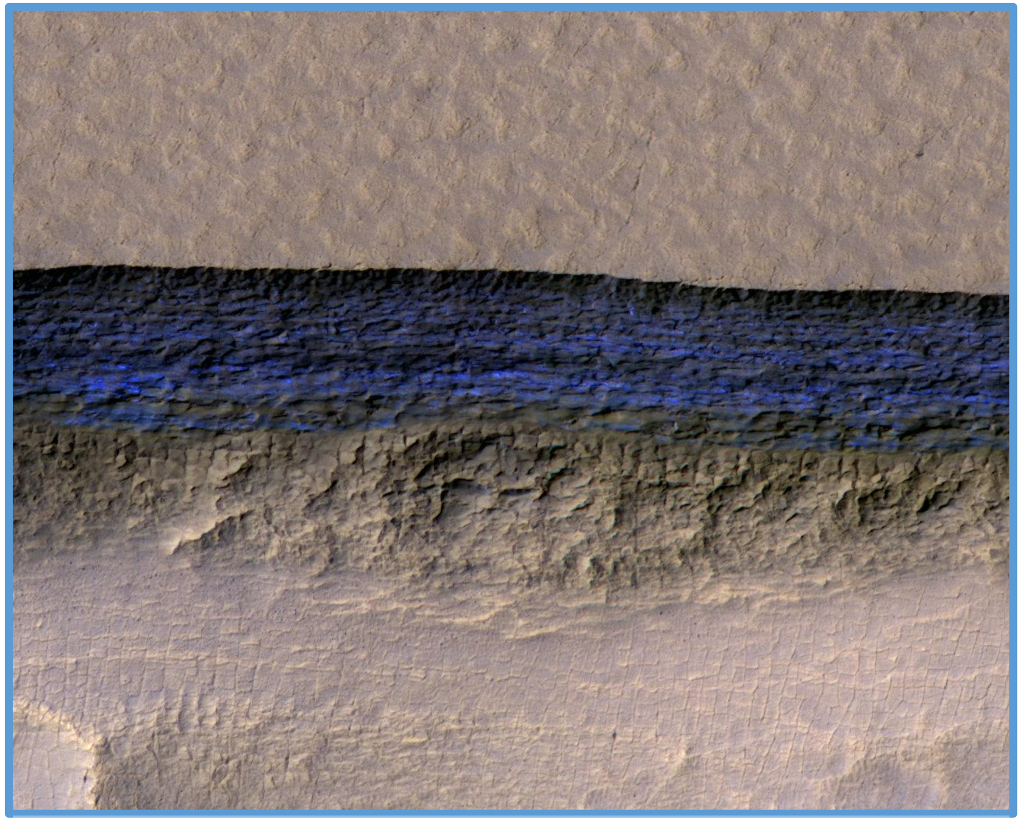
- Discrete Element Method (DEM) Simulation:
  - Compare test observations (clear casing) with particle-scale numerical model
  - Cluster simulates non-spherical particle while cohesion, particle size, and particle count varied until model mimics test results
  - After validated, optimizations to regolith plug seal, auger flight geometry, and flow rate can be performed
  - Gravity can be reduced to lunar conditions to predict lunar performance



DEM Model Geometry

Summary

- 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
- Knowledge obtained will be used as a steppingstone to develop a future Mars auger dryer (combined with a Sabatier reactor) to produce oxygen and methane



Enhanced-color Cross-section of Martian Underground Ice

Backup Slides

- Acronyms
- Image Credit / References
- Water Phase Diagram

Acronyms

EDU	Engineering Development Unit	H_2O	Water
GCDP	Game Changing Development Program	H_2	Hydrogen
GRC	Glenn Research Center	O_2	Oxygen
ISRU	In-situ Resource Utilization		
JSC	Johnson Space Center		
KSC	Kennedy Space Center		
LADI	Lunar Auger Dryer ISRU		
LHS	Lunar Highlands Simulant		
LCROSS	Lunar Crater Observation and Sensing Satellite		
LRO	Lunar Reconnaissance Orbiter		
PSR	Permanently Shadowed Region		
RASSOR	Regolith Advanced Surface Systems Operations Robot		
SCD	Screw Conveyor Dryer		
TRL	Technology Readiness Level		

Image Credit / References

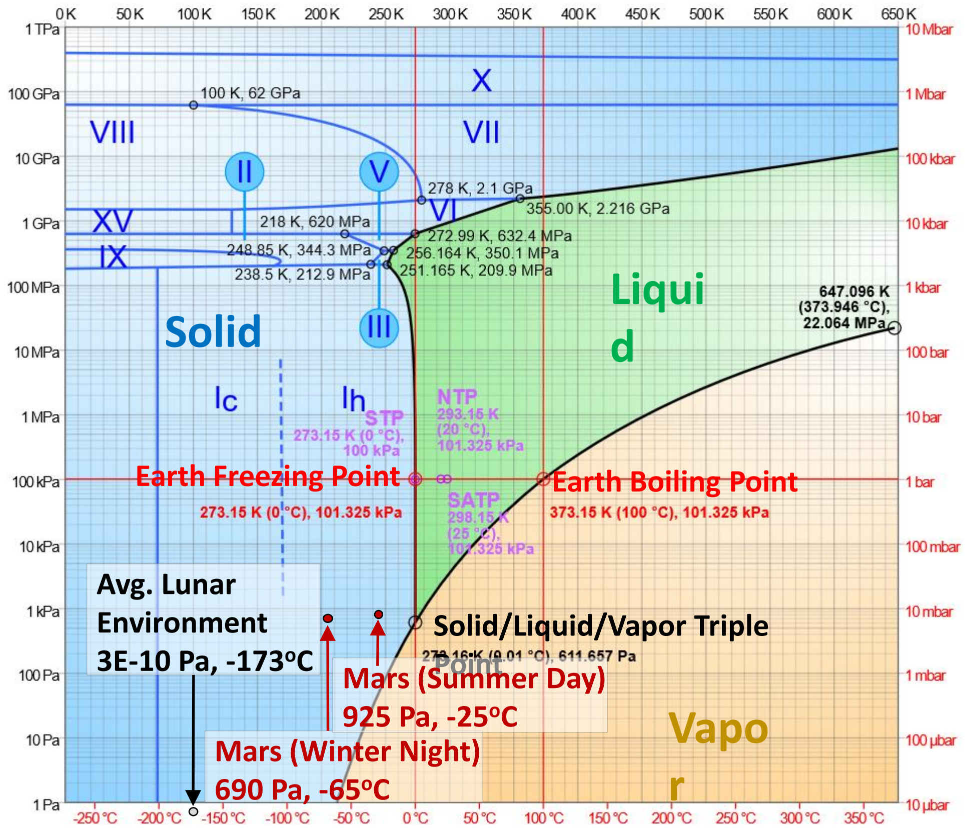
Slide	Image	Public Link
2	Mars-Moon Apollo Footprint	NASA/JPL-Caltech
4	LCROSS Lunar Impact (Artist's Concept) LCROSS Impact Data Indicates Water on Moon	Lunar Impact (Artist's Concept) Ejecta plume image
5	NASA KSC RASSOR Regolith Size Sorter and Hopper	RASSOR, MARCO POLO Demonstrate Resource Utilization on Mars Lunar ISRU 2019 (LPI) (Hopper p.142)
6	Breadboard Auger Dryer inlet/outlet plug soil seal	Chemical Engineering at NASA (Doc ID 20205007596; Video on slide 34)
7	LADI Breadboard Capability Video	New video with lunar simulant (no data shown) added to: Chemical Engineering at NASA (Doc ID 20205007596; Video on slide 34)
8	Existing Mars Breadboard Screw Conveyer Dryer	Chemical Engineering at NASA (Doc ID 20205007596; Video on slide 34)
9	High-Density Cryogenic Dry Ice (~ ⅛") Alternate Heater Configurations	Airgas Dry Ice Products Chemical Engineering at NASA (Doc ID 20205007596; Video on slide 34)
10	Thermal Desktop Model DEM Model Geometry	PTMSS SRR Abstract; Document ID: 20210013233
11	Enhanced-color Cross-section of Mars Underground Ice	NASA/JPL-Caltech/UA/USGS
15	Water Phase Diagram	By Cmglee - Own work, CC BY-SA 3.0 The International Association for the Properties of Water and Steam

[1] A. Colaprete et al. (2010) Detection of Water in the LCROSS Ejecta Plume, Science, Vol 330.

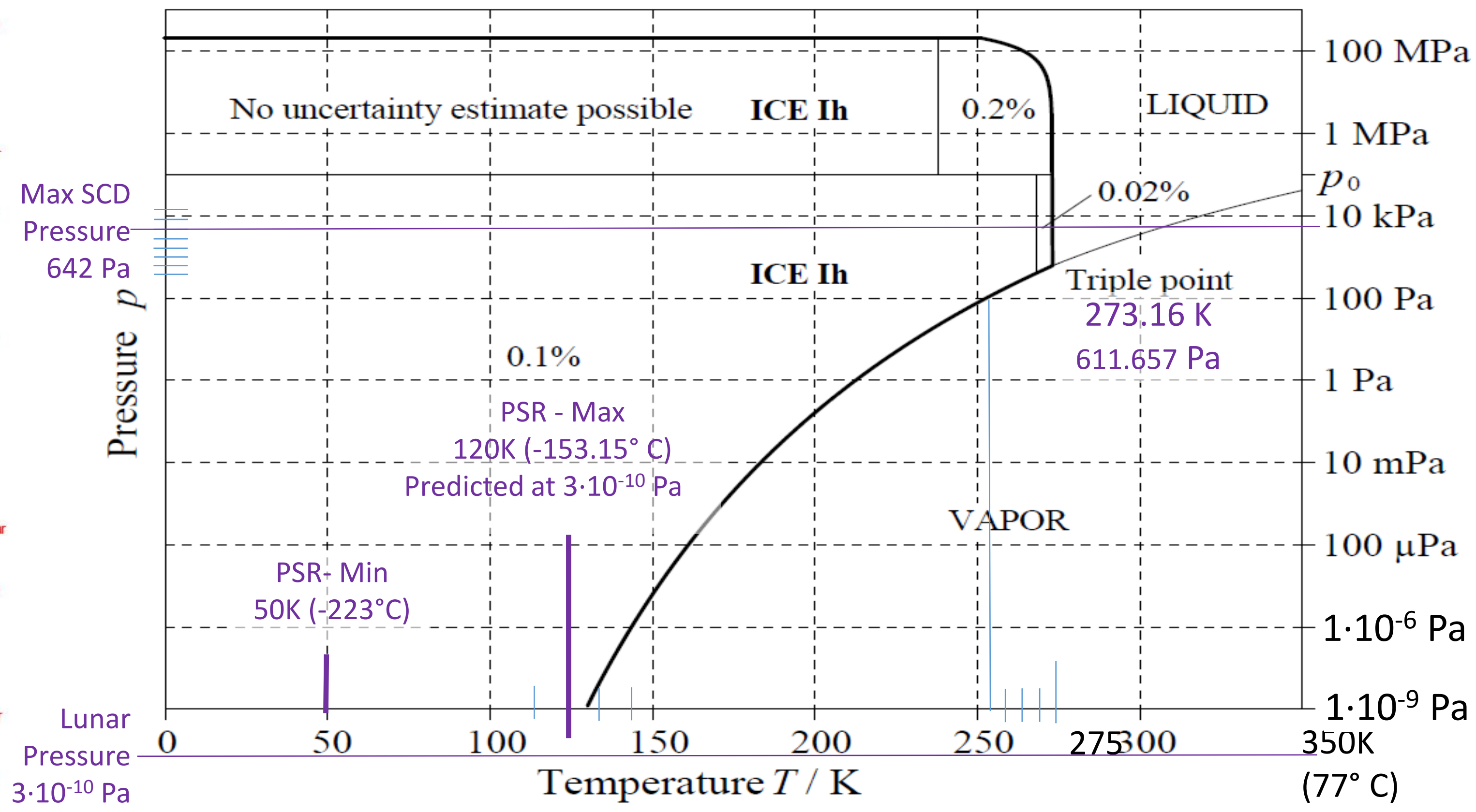
[2] D. Terrier (2020) NASA Technology Taxonomy, NASA.

[3] J. Collins and L. R. Erickson (2021) Lunar Auger Dryer ISRU (LADI) FY20 Formulation Report, JSC-67579 Internal Note.

Water Phase Diagram



Water Phase Diagram



Water Phase Diagram - International Association for Properties of Water and Steam; Doorwerth, The Netherlands, Sept. 2009

Moon to Mars Oxygen and Steel Technology (MMOST)

Mark Berggren
Pioneer Astronautics
Lakewood, Colorado

Presented at:
Planetary & Terrestrial Mining Sciences Symposium/
Space Resources Roundtable
Eleventh Joint Meeting
June 10, 2021

Moon to Mars Oxygen and Steel Technology (MMOST)

NASA JSC SBIR Phase II Sequential Contract 80NSSC20C0250

September 15, 2020 – September 14, 2022

Pioneer Astronautics

Colorado School of Mines

Honeybee Robotics

Moon to Mars Oxygen and Steel Technology

Description:

- Two-year design/build/test/demonstration program
- Integrated system to produce metallic iron/steel and oxygen from beneficiated lunar regolith.
- Employs particle size sorting/dedusting, magnetic-electrostatic beneficiation, materials handling, iron oxide reduction, electrolysis, and melt-refining.
- Iron product to be alloyed as required for demonstration of additive manufacturing, machining, and casting applications.
- Final design targets 35 kg/day Fe and 10 kg/day O_2 with integrated operation.

Moon to Mars Oxygen and Steel Technology

Pioneer Astronautics:

- Beneficiation, iron oxide reduction, and melt refining to produce iron.
- Materials handling/process automation.
- Alloying and casting to produce feedstock for additive manufacturing.
- Conceptual flight system design including mass/power/volume/consumables

Colorado School of Mines:

- Additive manufacturing studies and materials evaluation.
- Vacuum chamber testing of unit operations.
- Simulant and technology consulting.

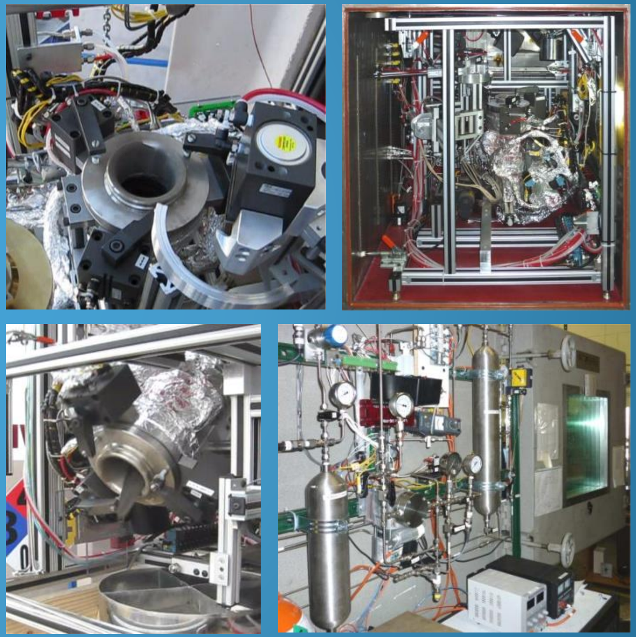
Honeybee Robotics:

- Host integrated system testing in vacuum.

Moon to Mars Oxygen and Steel Technology

Pioneer Precursor Technologies – NASA SBIR Phase I/II

Lunar Soil Particle Separator
(Beneficiation)



Lunar Materials Handling System
(Repetitive Feeding/Discharging;
Process Automation; Hydrogen Reduction)

Moon to Mars Oxygen and Steel Technology

Precursor Technologies – NASA SBIR Phase I/II (continued)

Iron Oxide
Reduction Reactor

Reduced Regolith,
Melting Furnace,
Iron Product

Iron Product
and Machining

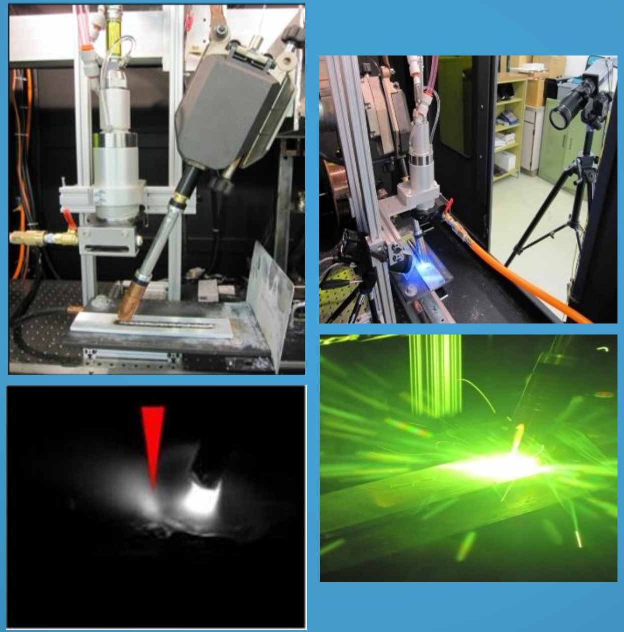
Extraterrestrial Metals Processing

(H_2/CO Reduction; Melt Refining)

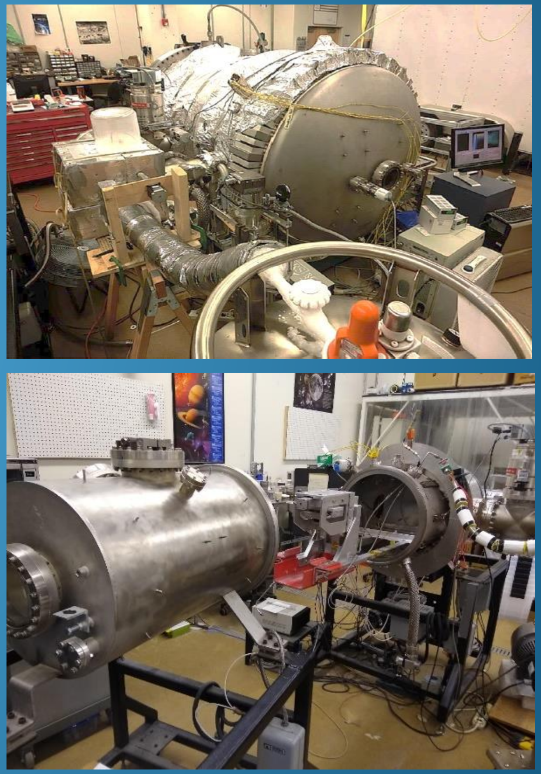
Moon to Mars Oxygen and Steel Technology

Colorado School of Mines – Supporting Technologies

Tubular Mill and
Wire Drawing
(Preparation for Additive
Manufacturing)



Additive Manufacturing Evaluation



High-Vacuum Chambers

NASA

PIONEER ASTRONAUTICS

Moon to Mars Oxygen and Steel Technology

Honeybee Robotics – Vacuum Chamber Testing

3.5 Meter Lunar Vacuum Chamber:

- Final integrated iron production system demonstration of:
  - Beneficiation, iron oxide reduction, metal recovery
  - Data acquisition and process controls
  - Remote operation

Moon to Mars Oxygen and Steel Technology

Flow Sheet Development

Lunar Mare – High Ilmenite Case:

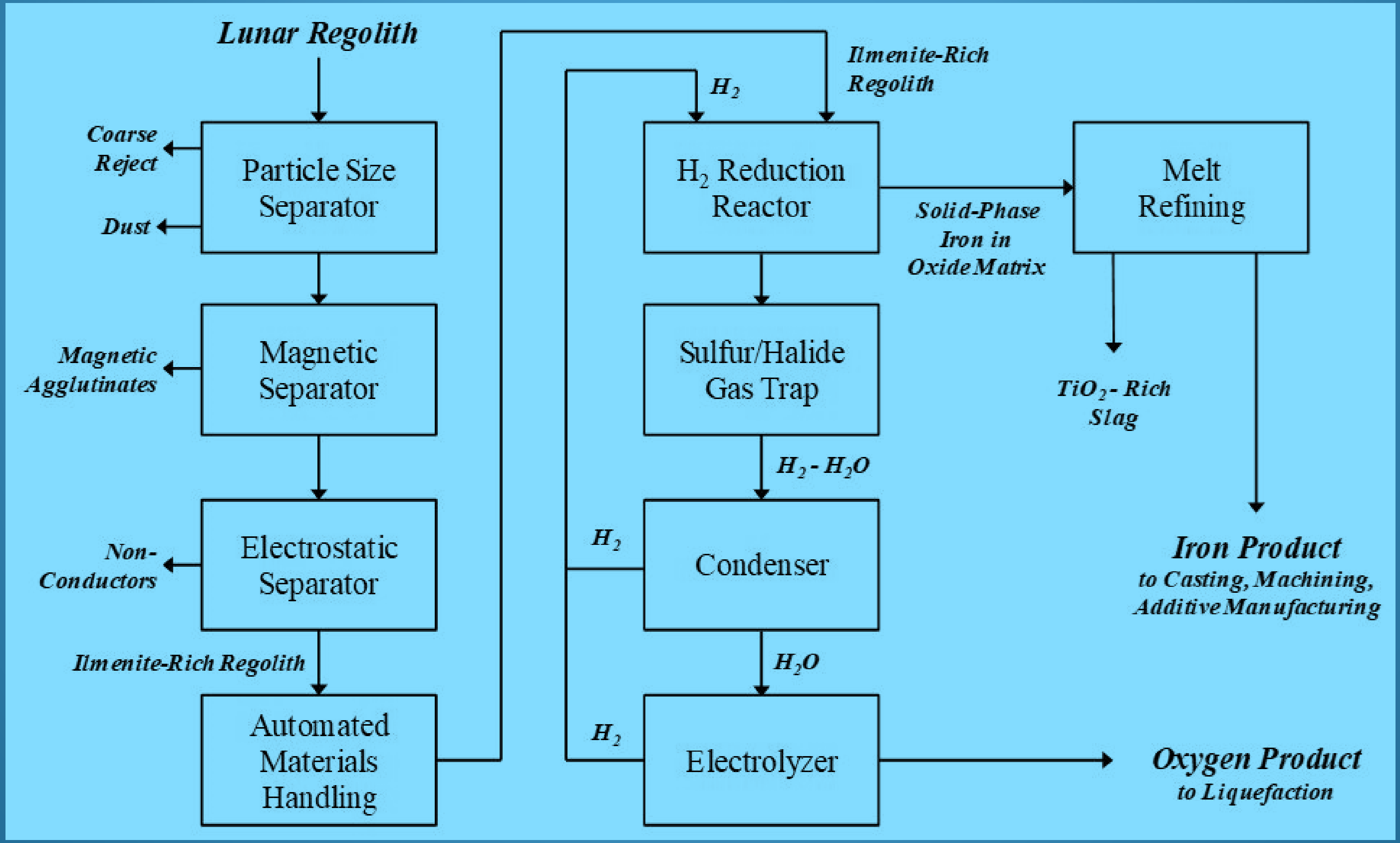
- For regolith containing ilmenite ($FeO \cdot TiO_2$)
  - Suitable for lunar mare regions such as Apollo 11
  - Beneficiation via particle size separation, magnetic separation (to remove agglutinates), and electrostatic separation (to boost ilmenite concentration)

Lunar Mare – High FeO Case:

- For regolith containing naturally high FeO content
  - Suitable for select lunar mare regions, particularly near the South Pole (Artemis)
  - Upgrades FeO concentration via particle size separation, magnetic separation (to remove agglutinates), and additional magnetic separation (to boost contained FeO concentration)

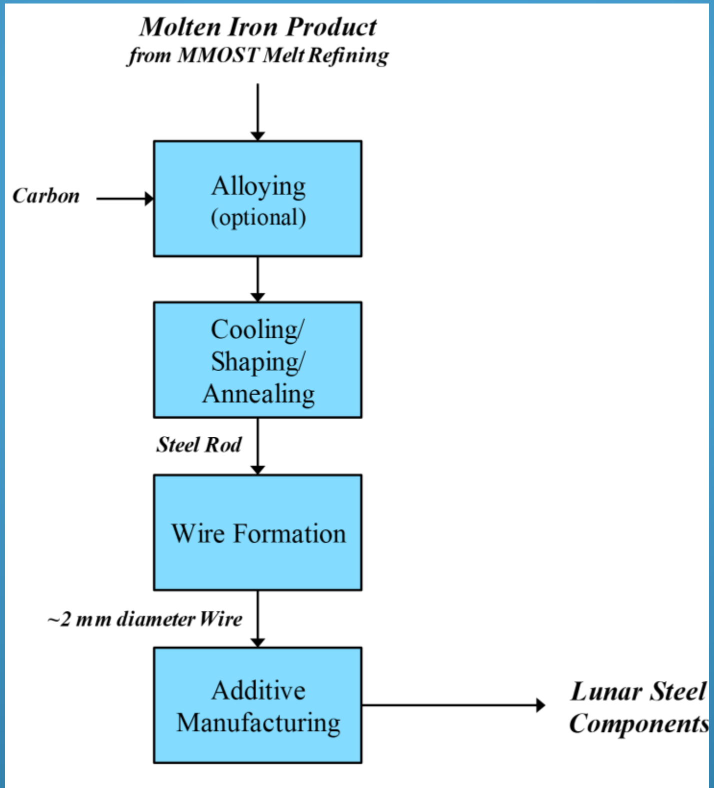
Moon to Mars Oxygen and Steel Technology

Example Flow Sheet – High Ilmenite Feed Case



Moon to Mars Oxygen and Steel Technology

Baseline Steel Component Production Scheme



Moon to Mars Oxygen and Steel Technology

Flow Sheet Development

Process Development and Scale-Up:

- Initial system for 3.5 kg/day iron (1 kg/day oxygen)
- Scaled-up system for 35 kg/day iron (10 kg/day oxygen)
- Advance TRL from 4 to 6

Parallel Support Activities:

- Lab-scale experiments
- Simulant formulation
- Data acquisition and control
- Automation
- Testing of modules in vacuum

Moon to Mars Oxygen and Steel Technology

Flow Sheet Development

MMOST Primary Process Energy and Power Requirements:

- For 35 kg/day iron production rate (10 kg/day oxygen)
- Six 4-hour batches per day of feed to iron oxide reduction
- 20.2 kg beneficiated regolith/batch at 70% ilmenite

Process Step	Energy, kJ	Power Parameters	
		Process Time, hr	Power, kW
Iron Oxide Reduction			
Soil Heat Up	16,350	2	2.27
Hydrogen Reduction	4,451	2	0.62
Electrolysis	29,670	2	4.12
Melt Refining	30,015	2	4.17

Values are for 100% efficiency

Process sequencing and process duration can be adjusted to minimize peak power demand

Heat recovery will be employed when possible

Moon to Mars Oxygen and Steel Technology

Simulant selection:

- Match lunar physical and chemical properties to the extent possible using terrestrial minerals
- Baseline (Ilmenite case) = basalt (JSC-1A equivalent) + ilmenite + agglutinate simulant
- Baseline (FeO case) = basalts of varying FeO concentration + agglutinate simulant
- Identify higher-fidelity simulant formulations as the program progresses

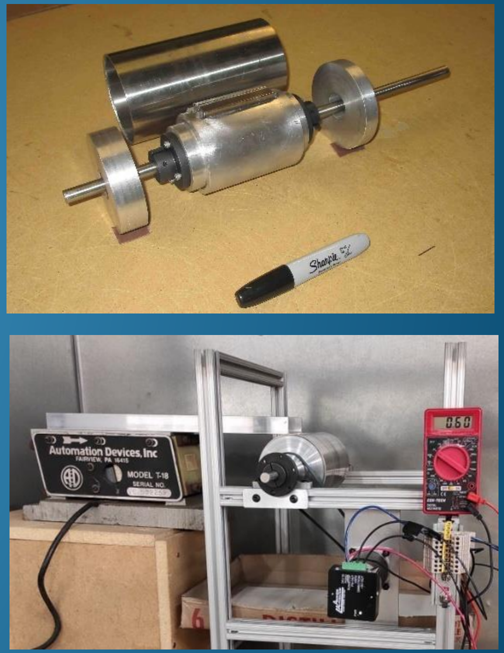
Moon to Mars Oxygen and Steel Technology

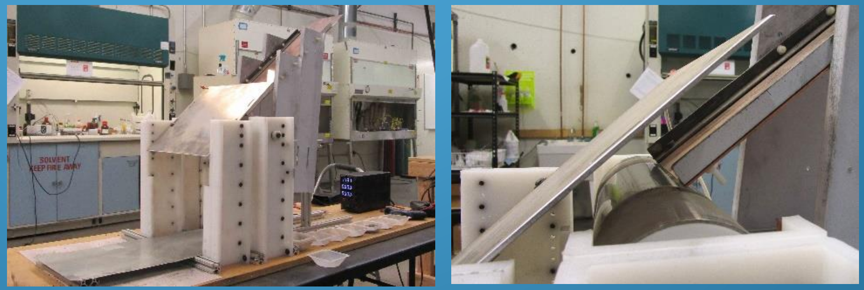
Activities in Progress:

- Beneficiation Module
  - Non-sieve particle size separation
    - No screen blinding; minimal moving parts
    - Remove coarsest, least reactive particles
    - Remove dust
  - Magnetic separator
    - Permanent magnet drum separators
    - Adjustable operating parameters to optimize separations
  - Electrostatic separator
    - >10 kV; low current
    - Grounded drum/Charged "lifting plate"

Slotted-Ramp Particle Size Separator

Magnetic Separator





Electrostatic Separator

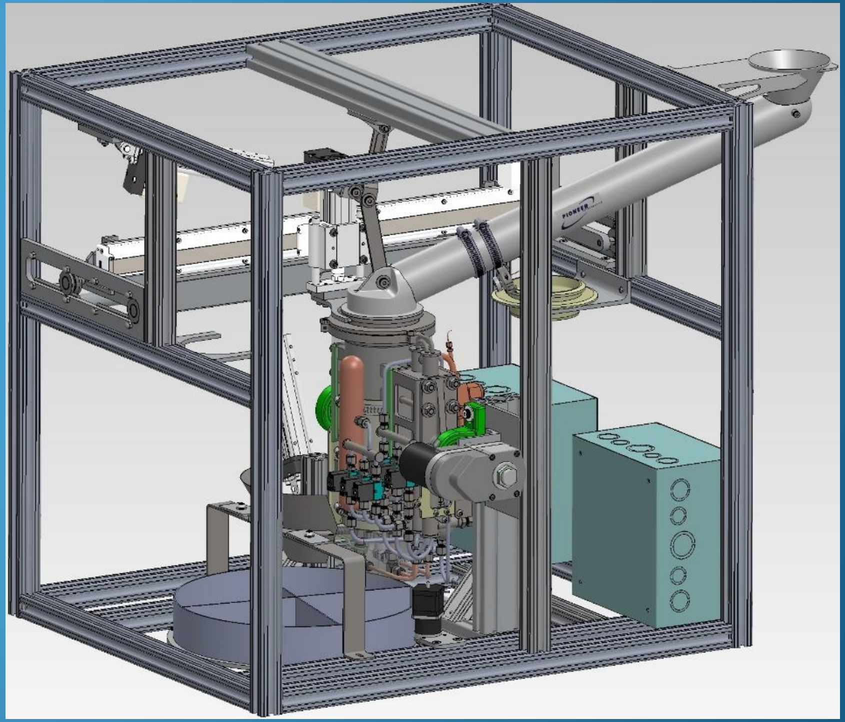
NASA

PIONEER ASTRONAUTICS

Moon to Mars Oxygen and Steel Technology

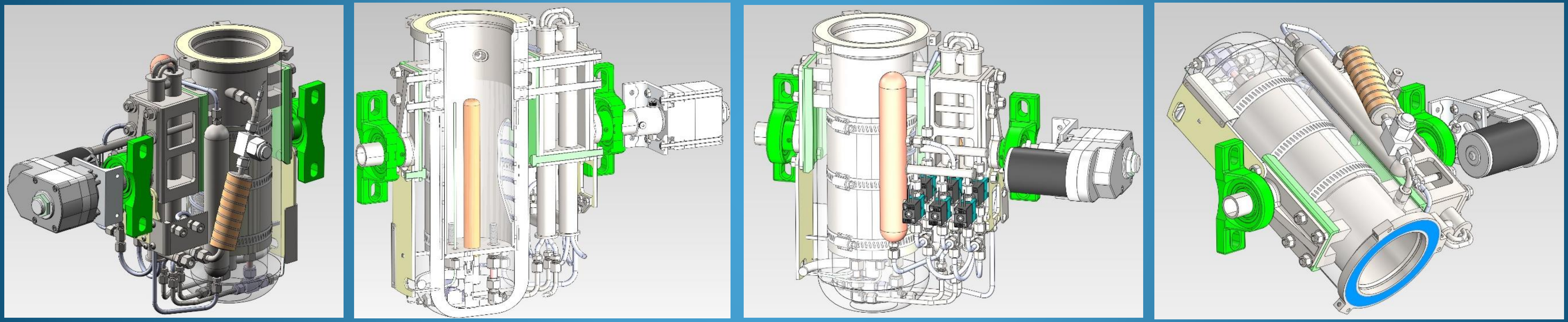
Activities in Progress (continued):

- Lab iron oxide reduction experiments
  - Identify range of operating conditions using various feed compositions
  - Produce samples for melt refining tests and evaluation of metal for manufacturing
  - Identify electromechanical automation/motion control requirements (linear sliders, rotary actuators, grippers, clamps)
- Sub-scale iron oxide reduction apparatus
  - Validate reduction performance and motion controls
  - Demonstrate operation in vacuum
  - Refine scale-up parameters



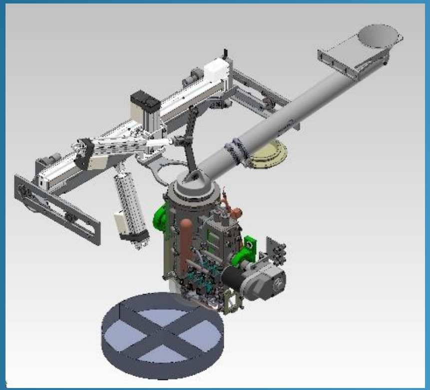
MMOST Sub-Scale Iron Oxide Reduction System
(configured to fit in a one cubic meter vacuum chamber)

Moon to Mars Oxygen and Steel Technology

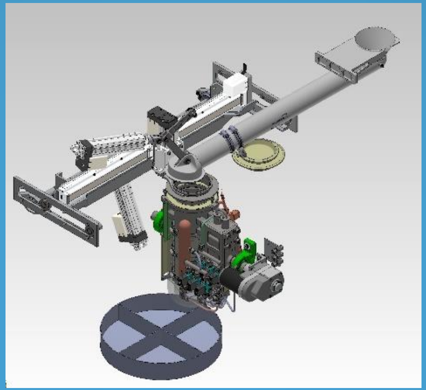


MMOST Sub-Scale Iron Oxide Reduction Reactor System

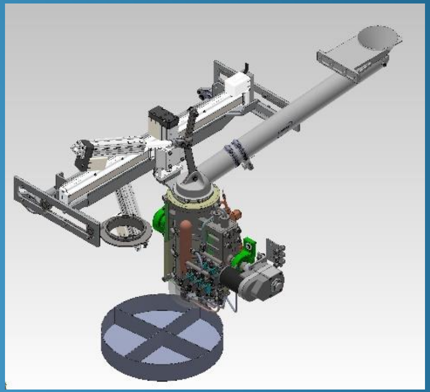
Moon to Mars Oxygen and Steel Technology



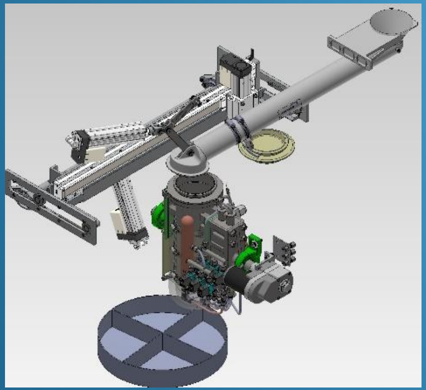
Load Regolith



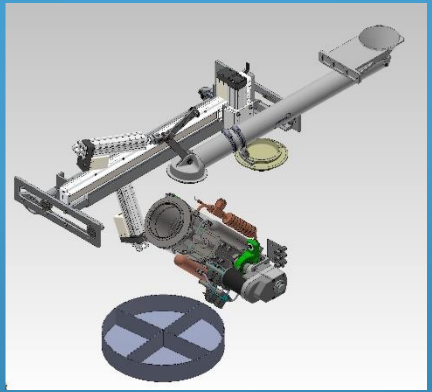
Remove Protection Sleeve/Install Lid



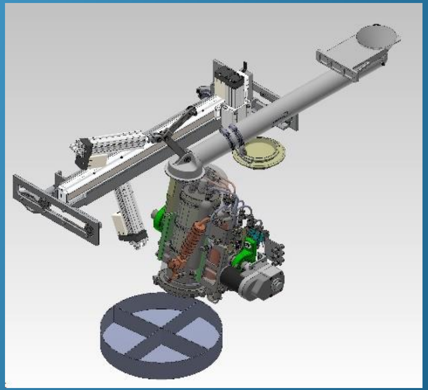
Reduction



Sleeve Installed/Ready to Discharge



Partial Inversion



Full Inversion

MMOST Sub-Scale Iron Oxide Reduction Motion Controls

Moon to Mars Oxygen and Steel Technology

Activities in Progress (continued):

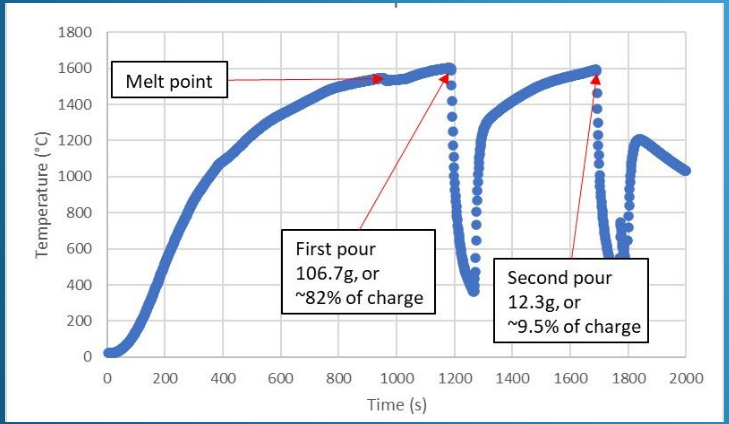
- Melt refining of reduced regolith
  - Electric Arc
    - Carbon or tungsten electrodes
    - Current-limiting AC / DC power source
    - Electrode positioning during heat up and melting
  - Preliminary controls requirements
  - Automation requirements

Lab Electric Arc Furnace and Iron Product

Moon to Mars Oxygen and Steel Technology

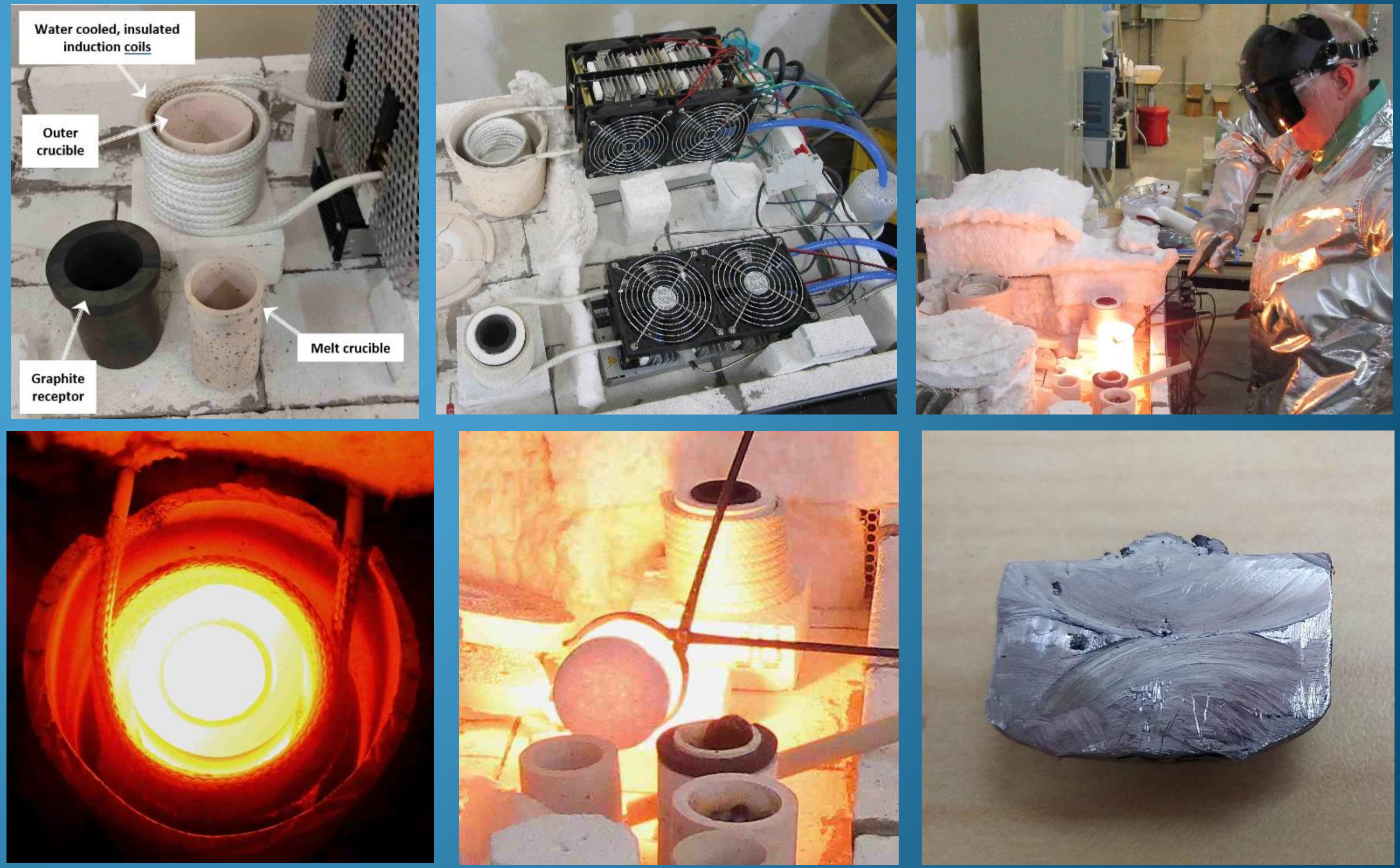
Activities in Progress (continued):

- Melt refining of reduced regolith
  - Induction Heating
    - No electrodes
    - Need to couple induction coils to reduced regolith



Induction Furnace Heating Rate

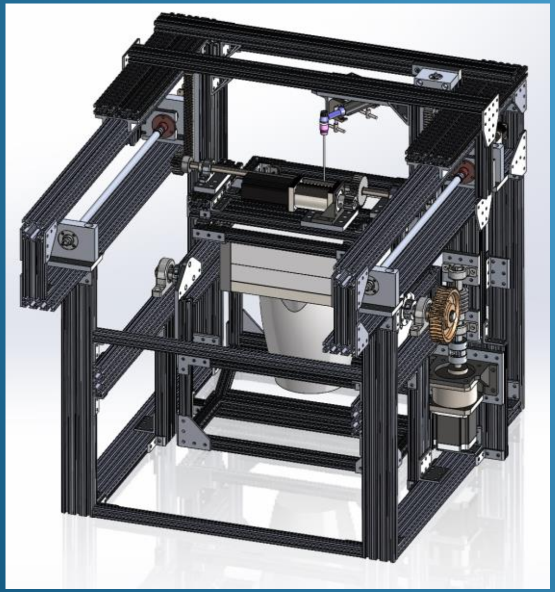
Induction Furnace Experiment

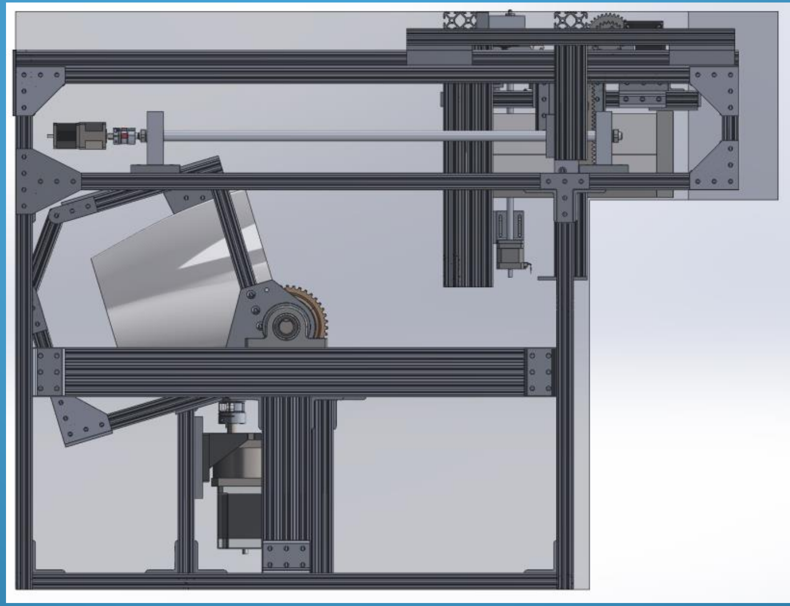


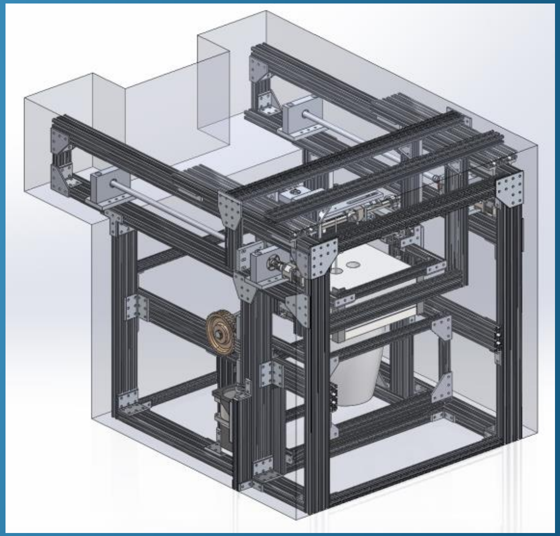
Moon to Mars Oxygen and Steel Technology

Activities in Progress (continued):

- Melt refining of reduced regolith
  - Preliminary sub-scale design







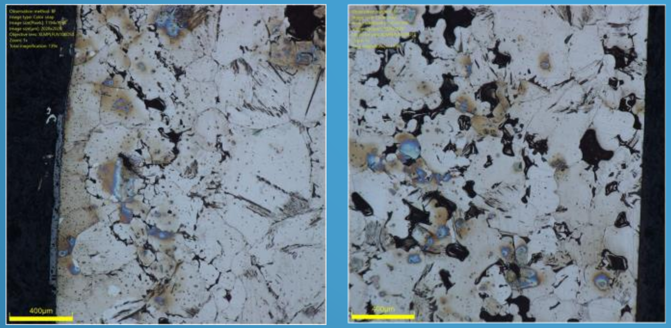
Moon to Mars Oxygen and Steel Technology

Activities in Progress (continued):

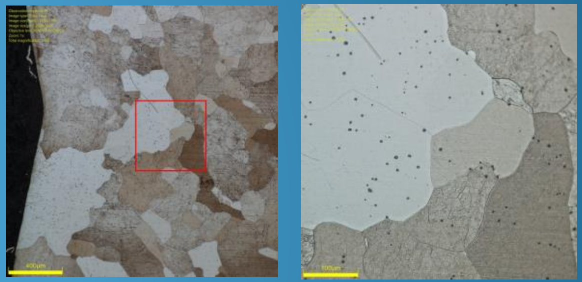
- Colorado School of Mines Materials Characterizations

Percentile	Size(um)
10	6.06
20	14.86
30	26.61
40	40.69
50	59.61
60	85.44
70	115.1
80	165.6
90	306.1
95	533

Simulant Particle Size Distribution



Electric Arc Melted Iron Porosity (edge and center regions)



Induction Melted Iron Inclusions

MMOST Induction Melted Iron Grain Texture

Moon to Mars Oxygen and Steel Technology

Conclusions:

- Beneficiation, iron oxide reduction, and melt refining results to date validate the MMOST concept
- Feedback from materials characterizations conducted at Colorado School of Mines provide valuable guidance for iron/steel process improvement and optimization
- Differences in physical and chemical properties between lunar minerals and their Earth analogs require that consideration be given to application of MMOST in the lunar environment
- MMOST provides technology to support lunar manufacturing

Moon to Mars Oxygen and Steel Technology

Potential Follow-on Activities/Mission Infusion:

- MMOST lunar flight experiment
  - Robotic sub-scale system
  - Delivered to the Moon on a CLPS lander
- MMOST pilot unit operation
  - Crewed Artemis mission
  - Demonstrate operations and manufacturing in the lunar environment
- MMOST commercial system
  - Support lunar base operations
  - Develop a cis-lunar economy

Moon to Mars Oxygen and Steel Technology

Acknowledgements:

- Project teams from Pioneer Astronautics, Colorado School of Mines, and Honeybee Robotics
- NASA Johnson Space Flight Center
  - Aaron Paz, Technical Monitor
- NASA SBIR program

June 10, 2021, Online

The 11th joint Planetary and Terrestrial Mining Sciences Symposium and Space Resources Roundtable

A Continuous Hydrogen Reduction Process for ISRU on the Moon

Eri Kumai[1], Manabu Tanaka[1], Takayuki Watanabe[1],
Takeshi Hoshino[2], Satoshi Hosoda[2], and Hiroshi Kanamori[2]

[1]Department of Chemical Engineering, Kyushu University
[2]Japan Aerospace Exploration Agency

KYUSHU
UNIVERSITY

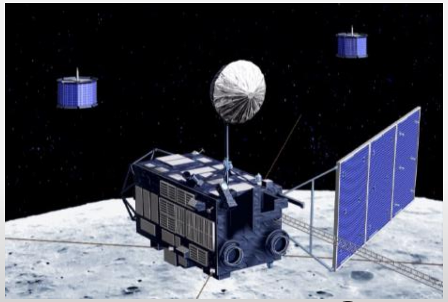
Manned lunar exploration

Water

- Food, drink and Sanitation
- Machine coolant
- Experimental water
- Construction material

Oxygen

- Respiration
- Fuel cell, Energy source
- Propellant of rockets



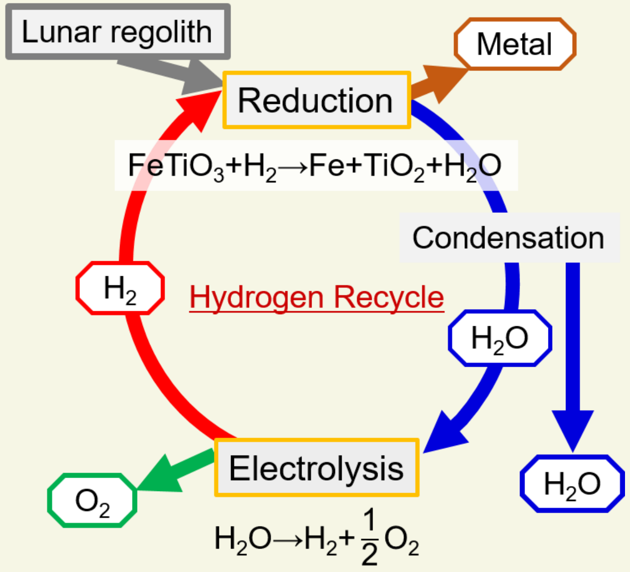
© JAXA

▲ SELENE

In-Situ Resource Utilization technology is required.

Reduction of lunar regolith

Reductant	Product	Advantage	disadvantage
H_2	H_2O	Simple reaction, Reusable of hydrogen	-
CO	CO_2	Large reduction temperature range	Difficulty of recycling CO_2
CH_4	CO, CO_2, H_2O	Diversity of reduced minerals	Complex reaction
C	CO	Diversity of reduced minerals	High reduction temp.
F	O_2	Oxygen extraction from all minerals	Complex reaction



Introduction

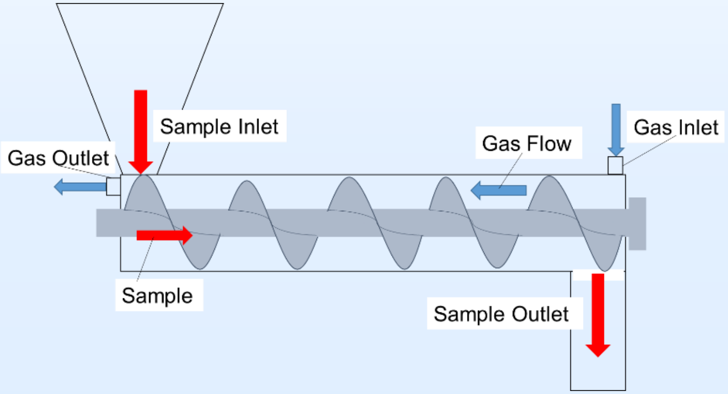
Reactors for hydrogen reduction

Previous works

Fixed bed reactor
- Scale up
  - Inhomogeneous temperature
  - Uneven H_2 flow channel
- Continuous reduction

Fluidized bed reactor
- Limited particle condition
  - Particle size and density affect the fluidization condition.
- Continuous reduction

Continuous screw reactor
- Continuous reduction
- No limit on particle conditions
- Scale up

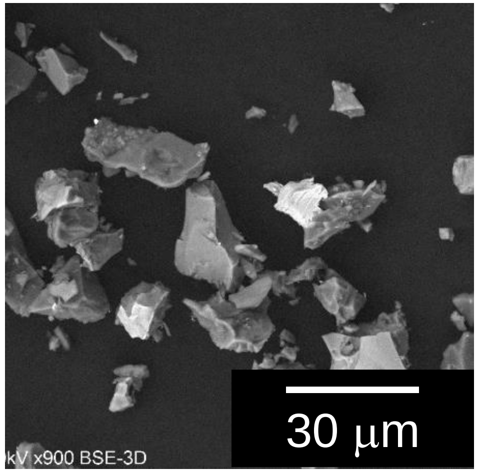


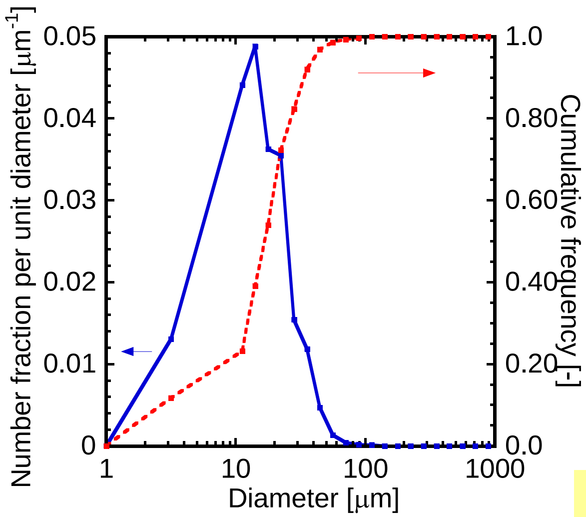
Purpose of this study

- To establish a continuous hydrogen reduction system
- To reveal the effect of parameters on hydrogen reduction

Lunar regolith simulant FJS-1

◆ SEM image





Mean diameter: 22 μm

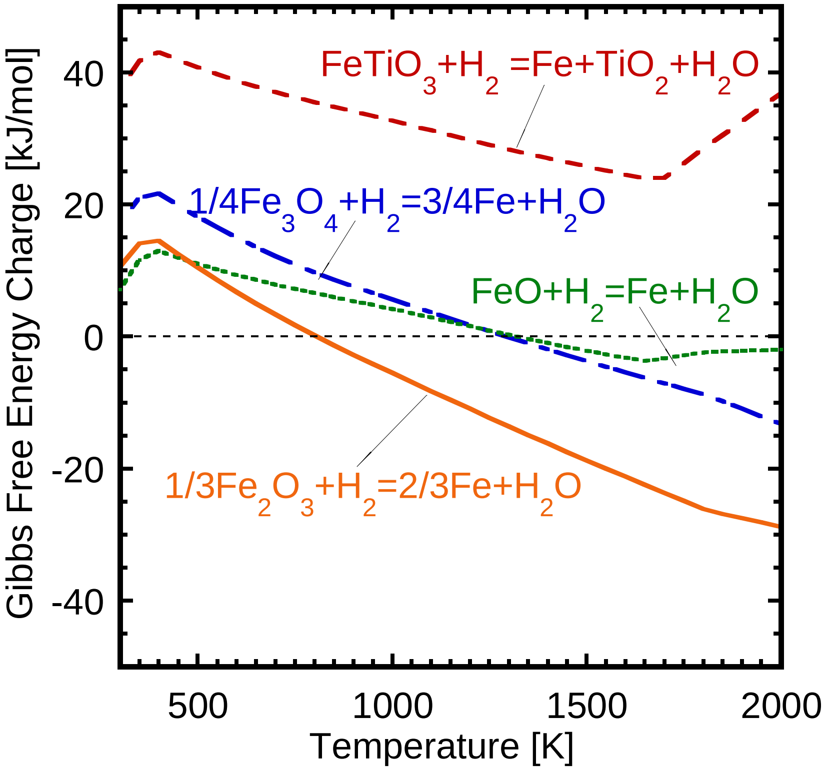
◆ Elemental components [wt%]

Oxide	Apollo 11	Apollo 14	FJS-1
SiO_2	42.2	48.1	49.14
TiO_2	7.8	1.7	1.91
Al_2O_3	13.6	17.4	16.23
Cr_2O_3	0.3	0.23	0
FeO	15.3	10.4	8.3
Fe_2O_3	0	0	4.77
MnO	0.2	0.14	0.19
MgO	7.8	9.4	3.84
CaO	11.9	10.7	9.13
Na_2O	0.47	0.7	2.75
K_2O	0.16	0.55	1.01
P_2O_5	0.05	0.51	0.44
S	0.12	-	0
H_2O	0	0	0.43
Total	99.9	99.83	98.14

Differences: FJS-1 contain Fe_2O_3
FJS-1 contain much Na

- Targets of hydrogen reduction: FeO, Fe_2O_3
- FeO exist as ilmenite($FeTiO_3$)

◆ Gibbs free energy

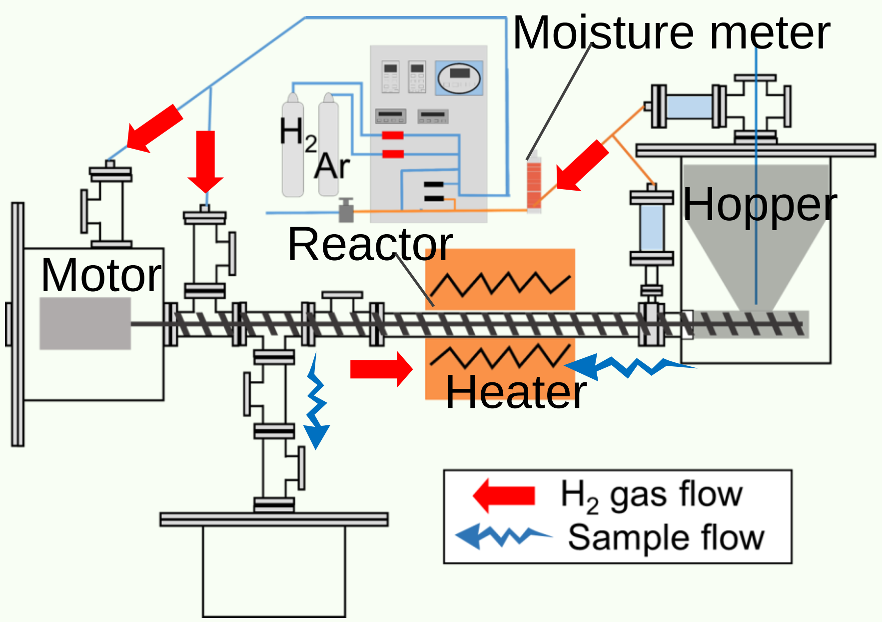


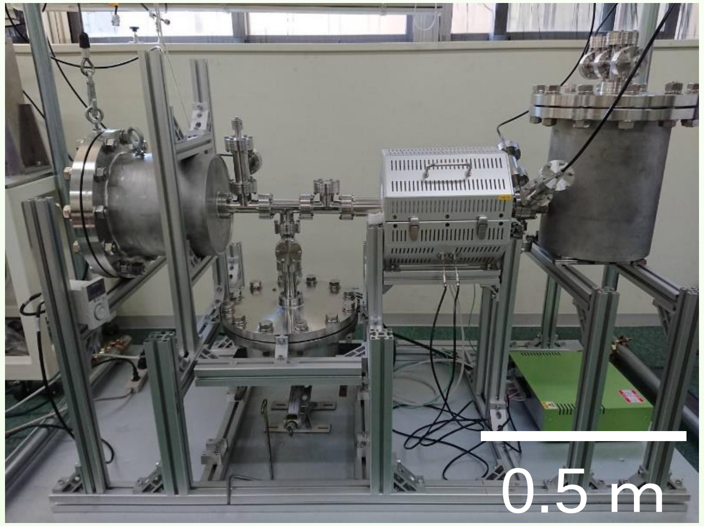
at ΔG> 0

Remove water vapor by large amount of hydrogen

→ Forced reduction of metal oxide

Experimental conditions





0.3rpm(×4)

- ✓ Sufficient contact between gas and solid
- ✓ Stirring of the sample

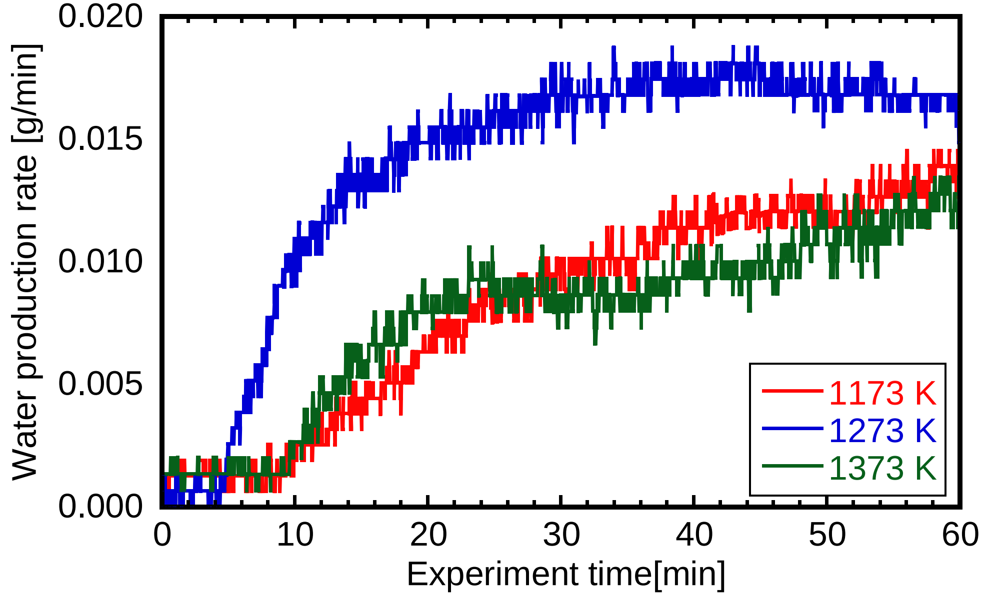
Sample	FJS-1	
Temperature	1173 ~1373 K	1273 K
Gas flow rate(Ar+H_2)	10 L/min	
H_2 gas concentration	3vol%	
Pressure	300 kPa	
Screw rotation speed	0.8rpm	0.5~1.1rpm
Reduction time	10min	26~7min
Sample feed rate	4.9 g/min	2.0~5.6 g/min

- Effect of reduction temperature
- Effect of reduction time

Effect of reduction temperature

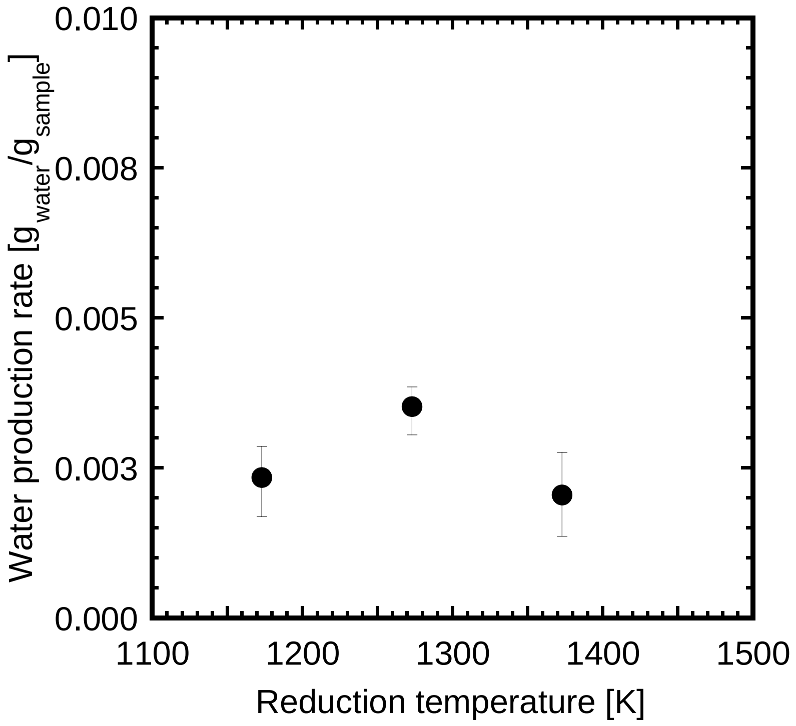
Temperature	1173~1373 K
H_2 concentration	3vol%
Reduction time	10min

◆ Water production rate



- Water production rate at steady state
  1273 K > 1173 K > 1373 K

◆ Water production rate per unit sample

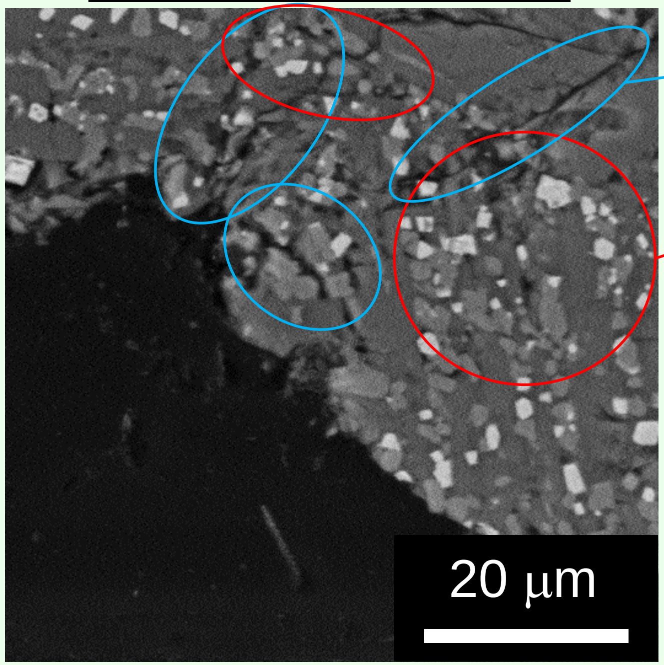


<u>1173~1273 K</u>
Reduction temperature ↑ → Reduction rate ↑
<u>1373 K</u>
Some components melt → fill up the halls → H_2 diffusion ↓ → Reduction rate↓

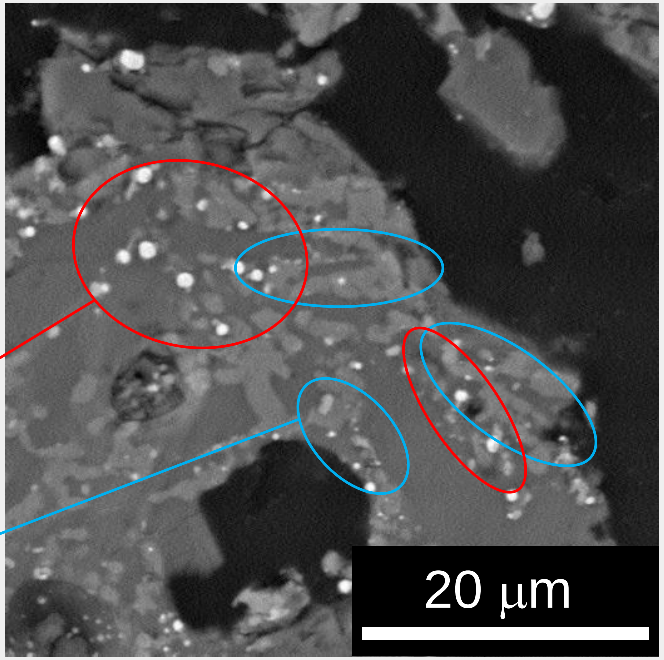
Effect of reduction temperature

◆ SEM image

Before experiment



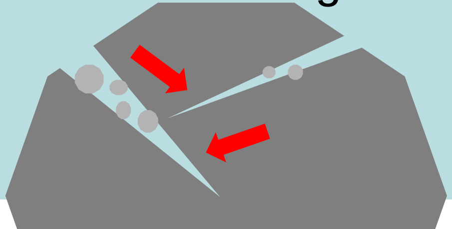
After reduced in 1373 K



- ✓ Numerous cracks
- ✓ Small particles with random shapes
- ✓ Small round-shaped regions
- ✓ Blighter regions in line

Before experiment

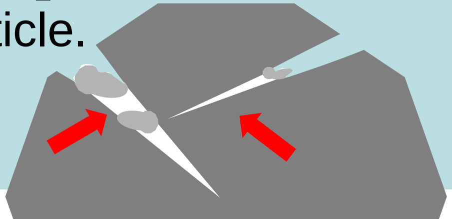
H_2 reaches inside the simulant through cracks.



H_2

After treated in 1373 K

Melting components inhibit the H_2 diffusion inside the particle.



1173~1273 K

Reduction temperature ↑ → Reduction rate ↑

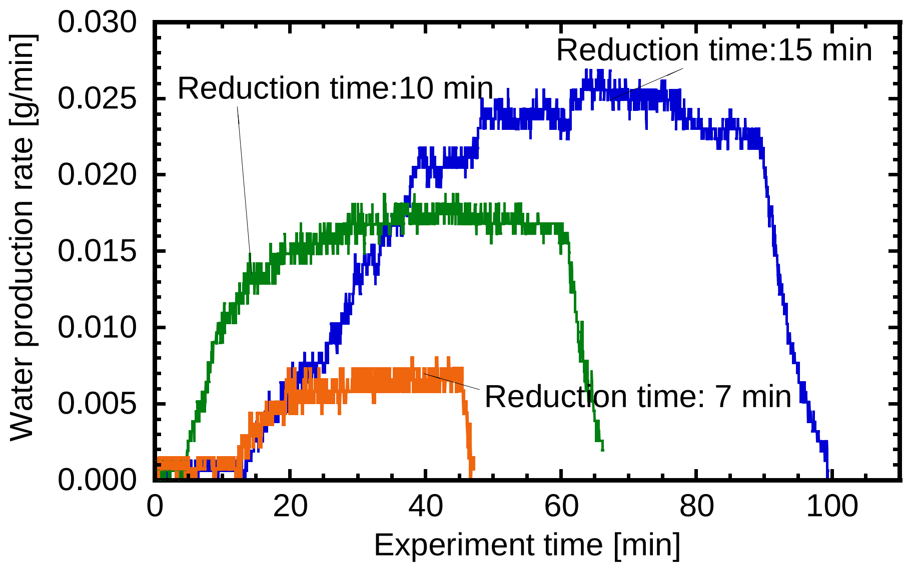
1373 K

Some components melt → fill up the halls → H_2 diffusion ↓ → Reduction rate↓

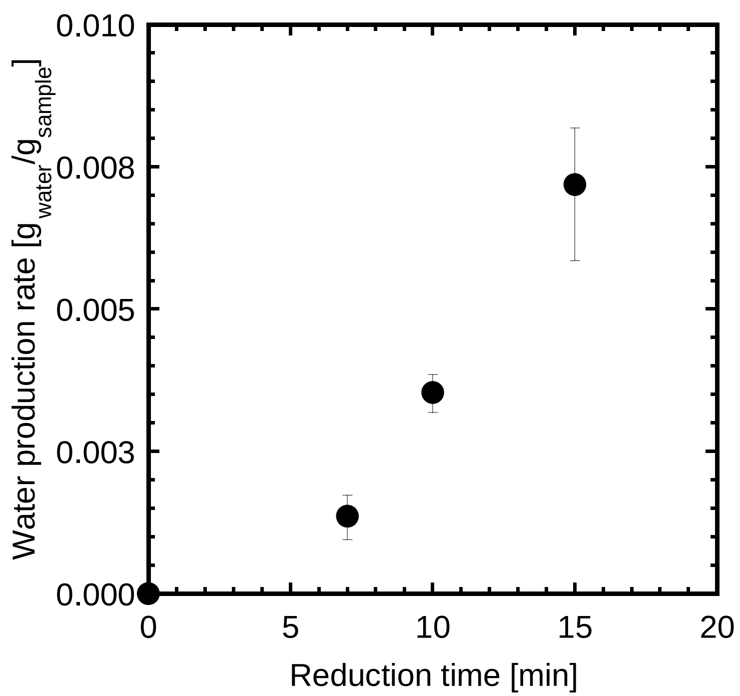
Effect of reduction time

Temperature	1273 K
H_2 concentration	3vol%
Reduction time	7~26min

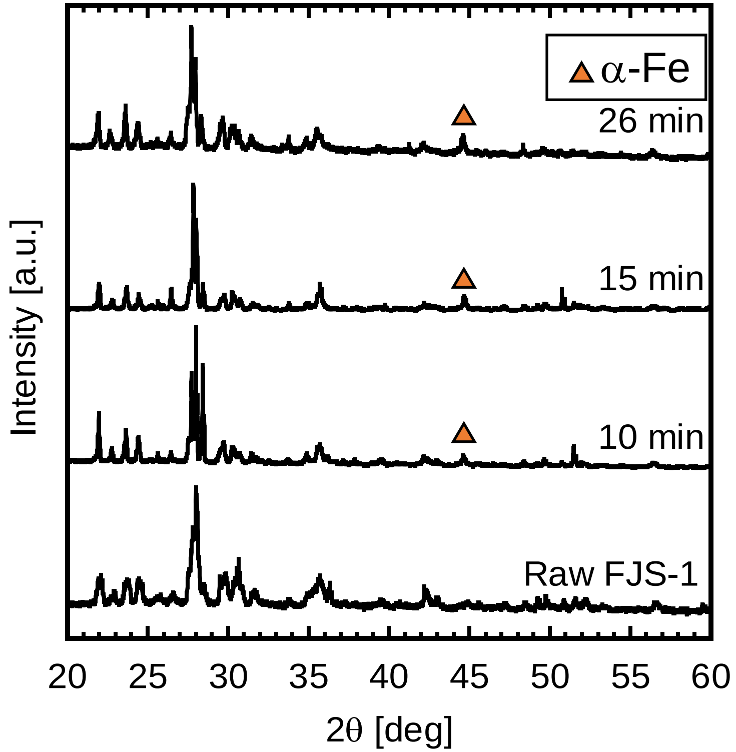
◆ Water production rate



◆ WPR per unit sample



◆ XRD chart

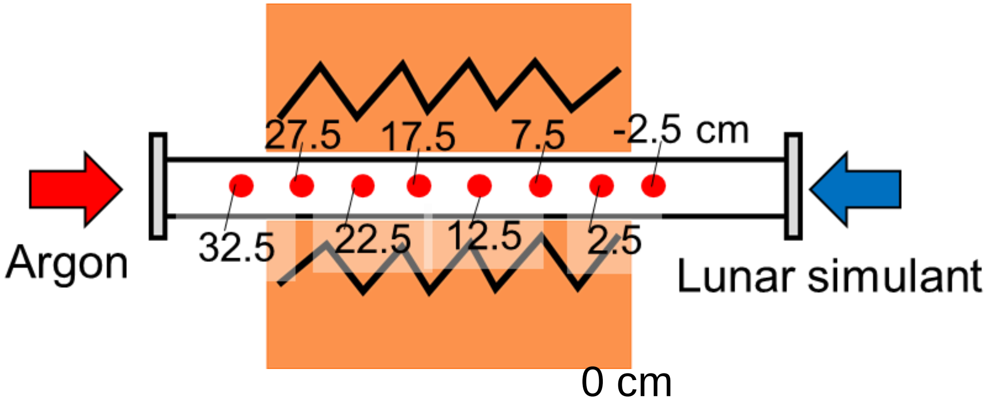


- Water production rate at steady state 15min > 10min > 7min

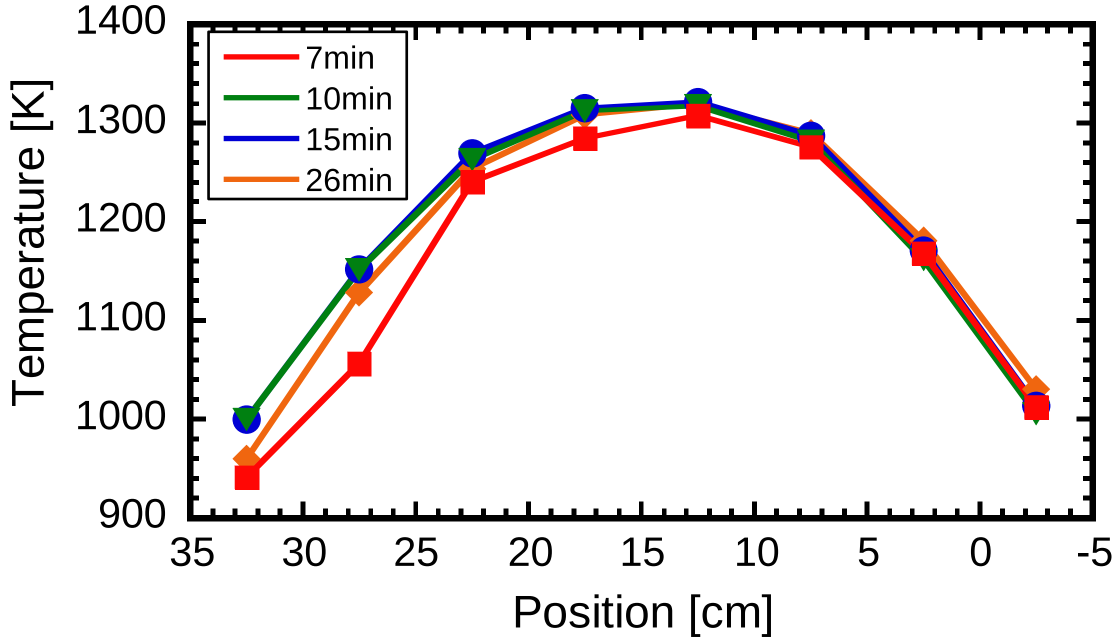
- The peaks of α-Fe were found in reduced samples.
- The peak intensity of α-Fe increased as reduction time increase.

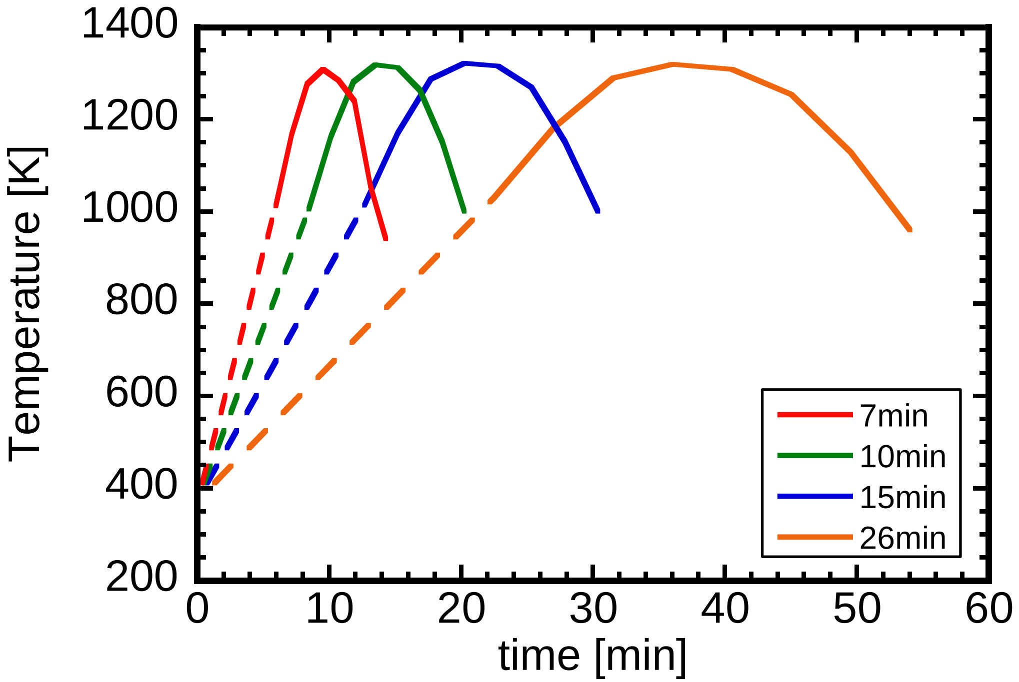
Effect of reduction time

Temperature	1273 K
H_2 concentration	3vol%
Reduction time	7~26min



◆ Temperature distribution



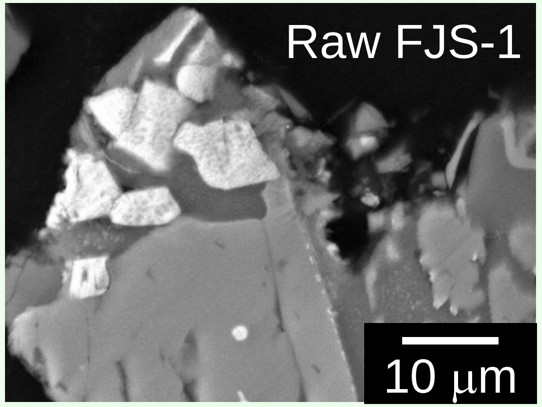


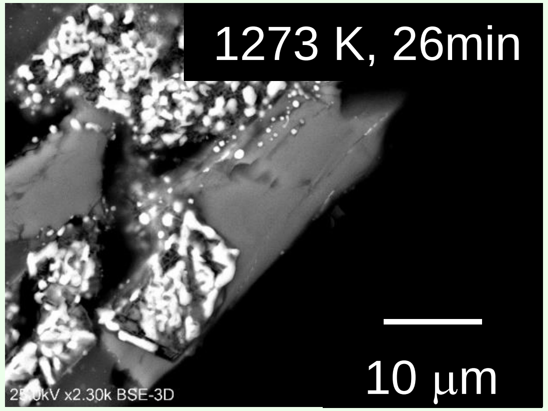
- Maximum temperature is lower at short reduction time.
- Temperature difference is less than 100 K.

- Time in high temperature region have much effect on reduction yield.

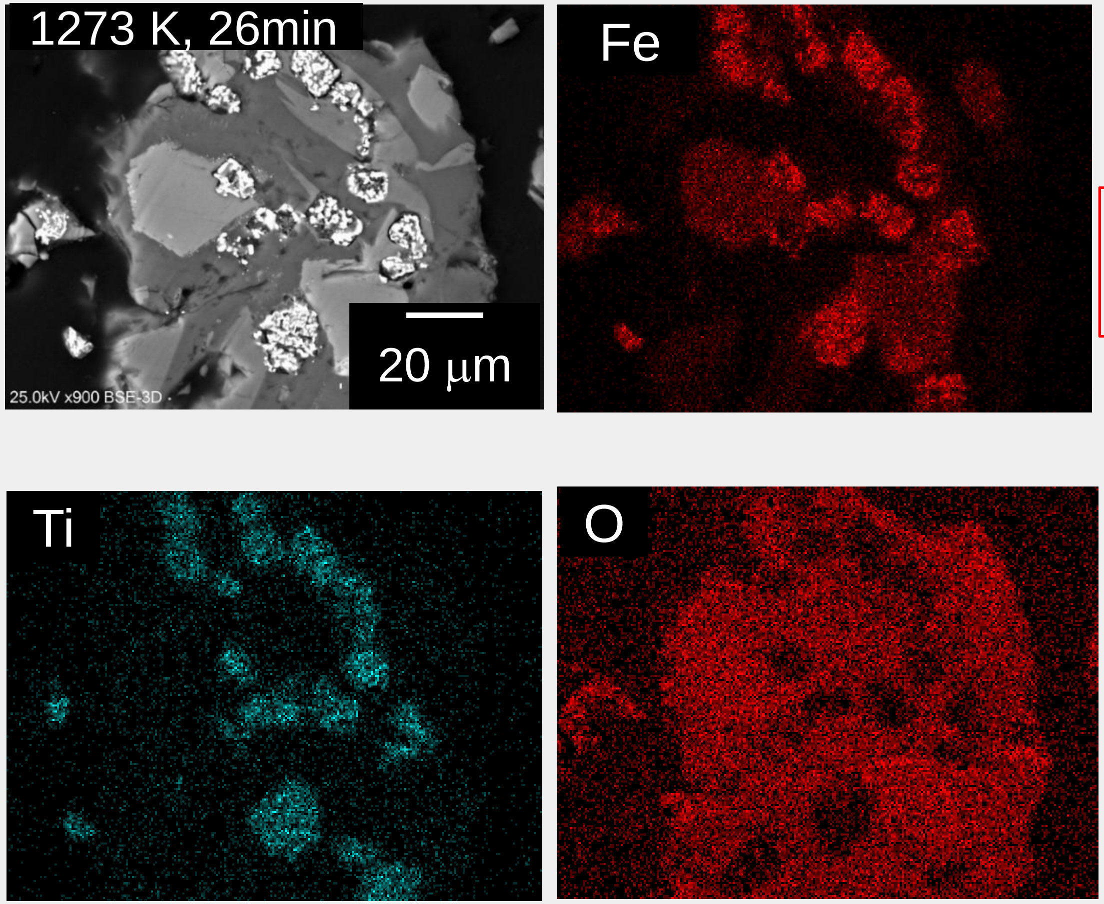
Effect of reduction time

◆ SEM image





◆ EDX mapping



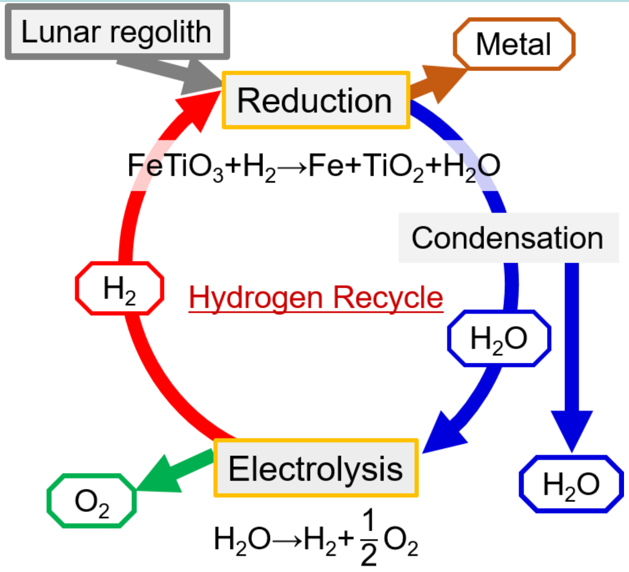
- ✓ Porous regions contain much Ti and O.
- ✓ Less O in porous regions.

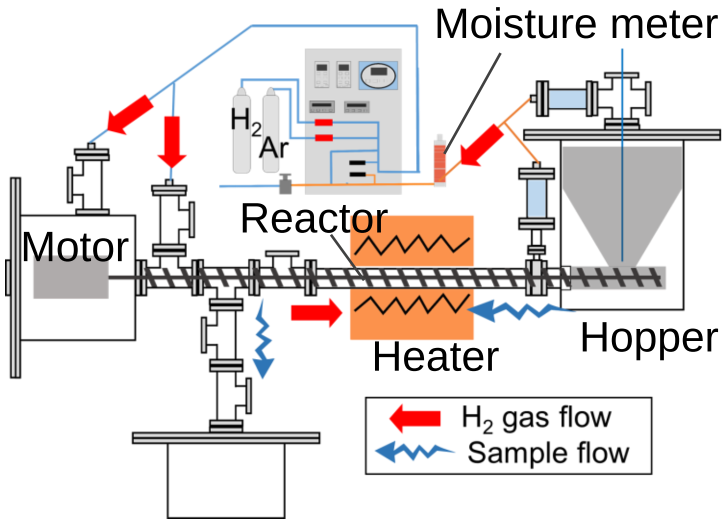
- Pores are produced by hydrogen reduction.
- EDX mapping suggests the reduction of $FeTiO_3$

Conclusion

Hydrogen reduction experiment with continuous screw reactor

- ✓ Continuous hydrogen reduction system was established.
- ✓ Water was produced by hydrogen reduction of lunar simulant.
- ✓ Effect of operating conditions on hydrogen reduction was revealed.
  Reduction time
  Reduction temperature
- ✓ Temperature distribution during experiments were investigated.





<u>Promising process to acquire oxygen on the moon. (ISRU)</u>

Details have been reported in: Eri Kumai, et al. : A Continuous Hydrogen Reduction Process for the Production of Water on the Moon, Int. J. Microgravity Sci. Appl., 38 (2), 380203 (2021), DOI: https://doi.org/10.15011/jasma.38.380203

The Regolith and Ice Drill for Exploring New Terrain (TRIDENT)

PTMSS/SRR

June 10, 2021

Kris Zacny, Phil Chu, Vince Vendiola: Honeybee Robotics
Jackie Quinn, Julie Kleinhenz: NASA

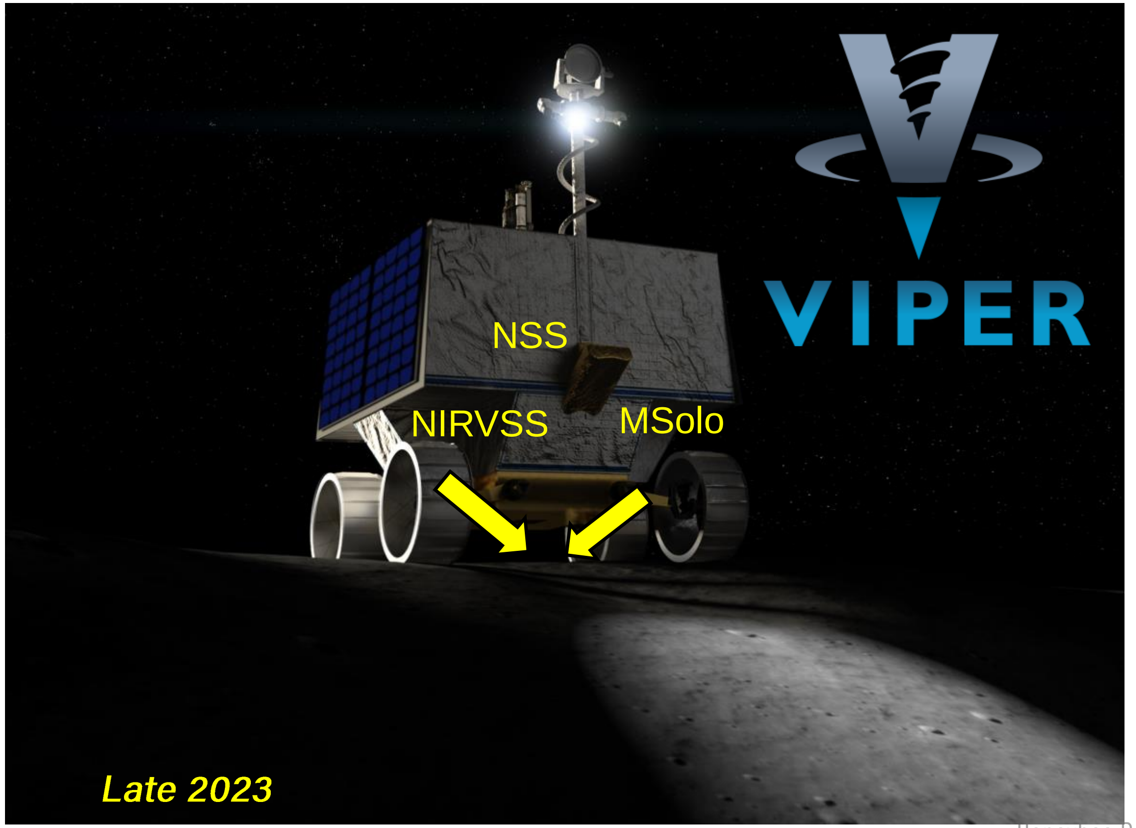
HONEYBEE ROBOTICS

Honeybee Robotics
2408 Lincoln Ave
Altadena, CA 91001
www.HoneybeeRobotics.com

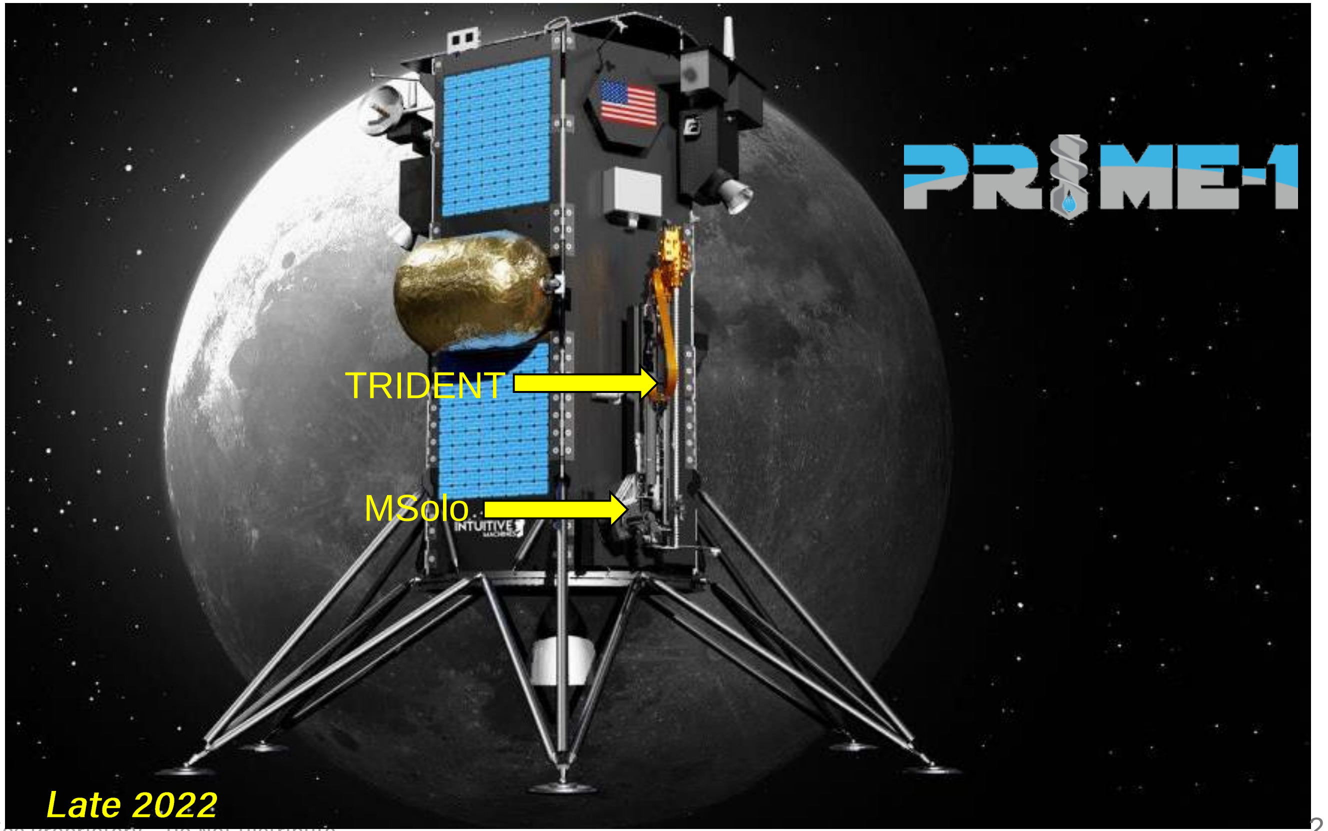
TRIDENT Objectives for PRIME-1 and VIPER

1. **Mining tool:** enables 4D exploration by providing subsurface sample for NIRVSS and MSolo
2. **Instrument:** determines geotechnical and thermal properties of the volatile rich regolith vs depth

Volatiles Investigating Polar Exploration Rover (VIPER)



The Polar Resources Ice Mining Experiment-1 (PRIME-1)



Lunar drilling: Past, Present and Future

HONEYBEE ROBOTICS
Exploration Technology

Timeline (Decades)

1970s

2020s

Depth regime [meters]

0.1

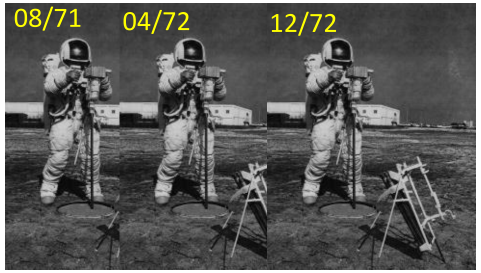
1

10

Luna16

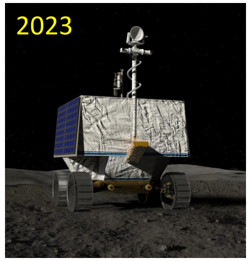

Luna 20


Luna 24


Apollo15 Apollo16 Apollo17


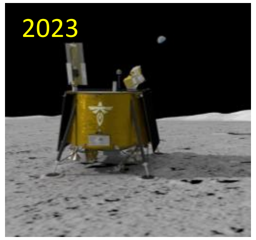
Chang’e 5

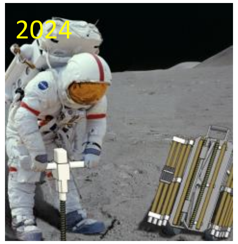

PRIME1


VIPER


Chang’e 6


Luna 27


LISTER


Artemis


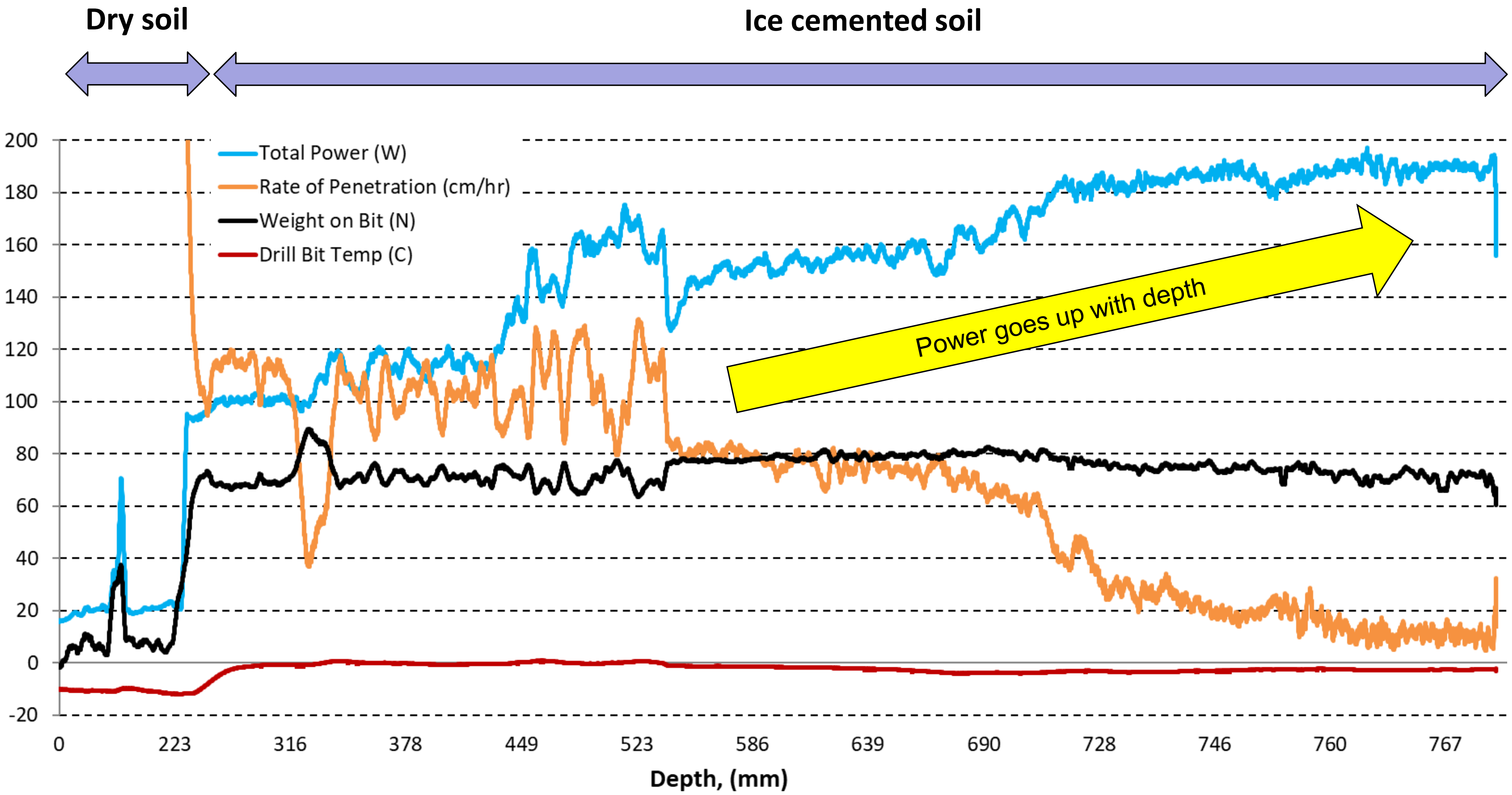
TRIDENT Description

Avionics

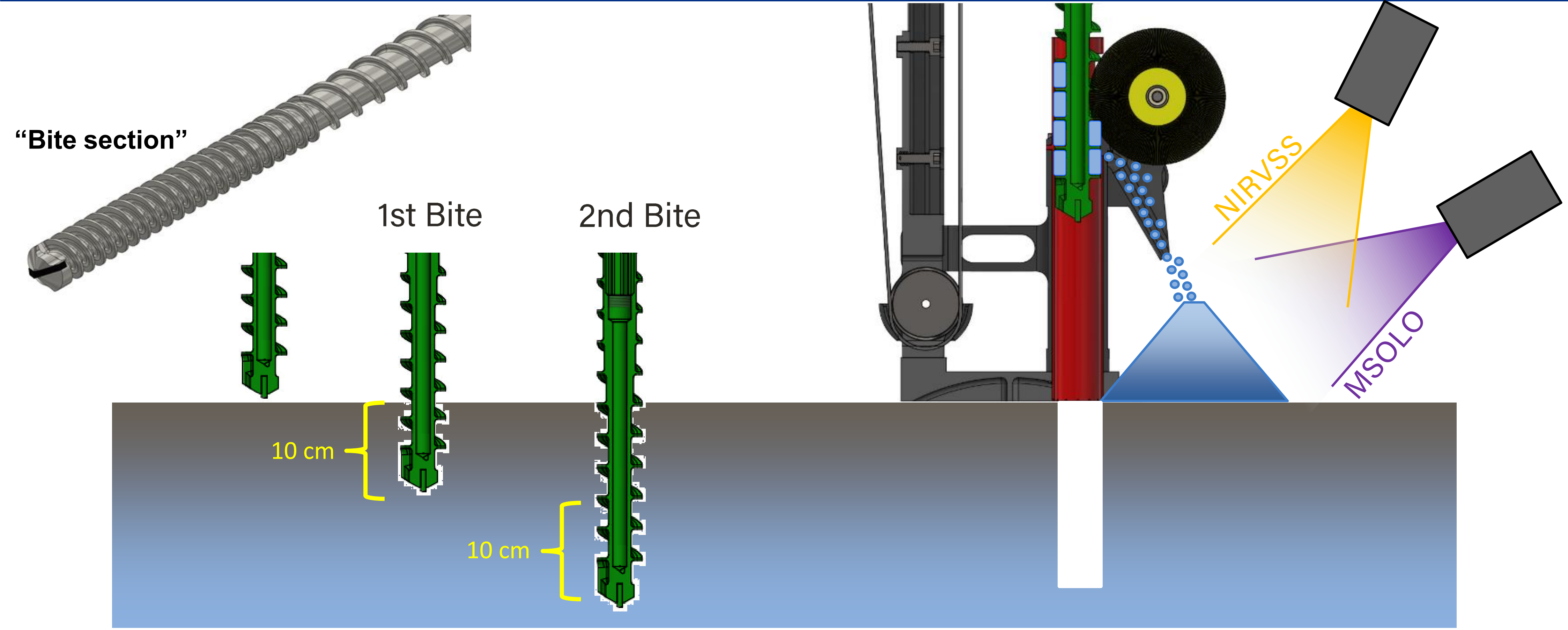
Parameter	Value
Bit Diam. (mm)	**25.4**
Nominal Auger Spin (RPM)	120
Auger Average Output Torque (N-m)	5.5
Auger Max. Intermittent Torque (N-m)	16.1
Auger Average Power Consumption (W)	87
Percussion Impact Energy (Joules/Blow)	2.0
Nominal Percussion Rate (BPM)*	972
Feed Stage Stroke (mm)	1240
Maximum Drill Depth (mm)	**1020**
Deployment Stage Stroke (mm)	380
Z Stage Force Cont. (N)	500
CBE Drill and Launch Locks Mass (kg)	**19.1 + 1.5**
CBE Avionics + Harness Mass (kg)	**6.4 + 0.9**

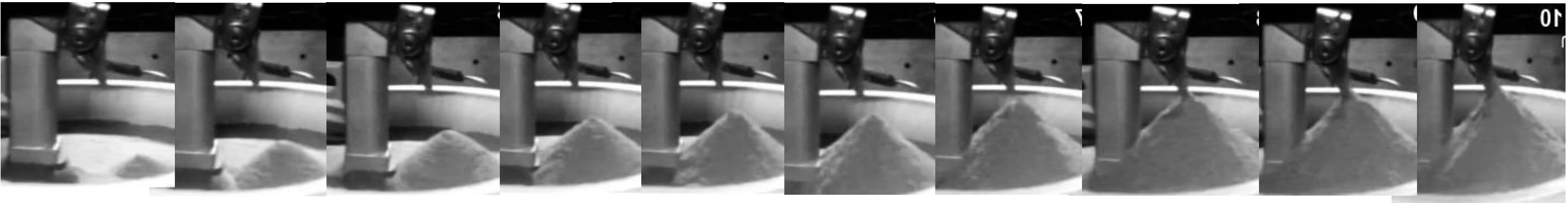
* Percussive indexing programmed to 8.1 Blows per Revolution

Drilling to 1 m depth



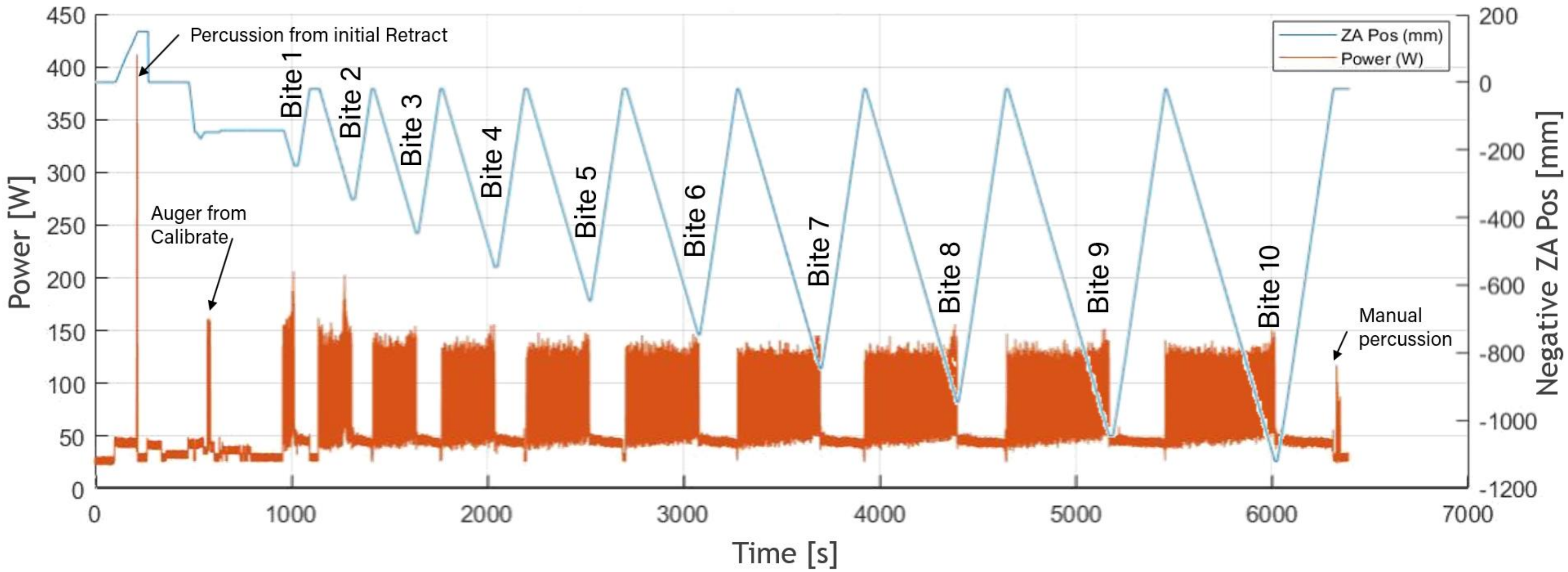
Bite Sampling





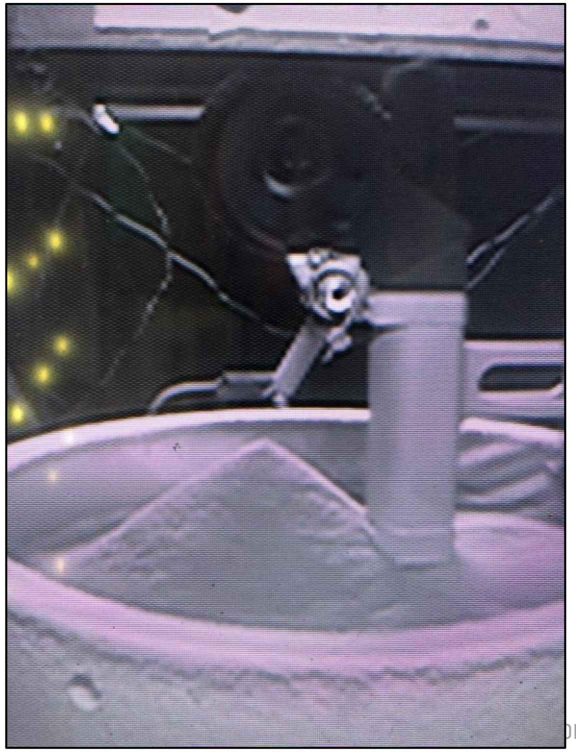
Advantage of Bite Sampling

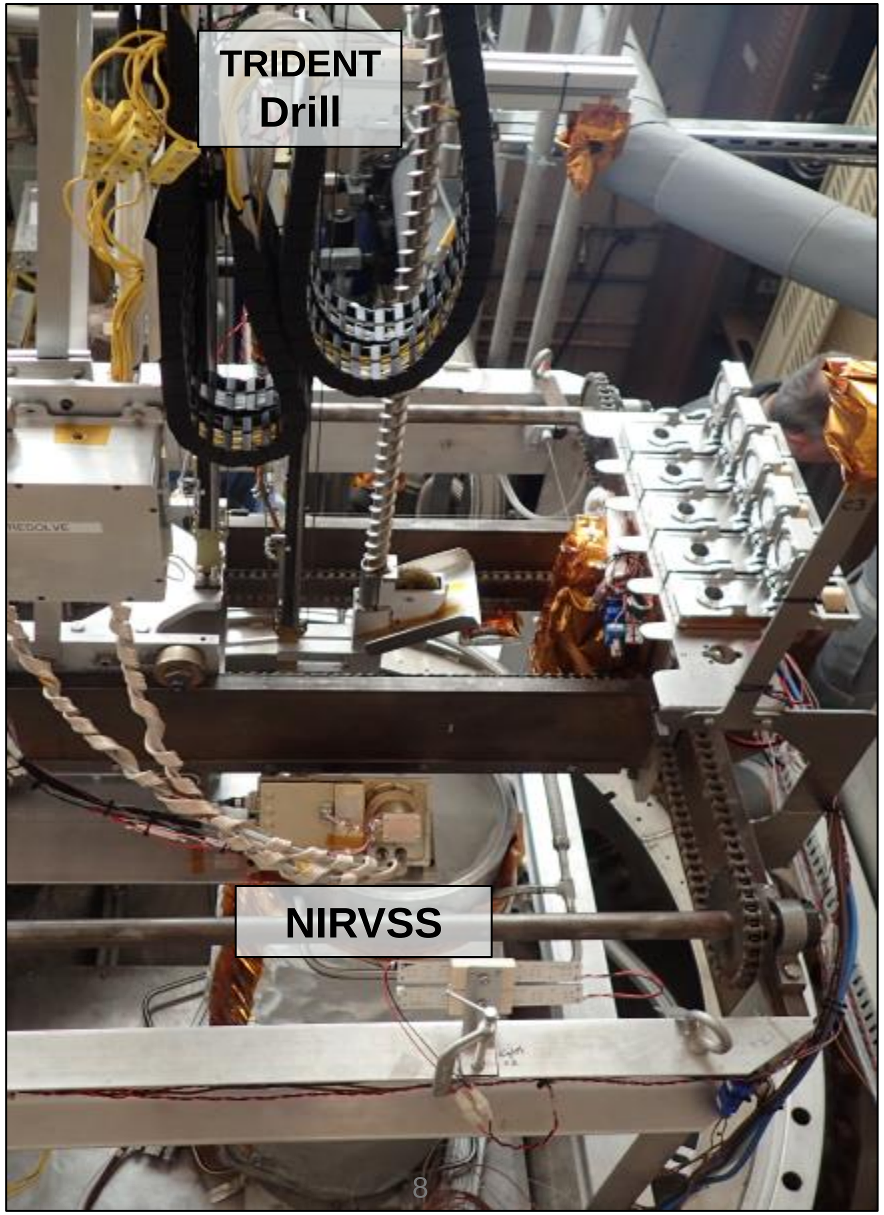
- Lower Power
- Stratigraphy is preserved in 10 cm "Bites"
- Accurate material strength determination
- More accurate downhole temperature
- Reduced risk of freezing-in



Cryo-Vac Testing at NASA GRC

- Test conditions:
  - Vacuum: < $1x10^{-6}$ torr
  - Chamber Temp.: < -80°C, Regolith Temp.: < -150°C
  - Regolith NU-LHT-3M water doped: room dry, 2.5 wt%, 5 wt%
  - Layers separated by Aluminum foil
- >>30 holes drilled in several soil bins
- **MSolo and NIRVSS data correlated well with water concentration**



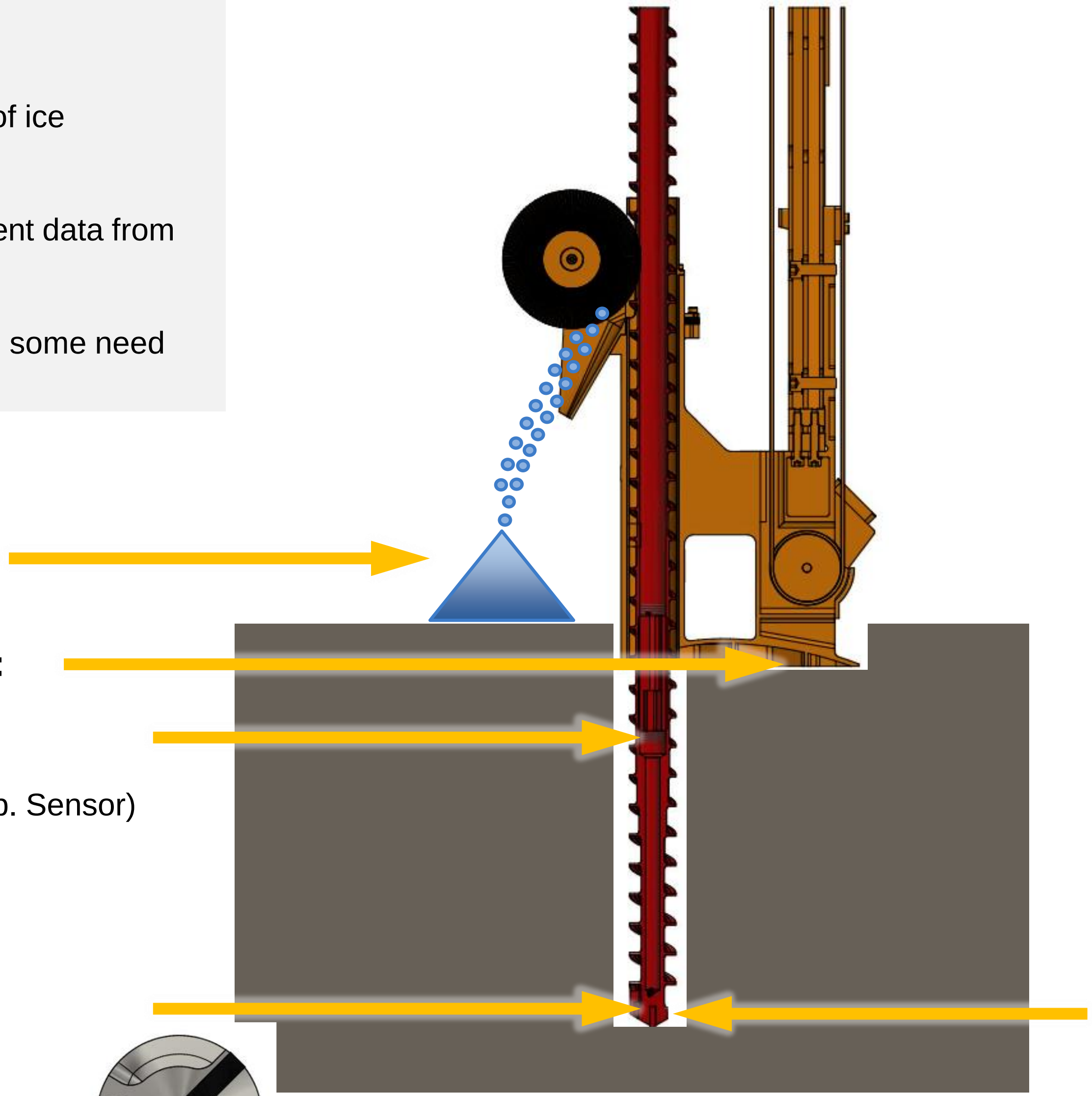


TRIDENT data:

- Geotechnical properties of regolith
- Volatile concentration and physical state of ice
- Thermal properties of regolith

TRIDENT data can constrain and/or supplement data from MSolo, NIRVSS, NSS

Some data products can be used as is (*) and some need modelling/analysis (#)



Cuttings cone (*):

- Angle of Repose
- Density at Dr of ~0%

Footpad sinkage provides (#):

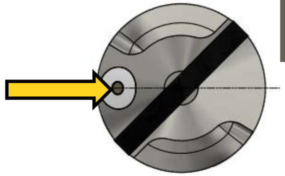
- Bearing capacity

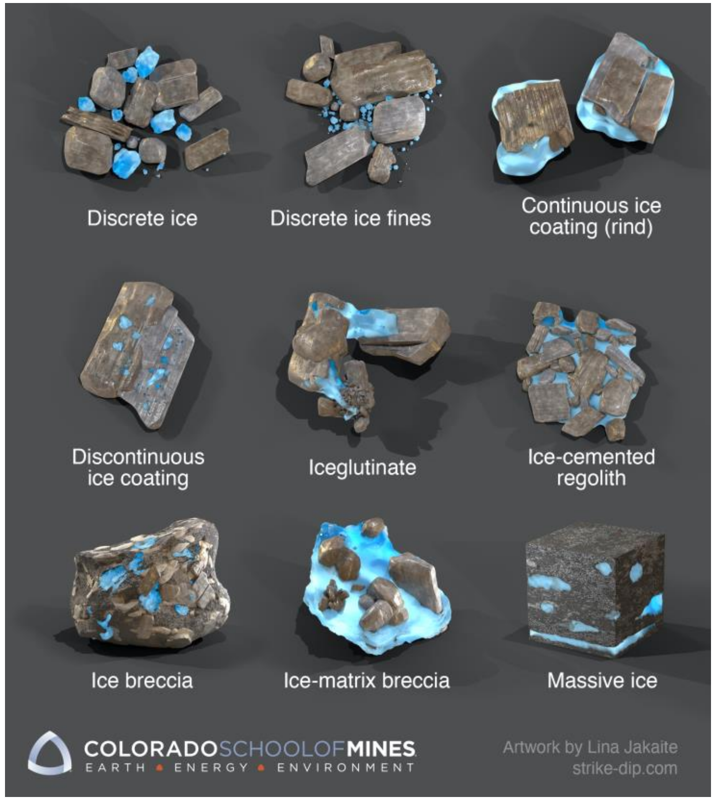
Heater (#):

- Thermal Conductivity (with Temp. Sensor)

Bit Temperature Sensor (#):

- Subsurface Temp vs Depth





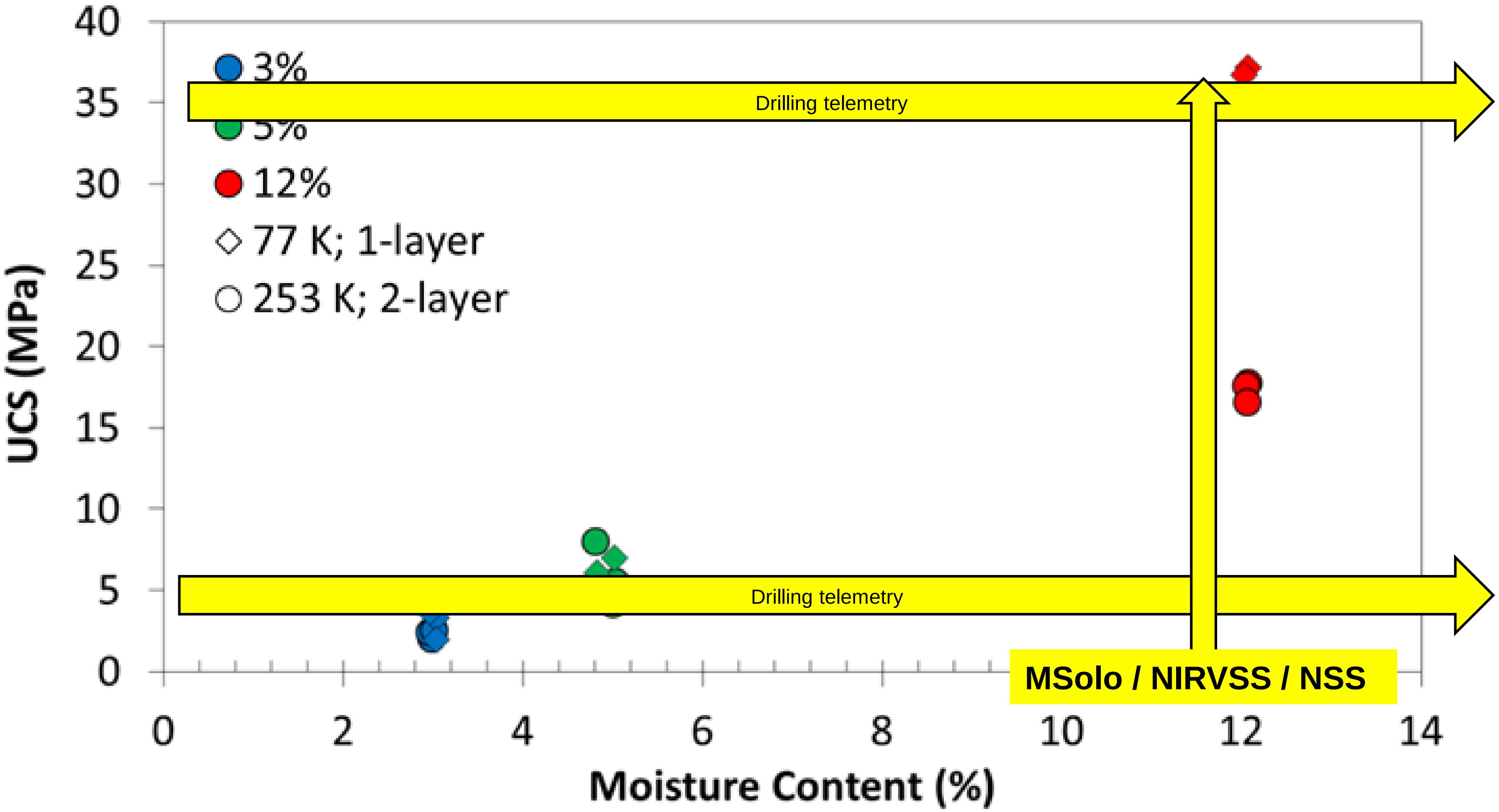
Courtesy Kevin Cannon

Drilling Power (#):

- Material Strength vs. Depth
- Water-ice concentration
- Loose ice grains vs ice cemented regolith

Steps:

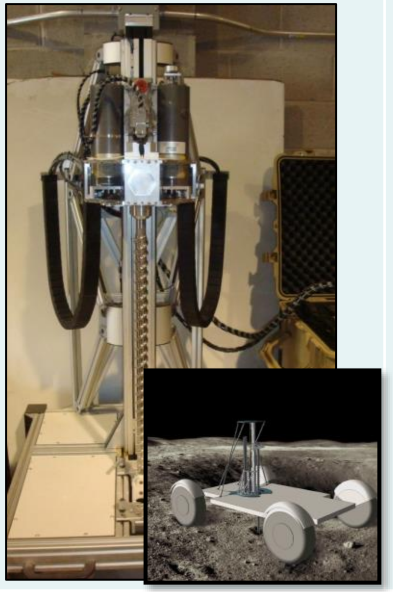
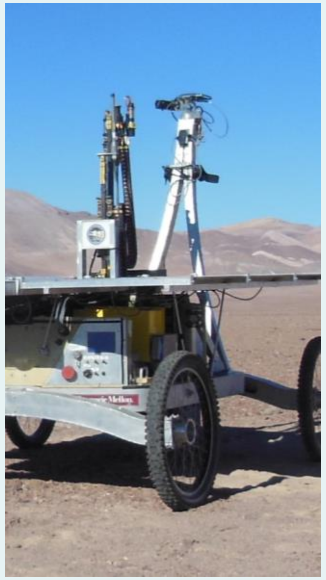
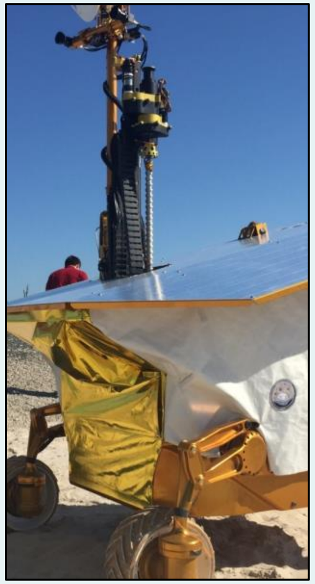
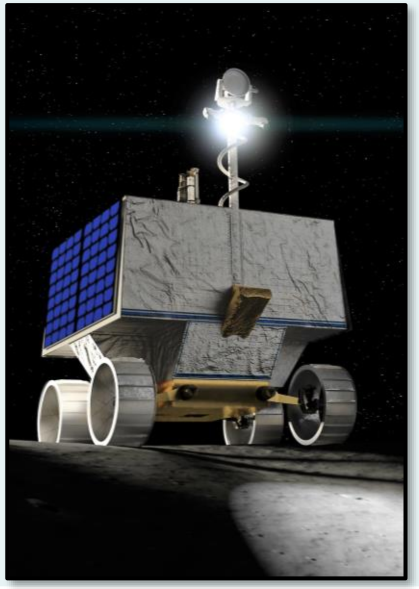
1. NSS/MSolo/NIRVSS constrain water-ice wt%
2. Drilling SE is used to determine how water-ice is distributed



Ice cemented ground

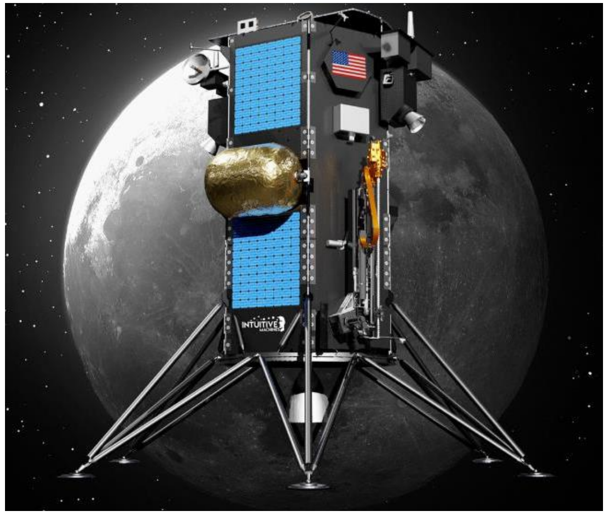
Ice grains mixed with regolith

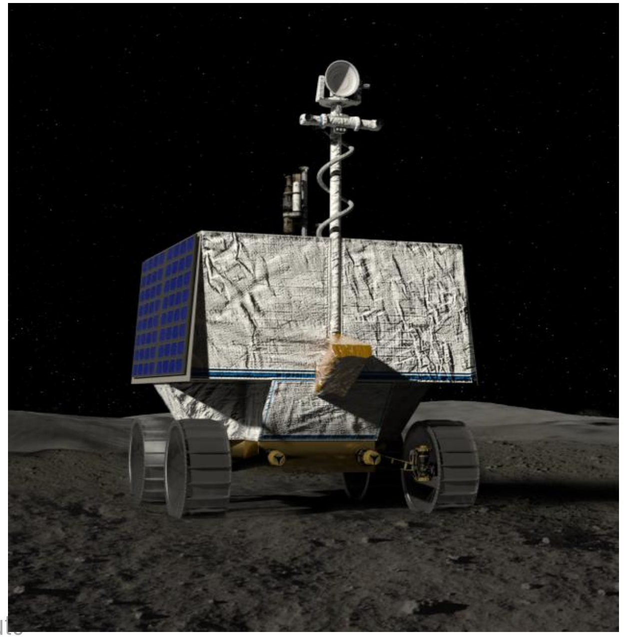
TRIDENT Technology Maturation

		CRUX ('05-'07)	Icebreaker ('08-'10)	LITA ('10-'13)	RP ('14-'18)	TRIDENT ('19-)
						
TRL		3	4	5	6	Flight!
Major Tech		Rot vs Rot-Perc	Cable-Pulley Z-stage Bite Sampling Hammer mechanism (Apollo)	Drill mass Avionics mass	Lunar-rating (P, T)	
Form-Fit-Function		Function	Form-Function	Form-"Fit"-Function	Form-Fit-Function	
Tests	**Chamber**	Mars	Mars	Mars	Lunar	Yes – The Moon!
	Field	Arctic	Arctic, Antarctica (Remote Ops)	Atacama, Arctic, Greenland	JSC Lunar Yard (rover) Atacama	
	Rover			CMU Zoe	RP, KREX2	
	Vibe				Vibe	

Conclusions

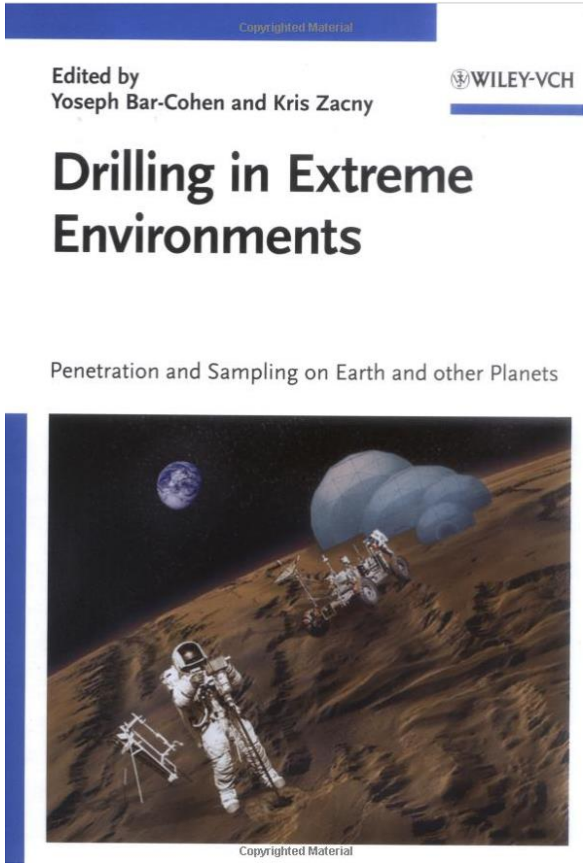
- Development of a sampling system is a highly iterative process that needs to start very early on in the mission formulation.
- Poorly designed sampling system that does not provide a sample in optimal state/position will affect science outcome.
- No two missions are alike. Only few sampling technologies can be ‘built-to print’ for other missions. However, some approaches and subsystems could be adapted across many missions.
- It takes a “village”
  - Success is dependent on a significant number of people, not all of them are involved in the mission daily
- It’s a marathon not a sprint
  - Technology development takes a long time!





Further reading

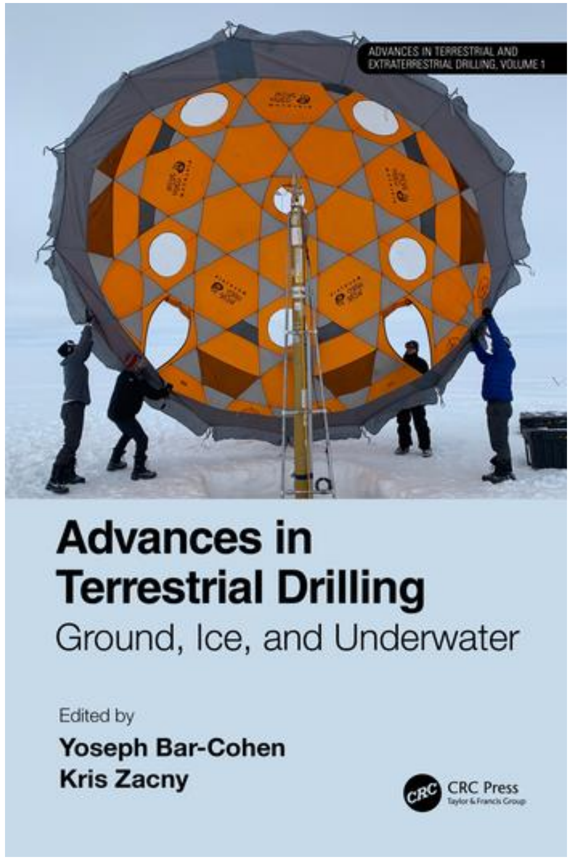
2009

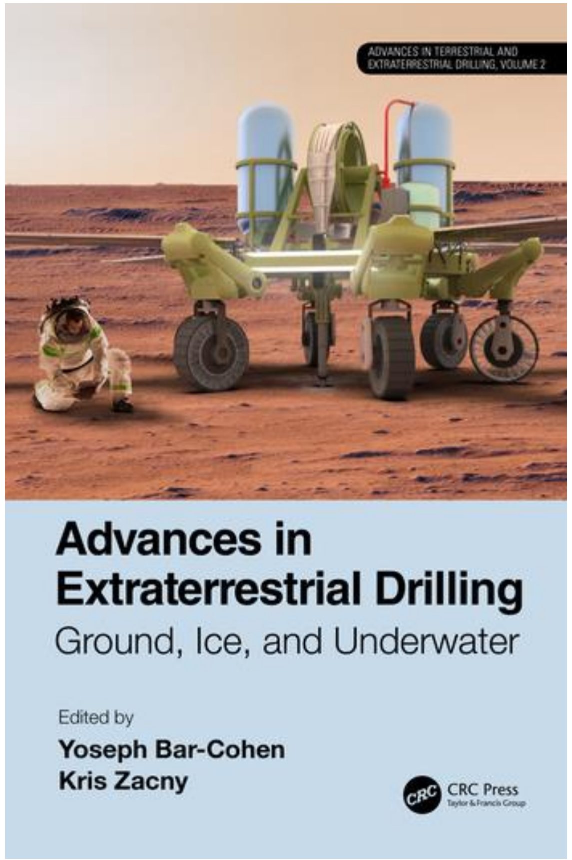


Topics covered:

- Extraterrestrial drilling
- Ice drilling
- Sample handling
- Instruments
- Planetary Protection

2020





Thank you!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A Lunar Water ISRU System Study for Human-Scale Propellant Production

PTMSS/SRR
June 10, 2021

Julie Kleinhenz, NASA Glenn Research Center
Aaron Paz, NASA Johnson Space Center

Objective

EXPLORE MOONtoMARS

- NASA's Artemis plan outlines a sustainable presence at the lunar surface in the 2028 timeframe and indicates the desire to develop ISRU technology to support this
- NASA's Human Exploration Mission Directorate (HEOMD) is developing mission scenarios and timelines
  - In order to infuse ISRU into these missions, estimates are needed for ISRU systems in term of Mass, Power, and Concept of Operations
- Two resources are available for Lunar ISRU for propellant production
  - Water from the polar regions
  - Oxygen bound in the regolith minerals
- NASA's Space Technology Mission Directorate (STMD) has developed a lead-follower approach where water-ice is the lead path and O_2 from regolith is the follower
- Detailed report of many of the finding are available in AIAA-2020-4042

The Goal of this study was to

- Perform a case study of an end-to-end ISRU ice water system; choosing baseline architecture and technology selections to determine:
  - Mass and Power estimates
  - Sensitivity to key variables associated with architecture and water deposit characteristics
- Compare the estimates for a water-ice system to those of an O_2 from regolith system

Ground Rules and Assumptions

EXPLORE MOONtoMARS

- Production requirement is based on propellant production, H_2 and O_2 with a mixture ratio of 6
  - The Oxygen requirement is stated, but hydrogen is the driving requirement, excess oxygen will be generated
- Power systems are NOT included in mass.
  - The power needs are stated, but a power solution is not included in this study.
  - Mass does not include the power plant nor any associated power transmission or conversion systems
- Packing is not addressed
  - System volume is not offered here, though much of this information is available as it relates to mass. Packaging of hardware on landers or other platforms is addressed. Therefore structural supports their masses are not included, though margin is held for this.
- Communication and command/control systems are not explicitly addressed
  - Mobility subsystems include estimates for mass & power load
- Margins held at subsystem level
- System level thermal management systems are not included
  - Subsystems/components may include radiators, insulation, and/or allocations survival heat

Mixture ratio (O/F)	6
Total production time	225 days
Commissioning time	48 hr
Mass Margins	20% growth 15% structure
Power Margins	20% growth
Extraction Efficiency	75%
Maximum battery discharge	80%
Regolith density	1.3 g/cc
PSR Min/Max/Sink Temperatures	50K, 120K, 85K
Ridge Min/Max/Sink Temperatures	100K, 300K, 152K
Radiative sky temperature	4K
PSR Traverse multiplier for hazard avoidance	1.5 x
Excavator Recharge time	5 hr
Tanker Recharge time	10 hr
Battery Energy density	140 Whr/kg

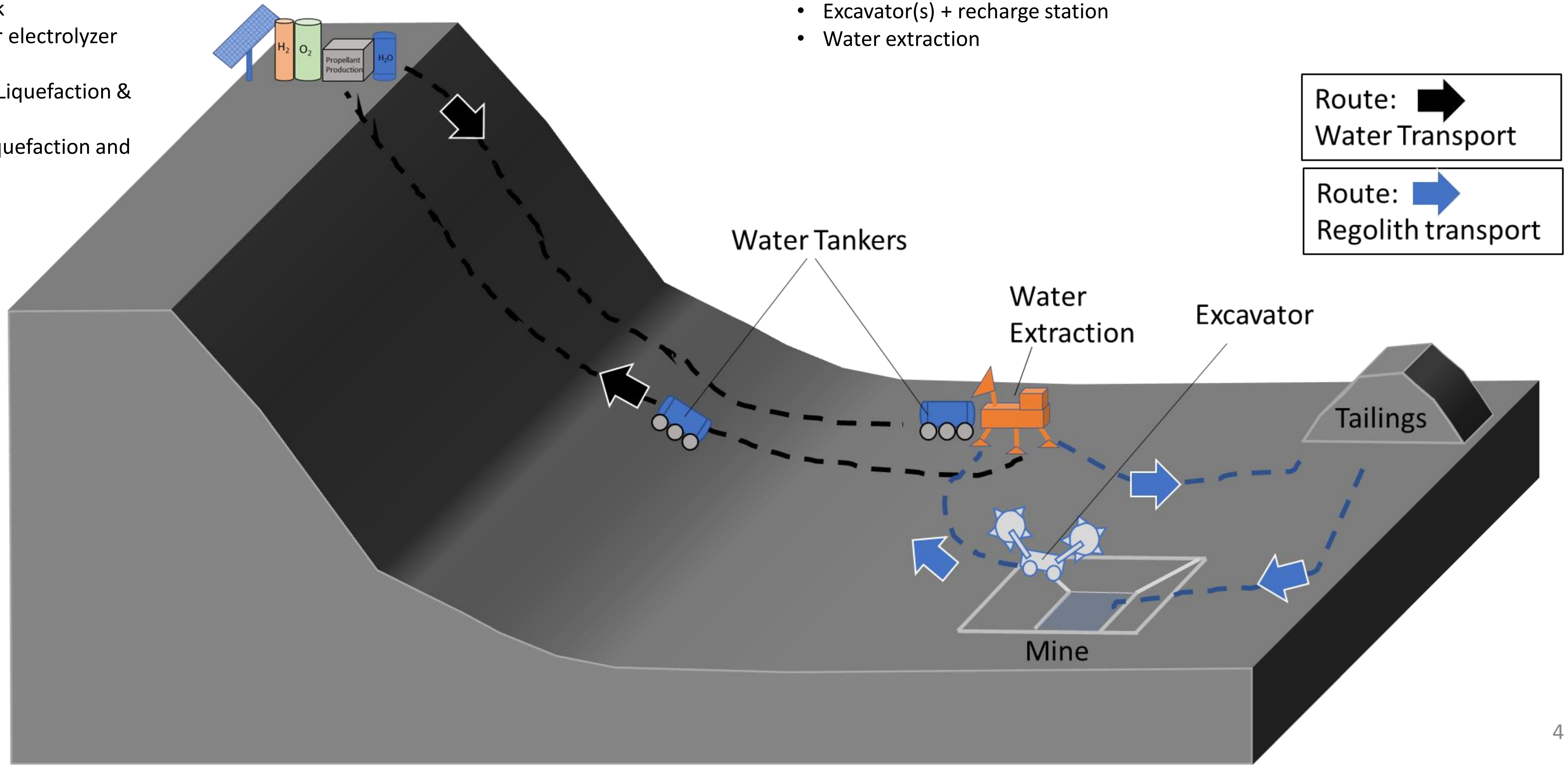
Lunar Water ISRU Architecture

High Illumination Site ("Ridge")
Propellant Production Site

- Water tank
- PEM water electrolyzer
- Gas dryers
- Hydrogen Liquefaction & Storage
- Oxygen Liquefaction and Storage

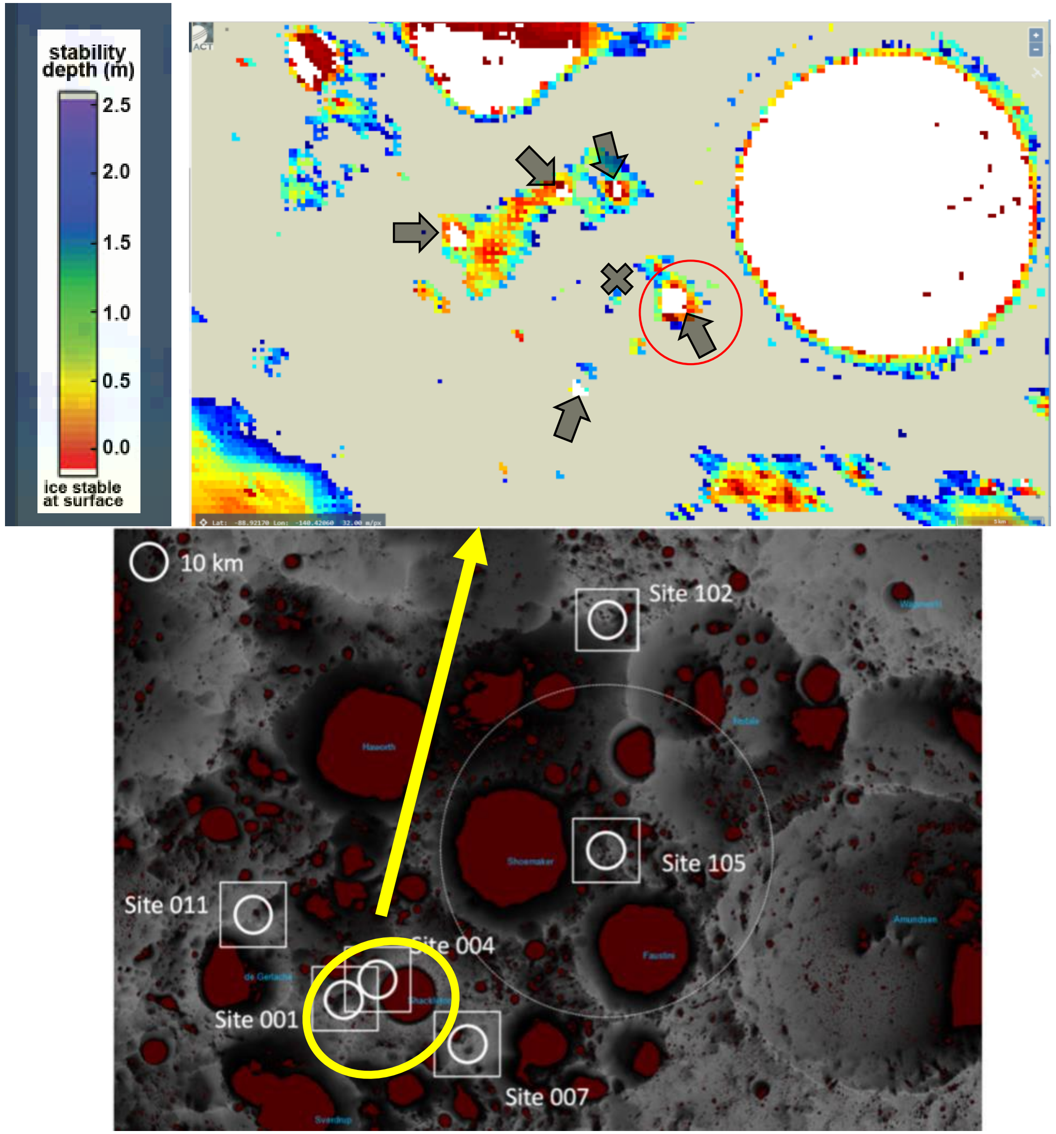
Permanently Shadowed Region (PSR)
Mine site

- Excavator(s) + recharge station
- Water extraction



Notional site selection

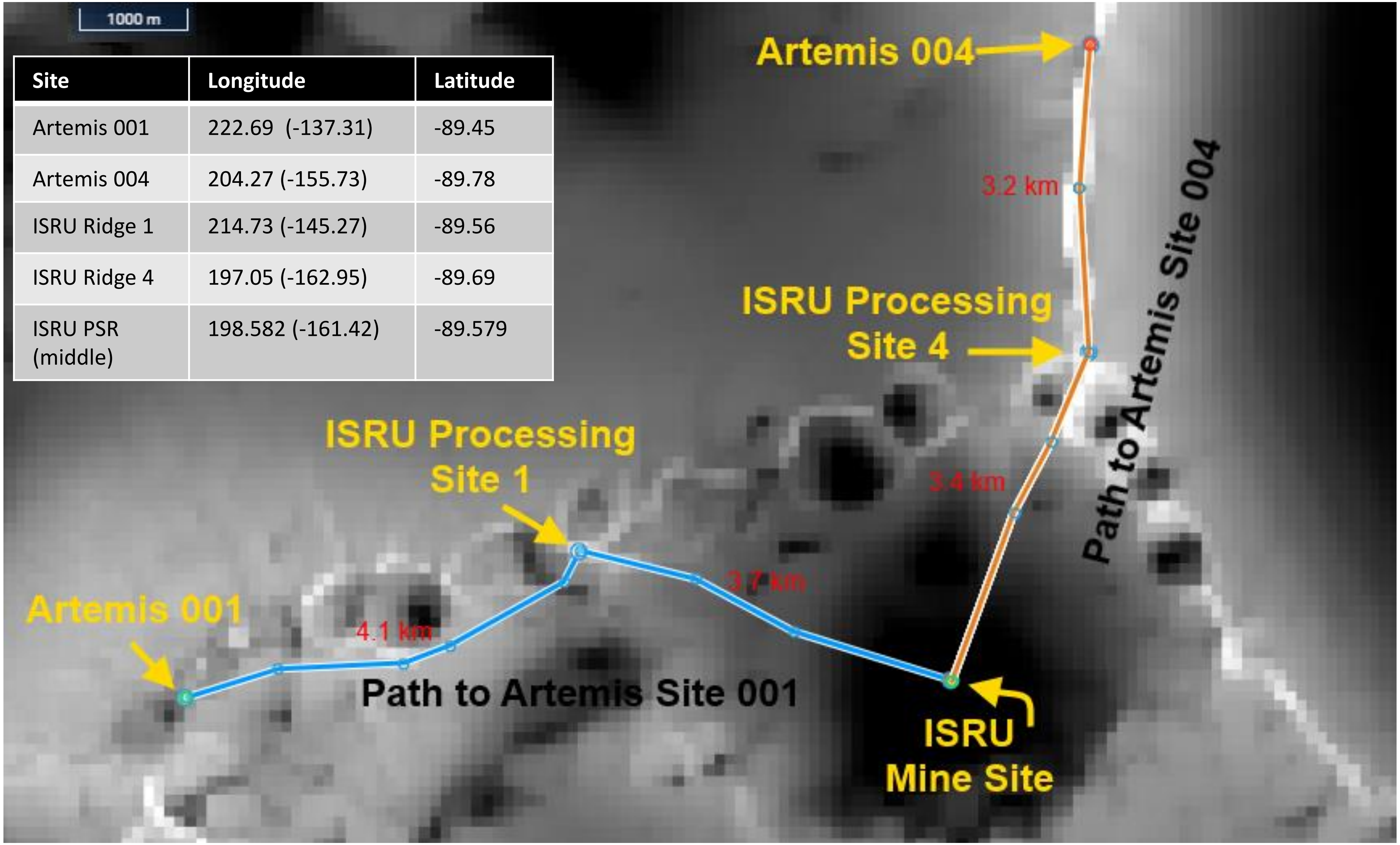
- A baseline site was selected for ISRU operations to facilitate environmental assumptions for the model including temperatures and travel distances
- A water-ice deposit for ISRU has not been located and much is still unknown extent and distribution of lunar water ice. The notional site was selected based on:
  - Notional Human Landing Sites: regions of high illumination
  - Water stability and temperature maps using LROC Quickmap software
  - Slope and traverse distance to HLS sites
- Only near surface (<1m) water ice stability was considered; so mid to large permanently shadowed regions (PSRs) craters.
  - Water ice deposits of sufficient extent may exist outside these craters but were not speculated for this study



Notional site selection

Paths to HLS sites

Site	Longitude	Latitude
Artemis 001	222.69 (-137.31)	-89.45
Artemis 004	204.27 (-155.73)	-89.78
ISRU Ridge 1	214.73 (-145.27)	-89.56
ISRU Ridge 4	197.05 (-162.95)	-89.69
ISRU PSR (middle)	198.582 (-161.42)	-89.579



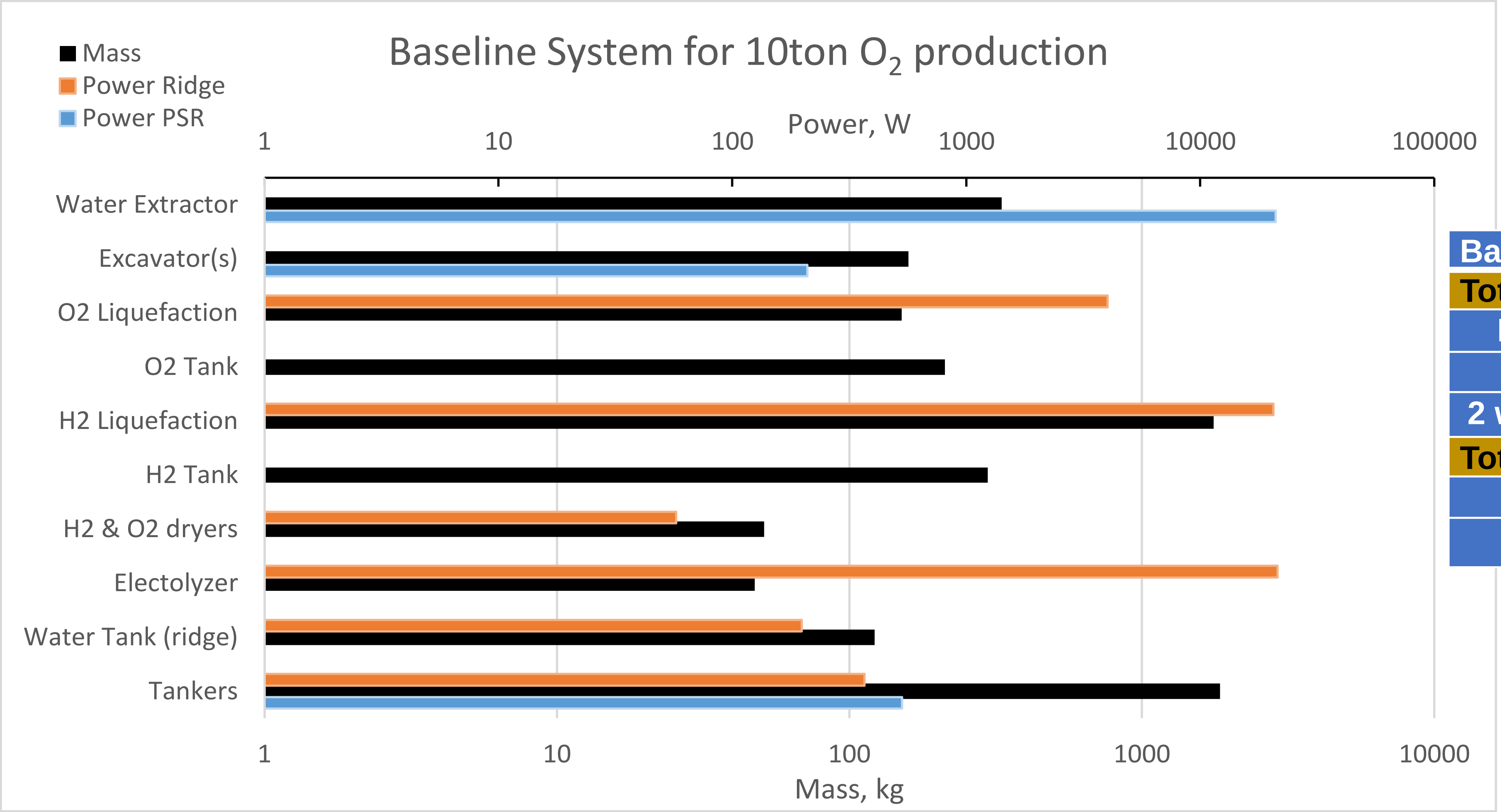
Revision: 225 day assumption

- The operational timeline assumption of 225 days was based on maximum illumination on the notional ridge area, as a starting point
  - The analysis shown in the following slides contain this assumption, even though this does not align with the site shown on the previous graphic.

- Further analysis of the region show that this illumination is only available at a few specific coordinates, which
  1. Limits flexibility of ISRU ridge site positioning
  2. Potentially requires co-location of ISRU propellant processing plant with other surface assets
  3. Extends traverse distances if current mine site is held

- Revisions to this architecture are being explored including
  - Adding Dormancy to operations
  - Exploring power sources options
  - Continued analysis/evolution of prospective ISRU sites

Baseline Case
Subsystem contributions



Baseline case: Results	
Total Mass	**4.9 tons**
Ridge System	2.6 tons
Mine system	0.49 ton
2 water Tankers	1.8 ton
Total power	**68 kW**
Ridge Power	46 kW
Mine Power	22 kW

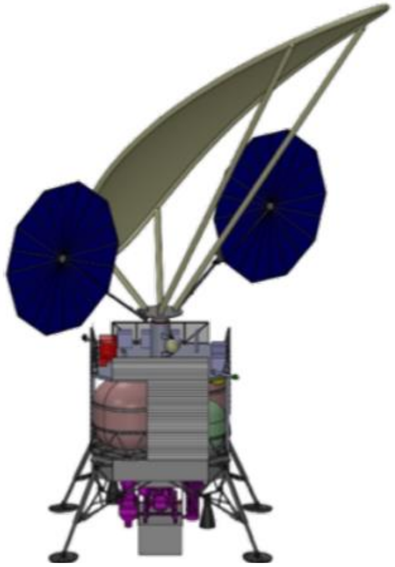
Sensitivity Study

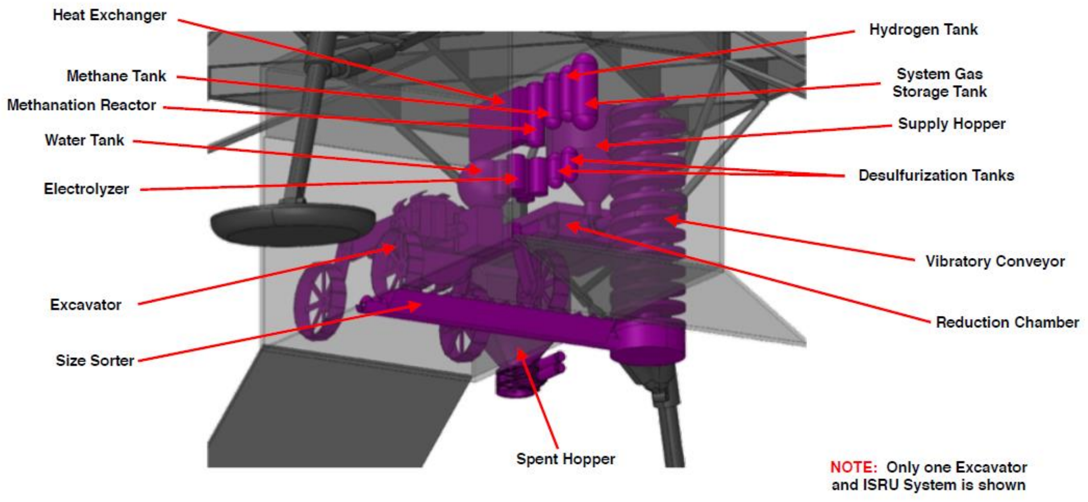
EXPLORE MOON to MARS

Parameter	Baseline		Reason
Production time	225 day	Decreasing time results in Increase Mass/ Power	System has to be sized for higher throughput
Production quantity	10 mT O_2	Increasing quantity for same production time Increases Mass and Power	System has to be sized for higher throughput
Depth to ice (overburden)	20 cm	Increasing depth delays the start of production: Stepwise increase to mass and power depending on excavator duty cycles	Number of excavators is variable based on timelines, if another excavator is required, stepwise increase in mass/power
Time between water transport	10 days	Increase time results in increase mass, minimal power impact	Longer time between trips requires a larger water tank. Power is in the recharge draw, which does not change much
Bulk Regolith water concentration	5wt%	Decreasing concentration increases mass and power, non-linear.	System has to be sized for higher throughput. When systems hit scalability limit, must add modules resulting in non-linearity

Comparison to O2 from Regolith
O2 system

- Oxygen from regolith system from Ref. 2 with production rate of 10 mT of oxygen
- Target oxygen from the silicate minerals in the surface regolith using a Carbothermal reaction process
  - Reduction of oxides with a carbonaceous source (Methane) at temperatures in the range of 1650 -1800°C (regolith melting temperature)
  - Methane is recycled.
- Resource is ubiquitous and in readily accessible surface material.
- System assumed to be in region of high illumination and leverages direct solar heating
  - Solar concentrator for regolith melting
  - Solar array for electrical power
- This study included lander packaging





Linne, D.L., Schuler, J.M., Kleinhenz, J.E., Colozza, A., Fincannon, H.J., Suzuki, N.H., and Moore, L., Lunar Production System for Extracting Oxygen from Regolith. Journal of Aerospace Engineering. Submitted February 2020. PENDING.

Comparison to O2 from Regolith

Assumption differences

EXPLORE MOONtoMARS

Mass

- The ISRU system, without the lander and bus was used for the comparison
- The O2 system included solar panels for power, this mass was subtracted since the water system does not include power
- The O2 system requires hydrogen from earth whereas the water system produces this. An approximation of the hydrogen mass and tank was added.

Power

- The water system power disregards thermal versus electrical power; assumes even thermal (heating) must come from electrical source
- The O2 system uses a solar concentrator to supply direct heating to the regolith for reaction.

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*	*$33.3\ kW_t$*

Comparison to O2 from Regolith

Results

EXPLORE MOON to MARS

Water Ice	O_2 from Regolith
4.9 mT	2.7 mT *each successive mission will require 2 mT of hydrogen from earth, so mass favorably is lost at 2nd mission.
68 kW	45 kW
Resource is not yet characterized, exploration is required prior to operations to determine extent.	Resource is largely known from returned.
Highly reliant on location with accessibility challenges; likely requires higher traverse distances and some operations in an extreme environment (PSR).	The resource is very accessible and ubiquitous.
This case study requires operations at two locations.	Case study does full operations at one location.
Thermal energy for resource extraction is lower; water vaporization energy.	Thermal energy for resource extraction is high, requires melting of regolith
Use of non-electrical heat sources is challenging.	The system can use direct solar thermal heating to reduce electrical power.
Provides full propellant for vehicles. Water can also be used for other applications.	Only oxygen is provided.

Backup

Summary

- A Case study was performed for a lunar water ISRU system to examine mass, power, conops, and sensitivities in order to enable infusion into mission architectures. The system assumed:
  - ISRU operations at 2 sites: a PSR and an highly illuminated Ridge site
  - Water was transported between the two sites using 2 alternating water tanker vehicles
  - Subsystem technologies with available empirical performance data were chosen, but may not be the optimum solution
    - A surface excavator was selected, necessitating a pit-mine approach to reach water rich regolith
  - Assumptions were made regarding resource distribution; 5 wt% water (bulk over mined depth) and a 20 cm dry overburden
- The study did not include a surface power solution, but power needs are stated
  - Thermal and electrical energy requirements were not separated
- The baseline system to produce 10 mT of O_2 and 1.67 mT of H_2 in 225 days was 4.9 mT and 68 kW
  - Water concentration of 1 wt% is not considered a viable solution
  - Increasing depth of the overburden results in step changes in mass and power, one occurs at >1m that results in an untenable solution
  - Increasing the number of water transport trips results in lower mass, but increases risk and wear in an currently unquantifiable way
- Extracting Oxygen from the ubiquitous silicate minerals is a lower mass and power solution (~2.7 mT, 45 kW) for the same production requirements
  - However, each successive mission will require an additional 2 mT of H2 from earth, so mass favorably is lost at 2nd mission

Subsystem Technologies

EXPLORE MOON to MARS

Subsystem technologies with empirical performance data were preferred, so the selections are not optimized and are not decisional

Subsystem	Technology	Description & Reference
Excavator	RASSOR	A dual bucket drum excavator.[11]
Regolith hopper	RASSOR hopper	Designed to match 1 RASSOR bucket wheel for laboratory use; 2 are used in model.
Water Extraction	Auger Dryer	An auger is used to convey regolith through a heated casing. Sizing model based on terrestrial models.[12]
Water Tank for water tankers	Sized: (Aluminum, 50% ullage)	Calculated based on water capacity.
Water Tanker: Mobility platform	Sized	Calculated assuming a payload ratio 1.5 where all battery mass and water tank are payload.
Fluid Transfer	DTAU + COTS water pump lookup table w/flow rate	The DTAU (Dust Tolerant Automated Umbilical) [14].
Water Tank for Electrolyzer	Sized	Calculated based on water capacity.
Water Cleanup	TBD	Not currently included in model.
Electrolysis	Liquid Cathode PEM + COTS water pump lookup w/flow rate	PEM based on performance from NASA SBIR
Gas Dryer	Regenerative desiccant	JSC in house development hardware
H_2 Liquefaction	Cryocoolers	Modeled off COTS, includes radiator mass estimate
O_2 Liquefaction	Cyrocoolers	Modeled off COTS, includes radiator mass estimate
H_2 and O_2 Storage (Tanks)	Sized: Aluminum thin wall (3mm)	Calculated based on capacity.

Baseline Case

- The baseline case for this study targeted the production of 10 mT of Oxygen for use as propellant in an O_2/H_2 system at mixture ratio 6
  - Estimate for the amount of propellant needed to support a human scale ascent vehicle or lander; approximation based on current and previous architecture estimates
  - At this mixture ratio, using water electrolysis, hydrogen is the limiting factor: excess oxygen will be produced.

Baseline Case Key Inputs	
Water concentration	5%
Production requirement	10 mT O_2
Actual production	13 mT O_2 1.7 mT H_2
Water required	15 mT water
Regolith required (75% extraction efficiency)	398 mT
Mine size at 30cm depth	32m x 32m
Time to water transport	10 days

Baseline case: Results	
Total Mass	**4.9 tons**
Ridge System	2.6 tons
Mine system	0.49 ton
2 water Tankers	1.8 ton
Total power	**68 kW**
Ridge Power	46 kW
Mine Power	22 kW

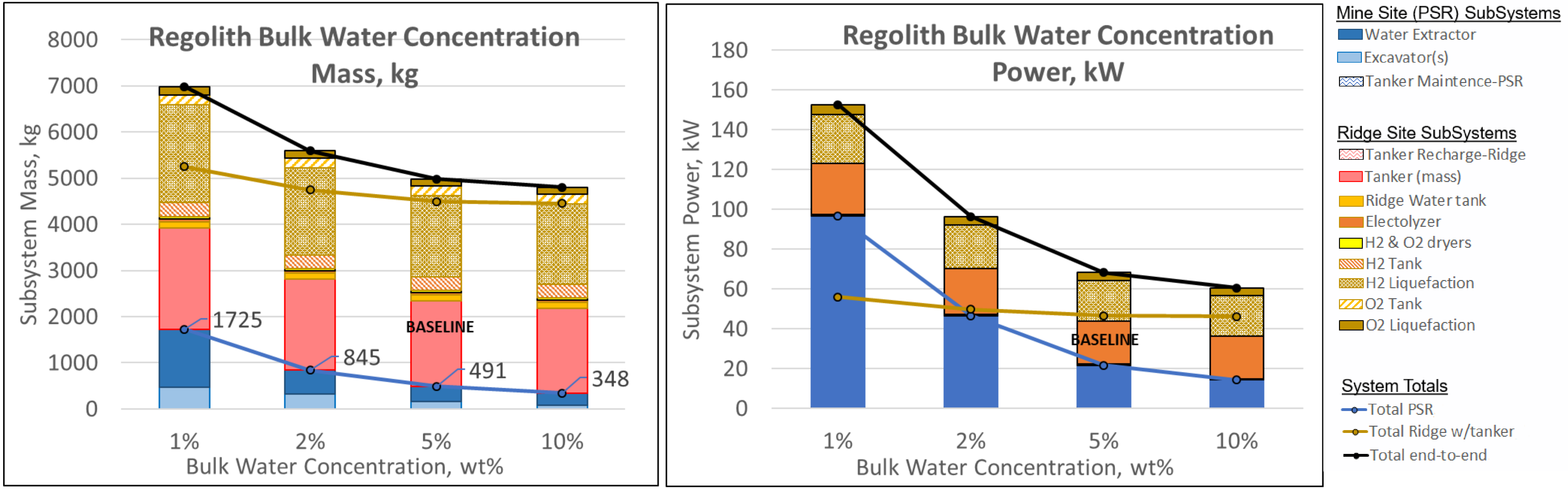
Sensitivity Study

Regolith bulk water concentration

Bulk water concentration is water content over the mine depth. Includes any heterogeneities

- Values chosen are consistent with possible interpretations of Neutron data

- The water extraction system drives results.
  - Water extractor subsystem reaches scalability limit, so multiple units are needed; increasing mass and power particularly at 1 wt%
  - At higher concentrations there is less impact since minimum number of units is reached
- 1wt% is unlikely to be a viable ISRU water-ice deposit (for these assumptions)



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Virtual 2021

Lightning Talks

FUSED FILAMENT FABRICATION LUNAR 3D PRINTER USING IN-SITU RESOURCES. R. Alçufrom[1], T. Aljindi[1], E. Allaire[1], F. Baumelle[1], G. Berestovoy[1], F.Y. Chen[1], I. Couder[2], R-A. De Luca[1], S. De Spiegeleer[2], T. Deschênes[1], J-C. Desmarais[1], D. Diffo[1], E. El Hoayek[1], E-A. Fleur[1], J-S. Giguère[1], J. Kostenov[1], B. Langlet[1], A. Lemieux-Bourque[1], J. Moukam[1], A. Plante[2], C-O. Poirier[1], A. Zahlawi[1], A. Hayes[3], O. Duchesne[1], F.P. Gosselin[1], [1]Polytechnique Montréal, P.O. Box 6079, Station Centre-Ville, Montréal, QC, H3C 3A7, frederick.gosselin@polymtl.ca, [2]HEC Montréal, Montréal, QC, [3]Canadian Space Agency, 6767 Route de l'Aéroport, Saint-Hubert, QC, J3Y 8Y9, andrewaaronmichael.hayes@canada.ca. The first 22 authors have contributed equally to the project.

Introduction: The SPACE'OVER project is an 8-month university capstone project led by a team of 22 multidisciplinary students mentored by the Canadian Space Agency (CSA).

Mandate. The objective is to design an autonomous lunar rover concept capable of printing objects in 3 dimensions from regolith powder, respecting the harsh conditions of lunar environment and launch. In order to produce complete and feasible results in the scope of our project, it was refocused around a proof of concept of 3D printing with lunar dust simulant.

Market analysis: Despite the global pandemic, the global space industry has grown significantly with an estimated total value of $366 billions in 2019 and an annual growth of 1.7% [1]. It is a field in which competitive advantage and growth are built through the search for technological innovations. This new dynamic attracts a diversity of other sectors around the space research centers.

To the space industry is added the rapidly expanding sector of additive manufacturing. Advances and discoveries are growing at an exponential rate (14.4% in 2020 [2]) and continue to expand their impact on the economy, with over 76% of companies having incorporated it into their manufacturing strategy. 3D printing is positioned at the crossroads of these two prolific industries and it must find its place in a closed but competitive market.

Motivation: It is in anticipation of the Artemis program's need for the development of a lunar base that we developed this project. Through the Artemis mission, the ambition of NASA is to use in-situ resources for the construction of a lunar outpost. In this framework, several international space agencies such as the CSA and other private companies are joining the new moon race. However, our project's ambition of development is wide and seeks to penetrate the more distant sectors, without any restrictions to the space domain. Potential applications have been specified: by the military for field interventions, by doctors deployed during disasters or other health crises in difficult environments, or by scientists in extreme explorations.

Prototype and methodology: The prototype design inspired by fused filament fabrication technology, is divided in four aspects: *Polymer*, *Screw extruder*, *3D printer* and *rover integration*. We designed and built a screw extruder and a 3D printer. The screw extruder allows mixing polymer pellets with an additive such as regolith, and extruding the composite into a filament. Fed with this composite filament, the printer can be programmed to print objects of size 100.0mm × 100.0mm × 100.0mm. Furthermore, we ran thermal and structural analysis on a lunar rover concept to ensure the integration of these printing components.

Polymer. We considered several potential polymers to mix with the lunar regolith to achieve the best printing results. A low temperature polymer, polylactic acid (PLA), was first used to confirm the proper systems' basic functioning. We then used a high temperature polymer, polyethylenimine (PEI), suitable for space applications, to confirm the system's proper functioning at high temperature. Once it was done, a sieve removed the aggregates larger than 150 μm in the regolith simulant (Chenobi, NORCAT, Sudbury, ON). The experimenter shaked a jar half-filled with the proper weight mixture of sieved simulant and PEI, in granular form, to mix them. We tested different weight ratios of simulant-PEI mixtures and with our single-screw extruder, we analyzed the feasibility and the quality of the filament extruded from each mixture.

Screw extruder. Since the chosen printing technology involves filament-based printing, a screw extruder (200.0mm × 600.0mm) inspired by the RepRapable Recyclebot process [3] was designed to create a filament from the polymer and regolith/ceramic powder mixture, as presented in the Figure 1.

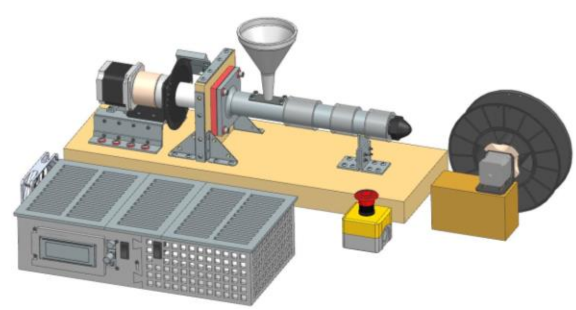

Figure 1: Final screw extruder prototype

The mixture is introduced in the system by a funnel, where it is conveyed by the worm screw while being heated, until it is extruded by the nozzle at the end of the barrel. The heating temperatures of each heating zone and the motor speed are some of the controlled parameters that can influence the results. Therefore, these settings are tested alongside the mixture's homogeneity.

This system produces filaments provided to the 3D printing system.

3D printer system. The 3D printer presented in Figure 2 is of dimensions 510mm × 565mm × 385mm.

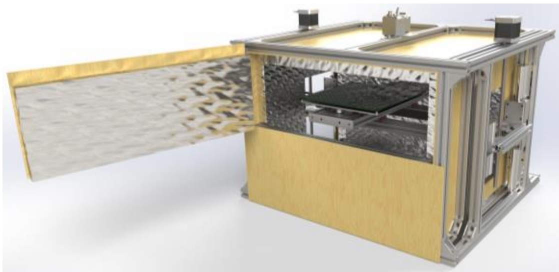

Figure 2: Final 3D printer prototype

The motion system inspired by the open source high-temperature RepRap [4], includes four subsystems: the three *x, y, z* axes and the heated bed on which the printing takes place. The bed has three degrees of freedom to ease the possible future integration with other subsystems such as the screw extruder. The choice of the 3D printer's extrusion system (DyzeEnd Pro and DyzeXtruder Pro kit, Dyze Design, LeMoyne, QC) is justified by the nozzle being able to withstand 500°C, the abrasion resistance of the tungsten carbide nozzle, its ceramic coating and the adaptable liquid cooling system. This system allows calibrations and tests to be performed with high-performance polymer/regolith mixtures, which will help better understand and improve the manufacturing process.

Rover integration. The integration of the prototype to a theoretical rover in the space environment was necessary. This part includes the structural and thermal analyses. The purpose of the structural analysis is to verify that the internal stresses induced by the loading conditions did not exceed the safety factor of 1.25 when using the loading conditions established by Falcon Heavy requirements [5]. The second objective of the analyses is to optimize the thickness of a composite rover designed to provide thermal insulation and to minimize the mass of the rover. The thermal analysis verified that all subsystems operate within their required temperature limits throughout the mission. The thermal design process started with research on the requirements and space environment conditions, followed by the study of thermal transport mechanisms, thermal control subsystem methodologies and concluded with the thermal analysis and validation.

Results And Analysis

Screw extruder. The prototype succeeded in extruding a filament of polymer mixed with ratios of regolith of 5%, 10% and 20% in mass. The strength needed to produce a filament of 70% PEI and 30% regolith exceeded our screw extruder design. Thus, further tests will seek to find the limit between 20% and 30% in mass of regolith that the screw extruder can withstand.

Printer. When printing with filaments composed of PEI and regolith (5%, 10% and 20% in mass), the printer performed fine, as presented in Figure 3. The printer nozzle clogged occasionally but the problem was due to inconsistent filament diameter and not the presence of regolith. Filament inconsistency combined with the presence of humidity led to weak and brittle parts. Therefore, it is difficult to properly compare parts printed with pure PEI and the ones printed with PEI mixed with regolith. Further tests and research will be needed to assess the addition of regolith to the polymer.

Figure 3: 3D printed cubes with regolith (each with dimensions 20.00mm×20.00mm×20.00mm)

Rover integration. Following a series of structural analysis, the team concluded that the structure of the rover, the screw extruder and the printer will resist the launch loads. The thermal analysis indicated that the internal components stay within acceptable operating temperatures and perform in lunar conditions.

Conclusion: This 3D printer lunar rover concept proved the reliability of using regolith to print objects.

Limits. The materials used for the screw extruder's structure can't withstand the torque demanded by the higher concentrations of regolith. Hence, the first limit involves the low regolith percentage of 25% in mass. Secondly, the produced filament experiences inconsistencies in its diameter due to the production still involving craftsmanship skills. Also, the presence of moisture in the polymer produces low-quality prints in which gaps are produced due to the water evaporating during printing. As a result, without proper solutions to control the humidity and the diameter, it is difficult to properly assess the effects on the mechanical properties.

Future work. The team recommends improving the screw extruder's performance and test other polymers to increase the regolith mixture ratio. Finally, it would also be interesting to build a rover prototype to integrate the entire system inside.

References: [1] L. Rapp (2020), *"Quelle industrie spatiale après la Covid-19 ?", The Conversation*. Available: https://theconversation.com/quelle-industrie-spatiale-apres-la-covid-19-144820. [2] W. John (2020), *"Additive Manufacturing Market to Reach USD 26.68 Billion By 2027 | CAGR of 14.4%: Reports and Data", Reports and Data*, Available: https://www.prnewswire.com/news-releases/additive-manufacturing-market-to-reach-usd-26-68-billion-by-2027--cagr-of-14-4-reports-and-data-301163846.html. [3] A. L. Woern, J. R. McCaslin, A. M. Pringle, et J. M. Pearce, « RepRapable Recyclebot: Open source 3-D printable extruder for converting plastic to 3-D printing filament », *HardwareX*, vol. 4, p. e00026, oct. 2018, doi: 10.1016/j.ohx.2018.e00026. [4] N. G. Skrzypczak, N. G. Tanikella, et J. M. Pearce, « Open source high-temperature RepRap for 3-D printing heat-sterilizable PPE and other applications », *HardwareX*, vol. 8, p. e00130, oct. 2020, doi: 10.1016/j.ohx.2020.e00130. [5] , Space Exploration Technologies Corp. Space X (2020), "*FALCON USER'S GUIDE*", Available: https://www.spacex.com/media/falcon_users_guide_042020.pdf#page=39%20zoom=100,93,96.

Acknowledgements: We would like to thank the many people who took the time to answer our questions and share their knowledge with us during the progress of this project. We would also like to thank our partners, the CSA and Dyze Design for supporting our project.

A Good Look Back: Implementing Coal Mining Techniques for Water Ice Extraction in Permanently Shaded Regions of Lunar Regolith

KW Brown[1], KJH Kingsbury[2], and V Tenorio[3]

[1]Mine Operations Engineering Undergraduate at the University of Arizona Department of Mining and Geological Engineering, katebrown@email.arizona.edu

[2]Mineral Processing Engineering Undergraduate at the University of Arizona Department of Mining and Geological Engineering, kerstk@email.arizona.edu

[3]Professor of Practice at the University of Arizona Department of Mining and Geological Engineering, vtenorio@email.arizona.edu

Introduction

When considering the technology gaps involved in lunar water ice extraction, it is beneficial to consider the wide scope of terrestrial mining practices already in use. This includes both older mining methods as well as newer, cutting edge technologies and developments. When extracting mineral resources such as water ice in lunar regolith within permanently shaded regions, deposits are often assumed to be planar or near planar. This lends itself well to the use of strip mining, which entails the removal of mineral-poor overburden to expose a seam of mineral-rich ore. While strip mining has historically been used predominantly for coal extraction, this mining method has also been applied to the mining of evaporite deposits, such as near-surface salt and gypsum bodies.

As near-surface deposits on Earth become increasingly depleted, strip mining is quickly becoming obsolete. This method is, however, a good candidate for lunar mining of water ice deposits, as they often remain close to the surface of permanently shaded regions of the moon. Strip mining has proven itself as a time-tested, economical method for large scale extraction of flat-bedded coal and evaporite deposits.

The implementation of autonomous haulage systems has increased productivity and profitability of surface mining operations. These systems allow for scaling of operations to fit a site's requirements [1]. Using proven automation for mining of lunar regolith eliminates the necessity for direct human interface and could potentially remove the need to have humans on the lunar surface to manage operations. While initially designed for surface and underground haulage programs, this technology can be easily expanded to excavation with the use of continuous miners. This equipment can strip ore from the surface of a deposit and in turn transfer excavated material to a conveyor or haul truck, making it a good candidate for lunar applications.

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SPACE RESOURCES: SOONER OR LATER, LIKELY SUDDENLY. N. J. Bennett[1] and A. G. Dempster[2], [1]Australian Centre for Space Engineering Research (ACSER), UNSW Sydney NSW 2052 Australia, nicholas.j.bennett@student.unsw.edu.au, [2]ACSER a.dempster@unsw.edu.au.

Introduction: Whole-system models, from excavation to internal rate of return (IRR), are part of the research program of the Space Resources group within the Australian Centre for Space Engineering Research. So far, we have focused on parts of the value chain, used different metrics or figures of merit, and modeled sub-sets of the process flow. Our results point to an interesting underlying message:

Firstly, for a project with the typical pattern of resource project cashflows, the time horizon to reach an IRR threshold can be very sensitive to cost/revenue. Secondly, the many layers of the space resource utilization problem can each experience large impacts from small changes, and the impacts in one layer often multiply the effects of other layers. Ten 20% improvements multiplied together give a factor of 6, and even single improvements can deliver large multiples.

We think this means that over a relatively short span of time, small technical and CONOPs improvements will combine to move proposals from being distant possibilities to being in the money.

Here we give a high-level overview of some recent work. While one of our academic points of focus is modeling techniques, we also use that lens to look at the effect of restructuring proposals. To avoid straw men, we build on published plans. Bear in mind that when isolating a single effect for examination, one might leave optimization opportunities unexplored. We think and hope some of the approaches and perspectives are fresh but recognize that they might well only be new to us.

Sudden Viability: A common feature of Space Resource proposal cashflows is initial large net negative flows followed by a long sequence of smaller net positive flows. One can plot the IRR achieved by a point in time for a range of initial cost/revenue ratios.

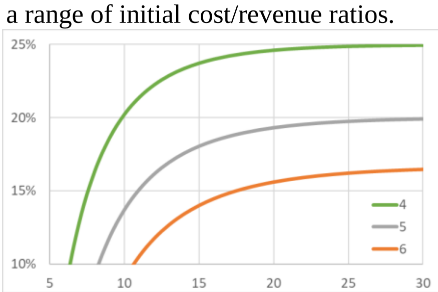

Figure 1: Sensitivity of IRR over time to initial cost/revenue

In Figure 1, as we expect IRR rises with falling cost/revenue ratios, but the time to reach a viability/hurdle IRR is much more sensitive. Small changes can move the project from never viable, through viability over thirty years, to viability over ten years. This dynamic can allow space resource proposal viability to rapidly transition from “decades from now” to “first movers have already moved”.

Sooner Than You Think: There is a current market in Geosynchronous Transit Orbits (GTOs) that lunar propellant tugs could service. If you owned a lunar water mine, you could sign customers now. Satellites in Geosynchronous Equatorial Orbits (GEOs) are launched into a GTO and use onboard propellant to reach their operational orbit. FAA data lets us estimate that we must annually be spending around $0.5 B on lifting propellant to GTOs. Newer satellites might forego $100 M while orbit raising with mass efficient electric engines. We have published work on this concept [1] and contributed further work to a NASA Innovative Advanced Concepts grant. One needs less than ten tons of water for a lift and could service the whole market at about 5-10% the size of proposals that lift from LEO (apples to oranges). Using conservative revenue estimates, one could recover $2,700/kg of lunar surface water at customer breakeven, about six times the rate of other proposals (apples to apples). [2]

Scaling Effects & Constraints Really Matter: Nuclear reactors are non-linear; triple the size can deliver ten times the power. Increasing the size of Molten Regolith Electrolysis (MRE) reactors reduces the power required per kg of output. A 2019 NASA paper analyzed the cost of lunar propellant produced using these technologies, taking the conventional approach of integrating a nuclear and an MRE reactor on Earth. That set plant scale and thus annual output; one needs 16 flights to meet demand.[3] If one allows plugging power into the MRE on the lunar surface, you can send one nuclear reactor and one MRE to almost meet demand with two flights. A modest reduction to tanker dry mass, commercial launchers, and positing a higher demand (to consume excess nuclear power) can drive propellant costs to 7% of the original proposal.[4]

Provide Services, Not Resources: The GTO tug example shows that focusing on the service provided can reveal opportunities. We applied this approach to landing cargo using lunar propellant. Often lunar propellant is pitted head-to-head against Earth propellant in a location like Low Lunar Orbit (LLO). We used a published paper with detailed costings as a baseline and compared a reusable lander based in LLO against the same lander based on the lunar surface.[5] A lunar based lander can land dry, and thus land more cargo. It also consumes less propellant than if it were based in LLO and using lunar propellant. Together this means one can recover more revenue per kg of propellant from a cargo landing service than one could from selling commodity propellant in LLO. Additionally, one can recover the customer's cost of vehicle ownership. Using the modified CONOPs, vehicle ownership recovery, and the competitive parity perspective bridged half the baseline paper's viability gap.

Do not Sell Hydrolox from Water: Hydrolox can be the least cost-effective product for a water mine, and there are likely to be markets for the more cost-effective oxidizer and hydrogen peroxide. The driver here is that water has too much oxygen, regular rocket propellant wastes about 1/3 of a mine's output as excess oxygen. In [1], we used the finance model of [2] to show that one can increase IRR from 5% to 50% by treating excess oxidizer as the saleable propellant and using all the hydrolox for transportation. For 2021 COSPAR, we took a systematic look at ice mine transportation costs, markets, products, and resources.

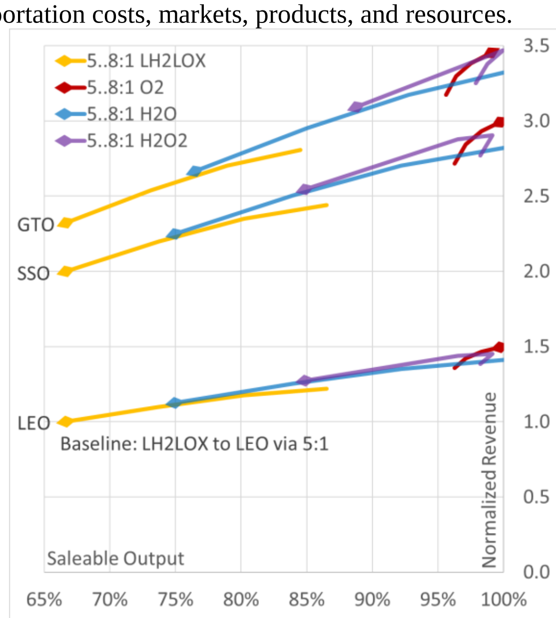

Figure 2: Saleable Output x Normalized Revenue

There is some detail to unpack in Figure 2. The x-axis represents the % of mined water one can use; the rest is a CAPEX opportunity loss, an increased cost per useful kg of mine output. The y-axis represents revenue normalized to the "hydrolox in LEO" case. Propellant products are color-coded; red for O_2 oxidizer, purple for H_2O_2 hydrogen peroxide, gold for regular hydrolox, and blue for water. There is a likely market for H_2O_2 tugs and station keeping in Sun-Synchronous Orbits (SSOs), which Orbit Fab is targeting. There are likely markets for O_2 anywhere from the lunar surface, through GTOs pointed at the Moon, to LEO. Transportation propellant O_2:H_2 ratios smear each product into a line. In all cases, O_2 oxidizer is the most remunerative and cost-effective product. With 6:1 transport, H_2O_2 can match O_2, with 8:1 water comes close to the other two. For hydrolox to be a desirable product one needs to either be delivering 8:1 (effectively water) or use trace hydrogen from impurities like H_2S and NH_3. Even for "commodity propellant" there is a tradespace where choices effect revenue by a factor of three.

Metal & Manufacturing Lags Decades Behind Propellant: The European Space Agency roadmap links this demand to substantial human bases. For 2020 IAC, we modelled propellant transportation efficiency for a large set of vehicle engineering changes; for example, inflating the tank to thrust ratio, aerobraking, lighter tanks, etc. An interesting result was that when supplying propellant propulsively to LEO, containerizing the propellant increased deliverables by 30%. Manufacturing tanks on the lunar surface raised revenue by 30%, equivalent to a demand for lunar manufactured propellant tanks. Regolith is about 0.5% free iron dust, enough to print tanks to hold the volatiles.

New launch sidelines space resources: Reusable heavy-lift vehicles from ULA, Blue Origin, & SpaceX could greatly reduce the cost to put a kilogram in LEO. Elon Musk has indicated $10/kg, 0.5% of current costs. Cheaper launch costs undermine the revenue streams of using space resources in space, but even without positing new markets, we might be able to "make it up in volume". SpaceX Starship launch cost projections are predicated on scaling up to support their Mars Project; 1,000 Starships to Mars every 26 months for thirty years. Each Starship needs about 960 tons of liquid oxygen, so the project represents a demand for about one megaton of oxygen in LEO every 26 months. Recall that oxygen is the product a lunar water mine can most profitably sell and that from the Moon, it is cheaper to deliver to the higher energy orbits that are expensive for Starship to reach.

Conclusion: There seems to be scope for significant impact from innovations on the goals of a business through to engineering details; there are good reasons to be hopeful that business cases are likely to improve rapidly.

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SPACE RESOURCES AND SOCIAL ACCEPTANCE. Y. Isabel CASASBUENAS[1] and M. NAKAGAWA[2], [1] Colorado School of Mines, Casasbuenascabezas@mymail.mines.edu, [2]Colorado School of Mines, Mnakagawa@mines.edu.co.

Abstract: Space resources is gaining much attention from the space industry as well as mining industry. The off-earth mining activities are becoming an interesting area where public and private companies want to engage in the extraction of value-added resources. The terrestrial mining activities have a great challenge to extract resources and perform them without compromising future generations' ability to meet their own needs. In this sense, activities in space cannot be very different from earth. The future extraction of space resources will require meeting sustainable development principles and a circular economy that do not affect future generations. This paper aims to analyze aspects of the learned sustainability concept and its applications to space resource activities. Literature review was conducted to identify the state-of-the-art of the space resources sustainability. We present a discussion of the challenges and opportunities to start thinking about sustainable development practices.

Introduction: Extractive industry has changed through generations. The previous generations of industry performed different extractive activities to meet their needs. Through generations, we have tried to secure our material needs according to the environmental, work, political and economic conditions; however, any negative environmental impacts caused long time ago are still being mitigated. Therefore, we must keenly aware that our action today will have a long-lasting impact on the future generations and may cause social and economic problems if we are not careful.

In the extraction process, the community was often not involved until a significant impact becomes apparent to the public eye. However, the arrival of the internet and the media's advancement have allowed the community to be more attentive and aware of what is happening with the impacts caused not only by the mining industry but by all other related industries. This has led companies to share a large amount of information about their projects, investments, extraction methods, and activities related to the mining operation. All the above need to be transparent in its operations and work under specific standards, methods, and meet the sustainability concept. The transformation has been very encouraging that now there are standards such as the Extractive Industries Transparency Initiative (EITI) that seeks to promote transparency and good management of the naturals resources for the extractive industry's sustainable development [1]. The foregoing aimed to actively engage the community to participate in the design, monitor, and evaluate the entire process of an extractive activity, which includes the technical and economical, and political aspects [2]. In this paper, we discuss the core concept of sustainability including its operational definitions and perception by the mining industry. We hope that lessons learned about the importance of the social acceptance in the mining industry will be extended to the future space mining activities.

Sustainable Development: The term sustainability has gain strength since 1980, and it is being more applicable lately by all industries (Figure 1). The core definition of sustainability states to perform human activities to meet our current needs without compromising the ability of future generation to meets their needs.

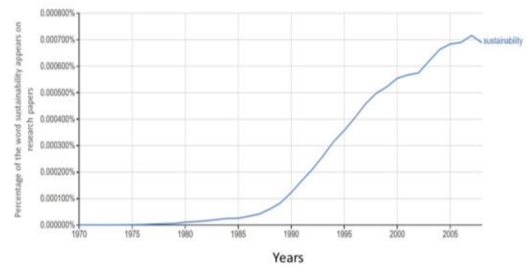

Figure 1: How often the sustainability terms appears in the literature from 1970 to 2005[3].

The sustainability concept is usually defined by three pillars or three dimensions: environmental, social, and economic (Figure 2). All the three dimensions are usually equally weighted in the analysis. However, it is sometimes argued that the environmental or social dimensions are more important than the others. For example, Watson states that the three pillar concept does not represent the fundamental roles of the environmental component in the sustainability discussion, and he proposes that the social and economic dimensions be embedded in the environment [3]. Therefore, the environmental dimension must be society and economics' top priority. In the extractive industries such as mining, the term sustainability is sometimes used to generate benefits without affect the environment or the society. However, the concept goes beyond this idea. For the mining industry, the sustainable practices must be the core aspect of the business and operations [5].

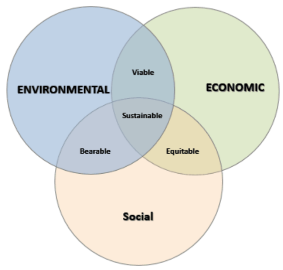

Figure 2: Sustainable development pillars [4]

Mining industries include the sustainable development pillars (Figure 2) in their operations because the only way for the mining industry to be economically viable is by operating environmental and socially responsible. However, the social acceptance has become a major concern for the mining industry, especially because millennials does not want to invest in mining [6]. Therefore, social engagement and social acceptance at every stage of the mining operations has recently become more than necessary. However, the question that arise is how the sustainability dimensions will be consider in the earth-off mining activities, even when mining is not fully accepted on earth.

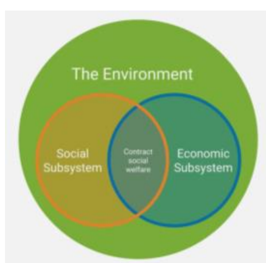

Figure 3: Sustainability dimensions diagram proposed by Watson[3]

Social Acceptance of the Space Activities: The extraction of the space resource must face a myriad of challenges such as conflicts between stakeholders because of resources rights, inequalities in benefits sharing, and environmental contamination [7]. All these challenges will affect the sustainable development of the earth-off mining activities. Therefore, the sustainable development concept for space resources would contribute to handle and mitigate these challenges [7]. Within the concept of sustainable development, the importance of the social acceptance or the social pillar will rise very fast because the concern of the impacts that it might be caused the space activities not only in the space but also on earth. Social acceptance has become popular at modern times, and it will be a high priority once the space resources became a formal industry.

Although the community will not have a strong presence on the earth-off mining activities, they will keep an eye on the development of the activities and possible impacts caused by these activities. Therefore, we propose a new sustainability development pillars for the off-earth mining activities (Figure 4). This proposal is based on the thesis that the social acceptance and the social pillar will be the core of the sustainable development for the off-earth mining activities.

Figure 4: Sustainability development pillars for the off-earth mining activities

Discussion: We argue that it is necessary to think about sustainability applied to space resources development in a different way as the social acceptance will most likely play a big role in the future. Activities related to space mining will be visible to anyone with internet, and a lot of information will be shared through the social media, either positive or negative. Therefore, social acceptance on earth regarding with the space activities and communities' perception will have an important role in the development of future space activities.

Conclusion: Extraction of the spaces resources may become an emerging industry in the future. Therefore, we think it is important to start thinking about the potential impacts this industry may cause. A new sustainable development concept for the off-earth mining activities is proposed. It is also proposed to consider new standards as the EITI that guarantee transparency in the extraction of space resources.

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Extending the depth range of light rovers using a bioinspired design. Saeedeh Naziri[1], Cyrena Ridgeway[1], Salvador Ibarra[1], Jose A. Castelo[1], Katarina Provenghi[1], Douglas D. Cortes[1], [1]New Mexico State University, 3035 S. Espina street, Las Cruces, NM 88003, p. 575.646.6012 (Contact: dcortes@nmsu.edu)

Introduction: Earthworms and other annelids have been the source of inspiration for a wide range of exciting limbless devices that use peristaltic motion to crawl on surfaces or move within tubes. However, most of these bio-inspired tools have not been put to the test of burrowing in granular media. As a result, it is easy for industry to underestimate the technology readiness of these designs, and flock to more conventional soil augering, and driving tools.

Penetrating the subsurface involves complex soil-tool mechanical interactions. The volume expansion and contraction that define peristaltic motion cause simultaneous localized densification of the soil (solid-like behavior), the formation of shear bands and subsequent cavity collapse (flow-like behavior). Therefore, the movement of the worm alters the structure of the soil and constantly changes the nature of their interaction. This makes it difficult to use simple continuum mechanics models to study subsurface peristaltic motion. We created a simple earthworm (*Lumbricus terrestris*) inspired soil penetration device by combining a miniature steel cone penetrometer with a soft membrane (figure 1) and deployed it in a bed of Lunar regolith simulant (LMS-1 Exolith Lab).

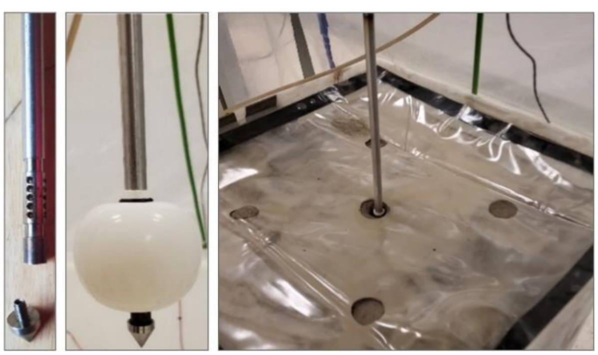

Figure 1. Earthworm-inspired subsurface penetration probe.

Testing and results: Instead of mimicing the entire body, our device is inspired on the earthworm's anterior end. Forward movement is driven by a linear actuator set on a load frame. Hence, our study focuses on the potential changes in penetration resistance caused by volume expansion and contraction of the soft membrane. Bioinspired penetration tests are conducted under displacement-controlled conditions (velocity 2 = mm/sec) to a pre-set depth of 10 cm while logging the penetration resistance via a load-cell. The driving linear actuator is locked at this position and the membrane is inflated to a selected volume. Pressure sensors in the hydraulic system allow for the determination of the pressure required to inflate the membrane. After that, the membrane is retracted, and the probe is driven deeper into the regolith bed. The subsequent depth intervals and the final membrane volume at each stage are variables used in the study. Some of the test results are presented in figure 2.

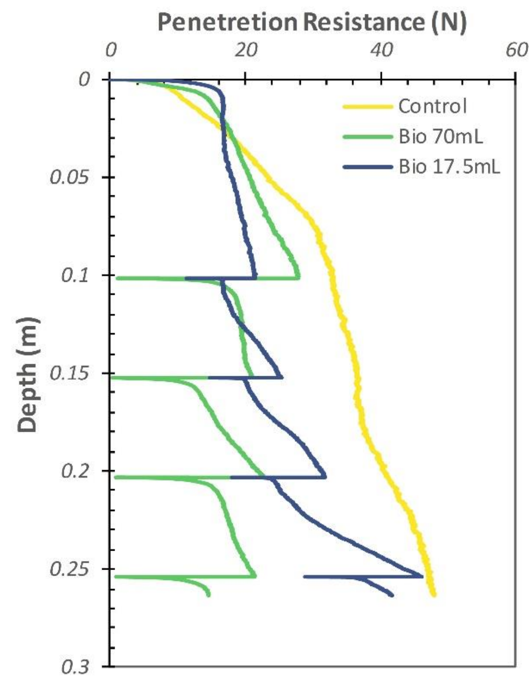

Figure 2. Penetration resistance of bioinspired and control tests.

Capabilities: Test results show that an earthworm-inspired penetration strategy can effectively reduce the the penetration force needed to drive a probe into Lunar regolith simulant. The magnitude of the decline depends on the inflation volume and pressure, which provides additional deggrees of freedom to optimize the penetration process. Compared to the control probe driving, the earthworm-inspired penetration can <u>eliminate 67% of the surface mass</u>, and <u>cut the penetration energy</u>

by a quarter while limiting peak power consumption to 8 Watts.

FRAMEWORK FOR LUNAR SITE INVESTIGATIONS. H. A. Danque[1], E. Butler-Jones[2], J. Hinton[3], E. C. Luken[4], and J. M. Sangree[5], [1,2,3,4,5]Center for Space Resources, Colorado School of Mines, 1500 Illinois St, Golden, CO. 80401. hdanque@mines.edu

Introduction: There is a growing interest in lunar exploration and resource utilization that is driving a need for detailed project and infrastructure planning. A critical step in infrastructure project planning is the "site investigation." Terrestrial site investigation organizations traditionally collect data, analyze, and report it to their customers – the project developers. The site investigation report organizes the knowledge gathered in a site investigation to clearly communicate engineering design requirements, provide regulatory reporting, and reduce program risk.

A framework for conducting site investigations for lunar applications was developed by analyzing terrestrial site investigations and practices from multiple industries, reviewing relevant current lunar research through interviews and publications, and then using these sources to adapt terrestrial site investigation practices to the lunar environment.

The proposed lunar site investigation framework was tested and applied to two different resource utilization architectures to test the framework's completeness and improve it through iteration. Numerous interviews were conducted with lunar professionals and scientists from government, private industry, and academia to develop and improve the framework.

Teams and organizations that choose to adopt this framework will find it helpful to identify gaps in data needed to design lunar mission architectures and hardware. It will allow prioritization of data collection to reduce program and operational risk efficiently.

Methods: This site investigation framework was developed through the systematic review of lunar research, terrestrial site surveys, survey-related literature [1], [2], and interviews with industry experts. The framework was then developed for two of the three common stages of a site investigation - the Desk Study and the Detailed Study. The third phase - Construction Review - was omitted. With the initial framework outline, two case studies were evaluated. One case study was done at a site suitable for an Oxygen-from-Regolith architecture. The second, at a Permanently Shadowed Region (PSR) suitable for a Thermal Ice Mining architecture. The lessons learned during the application of the site investigation framework to these case studies led to revisions of the framework. The framework was also revised based on additional input from concurrent interviews with lunar scientists and professionals.

Results: The review of terrestrial site investigations indicated that most projects start with a Desk Study that reviews current data and recommends additional data and analytic requirements. This is followed by a Detailed Investigation for Design that includes higher resolution data and more detailed analysis identified in the Desk Study. Finally, there is a Construction Review that modifies the Detailed Investigation for Design through observations during construction. The current state of lunar data acquisition and analysis allows for meaningful Desk Studies and initiation of a Detailed Investigation for Design for some lunar architectures.

Key Lunar Considerations. Several lunar environmental considerations modify traditional terrestrial site investigations [3], [4]. Some of these include Reduced Gravity, Solar Illumination, Landing and Launch Operations, Thermal Management, Electrostatic Properties, Long-Term behavior of regolith, Dilatancy and bulk density variation, Compaction Profile, Agglutinate % Content, Surface Dust, Temperature Variation, Geologic and Geotechnical variability, Regolith volatile content, Radiation, Behavior of disturbed/exposed regolith, and the Lunar seismic environment.

With the considerations above, the Desk Study and Detailed Study reporting structures are developed.

Desk Study Content

- Introduction
    - Project Description
    - Background
    - Previous Studies
- Site Surface Location & Conditions
    - Site Location Overview
    - Surface Topography
- Subsurface Conditions
    - Geology, Geophysics, Geochemistry, Geotechnical
- Hazard Analysis
    - Operational Hazards
    - Seismic Environment

Detailed Study Content

- Introduction
    - Project Description
    - Investigation Methods
- Surface Conditions

    - Local Environment (compare with Desk Study assumptions)
    - Topography
- Subsurface Conditions
    - Geotechnical assessment
    - Volatile/Chemical Assessment
- Design & Construction
    - Site Preparation & Subgrade Preparation
    - Fill Specifications & Grading
    - Groundwork Construction
    - Recommended Bearing Capacities
    - Seismic Requirements
    - Dust Considerations
    - Electrical Grounding
- Access Preparation
    - Launch/Landing Site
    - Travel Route Slope and Wall Stability
- Hazard Analysis
    - Detailed Hazard Analysis

The Desk Study and Detailed Study's proposed reporting structures were tested for two hypothetical but likely lunar resource architectures and plausible locations [5], [6].

Case Study #1 Oxygen from Regolith. There appears to be enough data available from orbital and lander datasets on the topography, temperature, and bulk regolith properties that an Oxygen-from-Regolith pilot plant could have a reasonably well-constrained project risk profile. The highest priority missing data is site-specific subsurface composition and particle size distribution, the geotechnical properties affecting rover excavation and mobility, and higher resolution images to determine boulder presence and small crater locations.

Case Study #2 PSR Thermal Mining for Water. There does not appear to be enough data from current orbital and existing lander data to adequately constrain the project risk profile of a typical thermal mining architecture. The highest priority missing data are high-resolution imagery or digital elevation models (DEMs) below 1-meter resolution in PSRs to determine elevation, slope, as well as boulder and small crater locations. PSR regolith's geotechnical properties are poorly constrained both in the near-surface for mobility and excavation and for understanding in-situ vapor transport.

Conclusion: This lunar site investigation framework is formulated to reduce risk to future lunar development and operations by identifying the critical site conditions that must be measured to identify hazards and considerations for site development. This framework is a potential solution to organize site investigation data acquisition and reporting. Several items in the framework apply to most locations on the Moon and are thus considered fundamental. These include the Project Description, Surface Conditions, Access Preparation, and Hazard Analysis. For more involved projects a Detail Surface Analysis, Subsurface Analysis, and Design and Construction Guidelines should be considered. There are many additional project specific considerations that may be necessary for some site investigations.

As a body of experience develops in lunar operations, construction, and development, supporting standards should be developed to provide a common language and procedures for industry and other entities operating on the Moon. Site investigations and engineering design will work iteratively to design better machinery and structures for mission success. A general observation is that more complex architectures require more detailed knowledge of the site and a more thorough site investigation.

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Acknowledgements: The authors would like to acknowledge the contribution of the lunar professionals who volunteered their time to give suggestions and feedback to develop and improve this site investigation framework. Our deepest thanks go out to Koorosh Araghi, Dale Boucher, Kevin Cannon, Peter Carrato, Anthony Colaprete, Sarah Deitrick, John Gruener, Carlos Espejel, Ryan Ewing, Ryan Garvey, Mike Gold, Julie Kleinhenz, Rob Mueller, Doug Rickman, Mike Seibert, Nicole Shumaker, Fred Slane, Hunter Williams, David Wilson, and Kris Zacny. The authors take full responsibility for any mistakes or omissions in this work.

Special thanks to Professors Chris Dreyer and George Sowers for guiding and reviewing the original versions of this project in the Colorado School of Mines Space Resources Program Project 1 and Project 2 classes.

ENVIRONMENTAL IMPACT ANALYSES FOR SPACE RESOURCES ACTIVITIES. A. Q. Gilbert[1], [1]Colorado School of Mines (425 Elm St NW, Washington, DC 20001, alex.gilbert@powerandresources.com)

Introduction: Although we are still at an early stage in space resources activities, government and commercial plans for space mining should consider their potential impacts on the outer space environment. Space and celestial bodies are often held to be lifeless, unoccupied areas where human activity can have little impact. Conversely, many areas of interest for space miners can be exceptionally fragile and could harbor extraterrestrial life. More directly, local pollution and disruption from space mining activities can pose operational risks to a mine site, as well as to adjacent space resources and other space activities. The emerging challenges of orbital debris highlight what can happen when activities are conducted without consideration of their potentially negative consequences.

On Earth, governments and the mining sector have long used Environmental Impact Analyses (EIAs) or similar mechanisms as due diligence tools to identify environmental impacts before operations commence. Forward-looking processes such as EIAs can identify alternatives that bring safety, operational, environmental, and other benefits. Depending on the type of activity involved, EIAs can also be helpful in securing social license to operate from local communities.

This presentation explores the potential development and applications to EIAs in a space resources context.

First, it identifies and characterizes potential environmental impacts from space mining activities on the Moon, Mars, and asteroids. While many of these remain speculative, it considers dust as a primarily near-term operational and environmental consideration, contrasting with similar concerns about dust from terrestrial mines.

Second, this presentation reviews the development and contemporary use of EIAs by both government and industry. The United States started the modern era of environmental law and environmental disclosure when it passed the National Environmental Policy Act (NEPA) in 1970. NEPA has served as a model for other nation's disclosure laws and has catalyzed the established of environmental assessments globally. Reporting on recent statutory and legal analysis, this presentation describes how NEPA may require an EIA-equivalent for government or government-authorized space resources activities.[1]

Third, and finally, the presentation evaluates the commercial use of EIAs by private companies as environmental management tools. It recommends that would-be space miners consider the voluntary use of EIAs as an extractive industry best practice and to mitigate potential space environment risks. While companies may raise concerns about the potential for added cost, this presentation provides an initial analysis showing that many near-term environmental impacts are likely to be operational in nature and may thus bring limited additional costs. Further, widespread use of EIAs by the space resources industry may be in companies' self interest as it can identify potentiall harmful activities from nearby operations or competitors. The presentation concludes by considering pathways forward to reduce industry risk and maximize the potential of due disclosure activities.

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A GEOMETALLURGY APPROACH OF THE EXPLORATION OF LUNAR ILMENITE FOR OXYGEN PRODUCTION ON THE MOON. Gustavo Jamanca-Lino[1]. [1]Colorado School of Mines, Golden CO 80401, United States, gjamancalino@mymail.mines.edu.

Introduction: Space mining will be the greatest challenge of the current century. Many researchers have developed metallurgical processes to concentrate lunar ilmenite and produce oxygen on the Moon. However, the achievements are limited in terms of recovery and purity grade. This study reviews the geological data of the regolith and breccias sample brought by Apollo 11 to verify ore features that affect the metallurgical behavior. This approach is known as geometallurgy and intends to combine geology with metallurgical engineering to solve the lunar context's mining problems. The authors review the characteristics of the "degree of liberation" and "chemical composition" of ilmenite on Mare Tranquillitatis and their impact on concentration under the geometallurgy using mineralogical calculates metallurgical balances, thermodynamic tools from HSC Chemistry software, and statistical analysis for lunar breccias with software Minitab.

Results

Degree of liberation: The degree of liberation (D.L.) is a quantitative measure of a mineral in a single particle. If the particle contains a single mineral, the D.L is 100, and it decreases with the association with other phases in the same particle [1]. This information is crucial for installing a concentrator plant in terrestrial mining to send concentrates with an acceptable grade and recovery to the refinery processes [2]. This sequence is validated for ilmenite lunar deposits to increase from 6% in the regolith to about 90% in the concentrate for efficient extraction of oxygen [3].

The texture of particles on the regolith in Mare Tranquillitatis, one of the highest ilmenite deposits, is preferent in mixed particles. Mare Tranquillitatis is an excellent soil to be processed since it is a fine grain size material. However, the fine ilmenite is hard to concentrate from the regolith up to an acceptable grade because other minerals lock its particles [4]. The results will be directly influenced by the degree of liberation, and it would not be feasible to apply current grinding technologies to increase it. In this work, we calculated the degree of liberation from previous microscopic observation and modal analysis. Also, we applied metallurgical balance in some previous tests to find the effect of the degree of liberation in the quality and recovery of an ilmenite concentrate.

Sample	Size	Grade %w Ilmenite Conc.	Recovery %	D.L.
A.Basalt 10058	45 - 90	62	39.0	78
B.Regolith 10084	45 - 74	24	8.8	37

Table 1. Metallurgical balance of magnetic separation calculated from the data of previous tests [5]

Chemical Composition: From a statistical analysis under 34 lunar breccias reported by Apollo 11 mission [6 -12], the oxides with more content are FeO and TiO_2 that define the composition ($FeO*TiO_2$). The third most abundant oxide is MgO, which in some cases has reported values greater than 9%. Furthermore, according to statistical regression, this element's presence is inversely proportional to FeO with a high correlation of $R^2 = 0.87$. There could exist a replaces of FeO with MgO in many particles, like "false ilmenite, " which overestimates the amount of real ilmenite in the deposit. It was reported this mineral's presence as geikielite or $MgTiO_3$ phases associated with ilmenite as inclusions in the crystal lattice due to geological formation conditions.

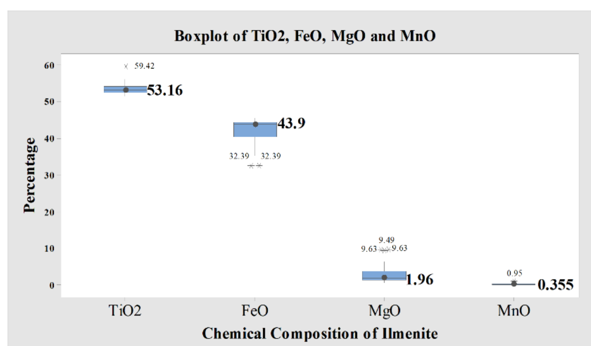

Figure 1. Pivot graph of the principal oxides in the ilmenite. Calculated by the Authors with Minitab Version 16.0. Data from [6 -12].

The authors measured the effect of geikielite in the process, the thermodynamic calculations for both minerals were carried out using the HSC 5 Chemistry software, Version 6.0, simulating hydrogen reduction. To reaction occur, the Gibbs energy must be less than 0.

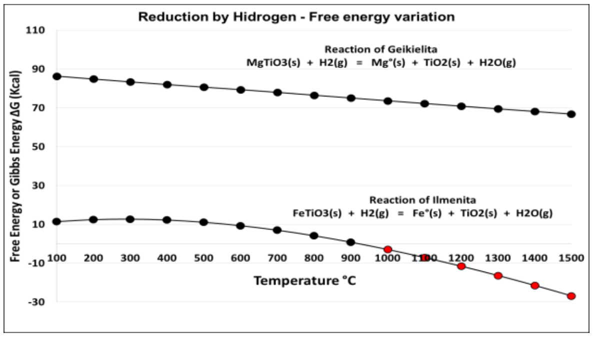

Figure 2. Energy free variation for both the minerals in the reduction by hydrogen. Calculated by the Authors with HSC Chemistry V. 6.0 and plotted in Excel 2010.

The ilmenite reaction will become spontaneous (free energy less than 0) at temperatures over 1000°C; however, geikielite's reaction never achieves the spontaneous state; the free energy variation is always positive and never produces water, as it is shown in Figure 2. It means that ilmenite with a high MgO content will have less water production yield since MgO * TiO2 does not reduce even at very high temperatures

Conclusion

Regolith particles are fine, but most ilmenite appears encapsulated. There are no data that describe the entire particle size distribution, but the size ranges analyzed by direct and indirect methods show less than 40% free ilmenite. This information should lead us to evaluate other ilmenite sources, such as the rocks and breccias mixed with the regolith, which have a higher content of free ilmenite (greater than 75%)[13].

In the same case, only ilmenite with low magnesium should be processed with chemical composition to increase performance. The lunar breccia samples show that the magnesium oxide content is highly variable in the ilmenite with a statistical non-normal distribution of the MgO content. There are very high values, reaching up to three times more than average (over 9%). According to statistical and thermodynamic calculations, the presence of this oxide in ilmenite is detrimental to the process since it dilutes the iron content and reduces the process's efficiency. Future mining operations must identify high MgO and low MgO ilmenite as a correction factor in the economic evaluation of the deposit.

Chemically, the Mare Tranquillitatis is a high deposit of ilmenite to mine. Instead, considering geometallurgy, the ilmenite in the deposit must be classified according to their degree of liberation (free or mixed) and according to its magnesium oxide content. This knowledge will assist in selecting the right location in the deposit to mine, the right size range to process, and an accurate metallurgical architecture to maximize the operative results and, therefore, the profitability.

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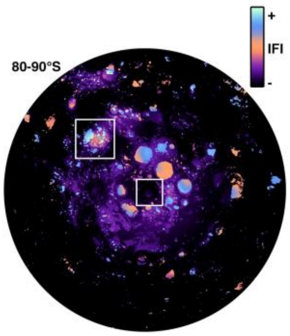
Multi-Product Lunar Regolith Beneficiation System. K.J.H. Kingsbury[1], I. Barton[2], & V. Tenorio[3]. [1]University of Arizona (PO Box #27822, Tucson, AZ 85726 & Kerstk@email.arizona.edu), [2]University of Arizona (1235 James E. Rogers Way, Tucson, AZ 85719 & Fay1@arizona.edu), [3]University of Arizona (1235 James E. Rogers Way, Tucson, AZ 85719 & Vtenorio@email.arizona.edu)

Abstract:

The utilization of in-situ resources such as water ice and regolith materials found on the surface & near subsurface of the Moon is fundamental to establishing a sustainable and permanent human presence there. There are substantial, financially significant, and accessible deposits of water ice found near the Lunar poles (principally the Southern pole).



Water ice is obviously necessary for all biological processes, but can also be broken down by electrolysis into O_2 , which can be further processed into rocket fuel. Water, for this reason, would be the primary mineable resource. This water ice is intrinsically mixed with the Lunar regolith however, which itself has multiple secondary in-situ resources.

Developing new beneficiation techniques that differ from contemporary terrestrial approaches is an imperative to sufficiently utilize all of those resources.

Step 1: Comminution

The initial step of the new beneficiation technique proposed would utilize a focused high-voltage electromagnetic pulse (E.P.D.) [1] to comminute both water ice and regolith. This technology would act as an alternative to contemporary mechanical crushers (such as jaw or gyratory). E.P.D. would result in drastically less ultra-fine dust being disturbed into the local exosphere than what contemporary mechanical crushers would produce, which would pose a significant maintenance and safety risk.

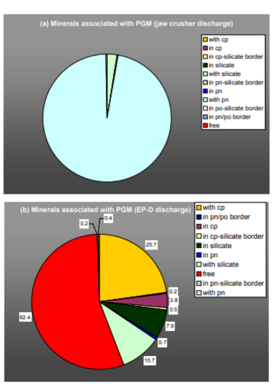


Figure 8. Area percentage of PGM grains in association with other minerals. (a) for the jaw crusher discharge. (b) for the electric pulse disaggregation (EP-D) discharge. Word "with" indicates that the PGM grain was found at the border of the associated mineral. Word "in" indicates that the PGM grain was found locked inside the associated mineral. The red colour is for totally free PGM grains.

E.P.D. would also lead to higher disaggregation of water ice enclosed within micropores of the regolith, because of its ability to reach much finer particle sizes (up to 5-10 pm depending on the mineralogy). While relatively new, this technology is currently being applied by the company Selfrag to improve recycling techniques, geochronological research, and conventional mineral processing plants.

Step 2: Separation

The resulting fine-grain material would then be partitioned using a triboelectric-charged belt (T.E.B.S.) [2] to separate water ice particles [3] from regolith material. This technology arises as an alternative to froth flotation and leaching, which are much less efficient on the moon due to the reduced gravity and pressure. The problem of utilizing flotation is further highlighted because of the technique's difficulty in separating particles smaller than 75 µm, while T.E.B.S. works well for particles under 1 µm and as large as 300 µm.

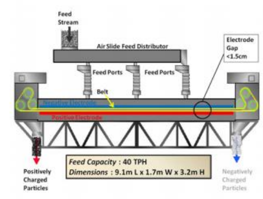


Figure 1. Schematic of triboelectric belt separator

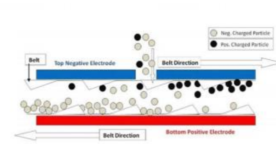


Figure 2. Detail of separation zone

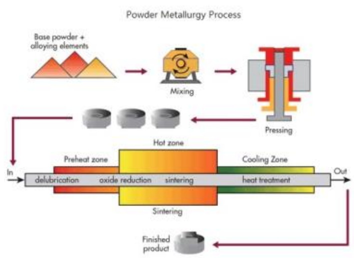
This process utilizes static electric charge differences on particle surfaces as the separating criteria, which is well-suited to Lunar surface materials due to the constant bombardment of the solar wind leaving all those materials highly charged. The intrinsic material properties of water ice, silicate minerals, and native metallic particles would lead to each of them carrying slightly different surface charges generated by the solar wind.

Therefore, the remaining fine regolith material would then undergo further belt separation where native metallic particles of iron, titanium, and aluminum [4] may be partitioned out and used for infrastructure or machine part repair.

Step 3: Sintering

The regolith minerals would then be subjected to sintering (i.e., powder metallurgy) via molten regolith electrolysis [5] to extract additional elemental resources. Powder metallurgy works by fine metallic particles being pressed into a mold and sintered together. The ultra-fine native metallic particles found in the regolith and separated by T.E.B.S. would need no further processing to be used in this system.

Molten regolith electrolysis would then be required to extract pure select pure elements from the regolith minerals. Thorium [6] may be removed and used as a fuel in a “melt-down-proof” fission reactor.



Sulfur may be removed and used as the bonding agent of a waterless lunar concrete which uses the remaining fine regolith particles as aggregates. [7]. The extremely fine particle sizes E.P.D. can produce and T.E.B.S. can differentiate are large assets in producing quality, uniform aggregate that would lead to the strongest possible concrete. The waste heat generated by the use of molten regolith electrolysis can be used for sintering the waterless sulfur-based Lunar concrete, which would further increase its strength and durability.

Ultimately, this process provides a feasible mineral processing system that would mitigate hazards, reduce infrastructure costs, and may be scaled down to fit the needs of a fledging Lunar outpost.

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ICY LUNAR REGOLITH ROTARY MINING IMPLEMENT WITH PNEUMATIC CONVEYANCE

T. E. Loop[1], [1]Colorado School of Mines, 1310 Maple St., Golden CO 80401 – thomasloop@gmail.com

Introduction: A new type of rotary mining implement with pneumatic conveyance is proposed for excavating and conveying icy lunar regolith located within the permanently shadowed cratered regions at the Moon's poles. The proposed mining system ("design concept") consists of, in combination, a lunar rover outfitted with a specialized drill rig configured to simultaneously drill and excavate (pneumatically) two separate holes (vertical shafts to depths of at least 350 cm for suggested drill bit diameters of between 10 cm to 30 cm). The drill rig, in combination with the rover, supports and powers two drill strings (pipes) each of which is fluidically coupled (at their respective lower ends) to a new type of nested rotary drag bit, which, in turn, is designed to cut, grind/smash and deconsolidate icy regolith (believed to be cementitious in nature) into deconsolidated particles (i.e., granularized icy regolith). A specialized gas-driven "venturi eductor" nested within each drag bit pneumatically excavates the granularized icy regolith out of the two holes through their respective drill stings. To offset the twisting force (torque) felt by the rover during drilling, the drill strings counter-rotate with respect to each other. A concept drawing of the proposed rover with its two-string drill rig set-up (omitting ancillary components) is shown below in Figure 1.

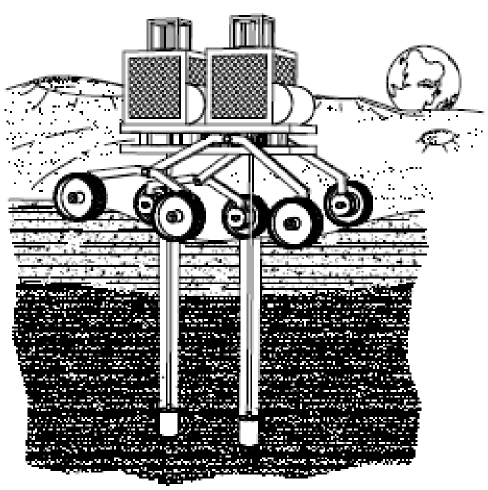

Figure 1

Lunar Excavation: At very shallow depths (<30 cm), excavation of lunar regolith is not challenging. However, at increasing depths the bulk density of the regolith increases sharply – and with this, so too increases the interlocking of adjacent regolith particles, as well as the friction and cohesive forces between particles. Indeed, and as demonstrated during the small-scale excavations attempted by Astronaut James Irwin during the Apollo 15 mission, a "stiff layer" of cementitious regolith is encountered at a depth of about 30-35 centimeters that could not be penetrated with a scoop, and required chipping to reach deeper levels [1].

The Moon is known to be largely devoid of water, except for small amounts existing within the so-called permanently shadowed regions (PSRs) located at the Moon's poles. Although not known with certainty, NASA has hypothesized that lunar ice deposits may contain up to 5, or even 10 percent, water (by weight). In addition, NASA has further hypothesized that as the regolith's water concentration increases (generally with depth), so too increases certain geomechanical properties such as bulk density (up to 1.85 g/cm^3), compressive strength (up to 35 MPa), and tensile strength (up to 12 MPa). For example, NASA has suggested a hypothetical water profile (weight percent) for icy regolith at various depths up to 350 cm as shown below in Figure 2.

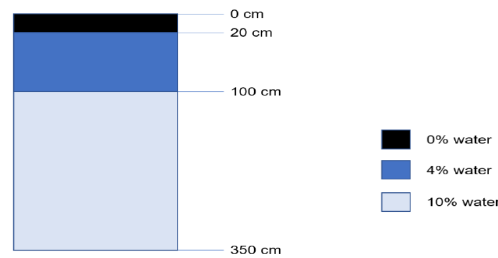

Figure 2

NASA has also suggested a preferred "Excavation Site" (outlined in green in Figure 3 below), which is located within a selected PSR near the lunar South Pole [2].

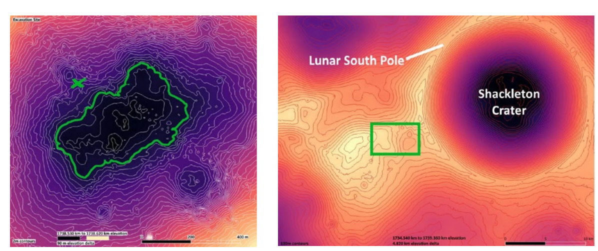

Figure 3

NASA contends that icy regolith within this PSR (and others like it) is likely cementitious but soft. Thus, and similar to sandstone, when cut and ground/smashed with an appropriate cutter/grinder, icy regolith will break apart (deconsolidate) to yield deconsolidated discrete grains of regolith like those found throughout the uncompacted uppermost surface layer (<30 cm) of lunar regolith (which exists everywhere on the Moon) [3].

Pneumatic Conveyance: Pneumatic conveying involves transporting a particle-laden gas flowstream through a pipeline. The gas flowstream transmits a propulsion force to the entrained particles, and thus conveys the entrained particles through the pipeline. All pneumatic conveying systems necessarily require a pressure difference between the beginning and end of the pipeline.

The use of compressed gas for the purpose of regolith excavation and transfer (mining) is not new – it was first proposed in 1993 by chief scientist David McKay at NASA's Johnson Space Center (JSC). McKay envisioned long tubes "sucking" lunar regolith and depositing it in far-away containers as generally depicted (concept drawing) below in Figure 4 [4].

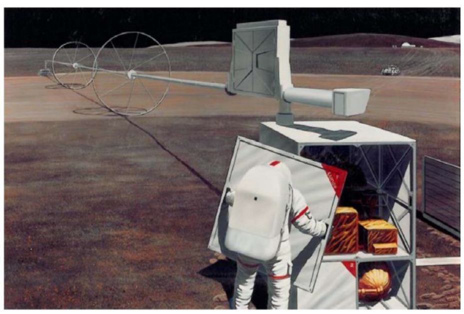

Figure 4

In view of this design concept, Sullivan (1994) determined that the saltation velocity (i.e., the velocity of gas required to keep particles suspended in a vertical tube) is only about one-third at $1/6^{th}$ gravity (i.e., the gravity on the Moon) [4]. Later, Zancy et al. (2004, 2008 and 2009) developed and tested various approaches to mining lunar regolith using compressed gases, and determined that just 1 gram of gas at <100 kPa absolute can loft almost 6,000 grams of lunar simulant at velocities approaching 10 m/s [5].

Pneumatic transfer (conveying) systems, like the one being proposed here, require a "venturi eductor" immersed (essentially at all times) within a contained body of granularized regolith to function properly. A venturi is a type of constriction within a pipe (classically an hourglass shape) that creates a powerful suction. The venturi effect (utilized by venturi eductors) works well in an atmosphere or under water (e.g., subsea mining), but in vacuum will not work unless the inlet to the venturi is largely sealed from the vacuum.

Proposed Lunar Mining System: In view of the foregoing background and in order to rapidly and efficiently excavate and convey icy lunar regolith from within the PSRs on the Moon (with minimal dust generation), a novel rotary drill with nested pneumatic transfer mining implement and system are proposed. As noted above, the proposed mining system preferably consists of a lunar rover outfitted with a specialized drill rig configured to simultaneously drill and excavate (via pneumatic transfer) two separate holes (to depths of at least 350 cm for suggested bit diameters of between 10 cm to 30 cm) by means of a new type of lunar mining implement. The proposed lunar mining implement is best characterized as a new type of nested rotary drag bit because it has no moving parts, and because it works best in soft to cementitious soils (like those found on the Moon at shallow depths). As shown below in Figure 5, the proposed mining implement comprises three nested components: namely; (1) an outer drum having a bottom bladed cutting crown (that, during operation, grinds and feeds regolith through openings into the interior of the drum); (2) an axially-aligned conical hopper within the drum (that, during operation, fills with granularized icy regolith); and (3) a specialized "venturi eductor" positioned lengthwise within both the hopper and the drum (that, during operation, uses a motive gas ejected from a nozzle to suck regolith in from the hopper, to thereby create a fluidized regolith-laden gaseous flowstream that, in turn, lofts and conveys the excavated icy regolith particles (grains) out of the implement through a central transfer pipe (aka drill string) for further processing.

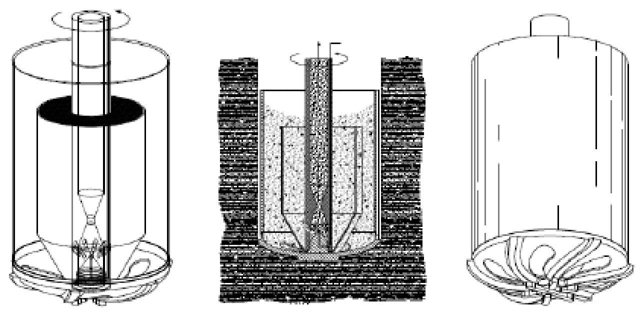

Figure 5

In this configuration, the outer cylindrical drum sealingly encases the hopper and the venturi eductor (thereby enabling the venturi suction effect to take place). As shown, the bottom cutting crown includes a plurality of spiraling hard metal blades that funnel cuttings (i.e., ground and smashed up icy regolith particles/grains) into openings and into the interior of the drum and hopper where it is then sucked away.

Preliminary estimates suggest that the proposed mining system, sized with two counter-rotating drags bits each having a nominally sized cutting crown can excavate icy regolith at rates exceeding 1,000 kg/hr.

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Lunar Mining Claim Optimization for ^{3}He and Other Solar Wind Implanted Volatiles. S. Ray[1], C. Olson[2], L. Robibero[3], S. Coutts[4], M. Sissman[5]. [1]Colorado School of Mines (1500 Illinois St, Golden, CO 80401, stew.is.ray@gmail.com). [2]Colorado School of Mines (1500 Illinois St, Golden, CO 80401, ckoloson@mymail.mines.edu). [3]Colorado School of Mines (1500 Illinois St, Golden, CO 80401, lisa.robibero.93@gmail.com). [4]Colorado School of Mines (1500 Illinois St, Golden, CO 80401, steven_coutts@berkeley.edu). [5]Colorado School of Mines (1500 Illinois St, Golden, CO 80401, mcsissman@mymail.mines.edu).

Introduction: Helium-3 (^{3}He) amongst other light volatiles implanted by solar wind into the lunar regolith is a valuable resource because of its potential to be used as a fuel in a fusion cell in the near future [1]. ^{3}He abundance and concentrations cannot be measured directly, and instead must be inferred through other measurable variables, which are referred to as proxies. The chosen proxies for the detection of ^{3}He are: the presence of the mineral ilmenite ($FeTiO_3$) inferred through TiO_2 abundance [2], and the age of the regolith inferred through optical soil maturity index (OMAT) [3] and the relative ages of lunar geologic units from the USGS [4]. The location of ^{3}He deposits is not useful if the resources are inaccessible. Engineering constraints such as the diurnal heating (as a power source for an extraction system) [5], the topography of the lunar landscape that is being excavated [6], the abundance of rocks in the lunar regolith [7], and the grain size of the regolith as solar wind implanted volatiles can be lost to the vacuum of space simply by agitation during their extraction process [7].

^{3}He Mapping Model: To create our model, the team utilized LROC: QuickMap [8] to perform data processing and visualization of datasets from LROC's WAC, LOLA, and DIVINER instruments, as well as Kaguya's MI instrument. Selected datasets include: abundance_TiO2 [2], lclem_omat [3], ldsm_16 [5] and abundance_rock [6] from Planetary Data System to create a ^{3}He favorability model that indicate areas where ^{3}He mining would be feasible.

Legal Lunar Mining Regime: Although finding a potential mining location for ^{3}He on the lunar surface is challenging, the legality of such activities must also be considered [1]. We propose a legal regime shall be establish a lunar mining claim under existing international space law. This project proposes a set of mining claim criteria to legally extract volatiles under current international and domestic policies with the aim of creating a safe and cooperative environment for private and governmental entities to operate within [9].

Preliminary Results: Our model of likely ^{3}He deposits includes a map indicating ideal mining locations of ^{3}He. Potenital mining sites include: Oceanus Procellarum, Mare Imbrium, and Mare Tranquillitatis. As this model further matures, it will help to determine locations on the lunar surface that are most viable for establishing a lunar mining claim for the extraction and utilization of ^{3}He on the lunar surface.

References: [1] Schmitt, H. (2006) Return to the Moon: Exploration, Enterprise, and Energy in the Human Settlement of Space. [2] Sato, H. et al. (2017) *Icarus, 296*, 216-238. [3] Lemelin, M. et al. (2019) *Planetary and Space Science, 165*, 230-243. [4] Fortezzo, et al. (2020) LPSC. [5] Williams et al. (2019) LPSC. [6] Smith et al. (2017) *Icarus, 283*, 70. [7] Bandfield, J. L et al. (2011) *Journal of Geophysical Research: Planets, 116*, (E12). [8] ACT-REACT QuickMap." LROC QuickMap, (2020). [9] International Institute of Space Law (2016) *IISL.*

ULTRASONIC LEADING EDGE FOR LUNAR EXCAVATION TOOLS.

E. T. Rezich[1], A. Schepelmann[1], D. J. Gotti, D. L. Linne[1]
[1]NASA Glenn Research Center (erin.t.rezich@nasa.gov)

Introduction: The lunar surface is once again within reach as the NASA's Artemis program aims to put the first woman and the next man on the Moon by 2024. Achieving long-term human habitation on the lunar surface requires in-situ resource utilization (ISRU) technologies to be developed in order to reduce dependence on Earth commodities.

Excavation of regolith and granular ice is the first step in the production of useful resources on the lunar surface. With its low gravity and distance from Earth, the Moon presents an exceptional excavation challenge. Terrestrial excavation is based around intentionally massive machinery to produce sufficiently large reaction forces that balance against very large excavation forces. This general structure does not scale to lunar operations where landing mass on the lunar surface is exceedingly expensive and only provides $1/6^{th}$ of the reaction force due to reduced lunar gravity.

Lunar excavator design must first be approached from the tool/terrain interface. This approach seeks to reduce excavation forces to minimize required reaction forces, and thus resuls in an excavator that is less massive and likely requires less total power.

The mTRAX Planetary Exploration Labs group at NASA Glenn Research Center is investigating the use of a resonantly vibrating leading edge on a bucket to reduce the penetration force as the tool engages the soil. Early studies show very successful results of ultrasonically vibrating horns and probes significantly reducing the penetration force in granular lunar soil simulants [1]–[4]. While forced vibration tools will increase end-effector power and mass, the goal is to achieve a net reduction in power consumption and overall system mass due to significant force reduction.

Currently, the research effort is looking at characterizing the behavior of an ultrasonic horn penetrating granular lunar regolith simulant in a lunar vacuum environment at a component level. The results from this experimental study will enable characterization of the impact of atmosphere on the effectiveness of the force reduction phenomenon.

In parallel, a design for an integrated leading edge on an excavator bucket is being developed for full scale testing in the Excavation Lab at NASA Glenn Research Center in ambient conditions. The Exavation Lab (Fig. 1) houses the Advanced Planetary Excavator (APEX) which is used as a highly repeatable path generation tool for excavation testing. Both the soil simulant and ultrasonic leading edge have directional properties so to better understand their coupled interactions testing via two-dimensional toolpaths generated by APEX are required. These tests will highlight toolpath restrictions for using ultrasonic blades in soil and will likely indicate which orienations are most effective at reducing penetration forces. These full scale tests will feed into the final branch of this research effort is working to develop modeling capabilities for the APEX platform. The purpose of the model is to enable more efficient design and development of novel excavation tools. This work will present the state of development of the ultrasonic bucket tool at NASA Glenn Research Center.

Figure 1. The APEX excavation platform in the Excavation Lab at NASA Glenn Research Center with the first generation Ultrasonic Bucket prototype attached as the end effector.

References:

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LUNAR POLAR PROPELLANT MINING OUTPOST (LPMO). Joel C. Sercel[1] , Philip Wahl, and Craig Peterson, [1]TransAstronautica Corporation, 10276 Foothill Blvd. Lake View Terrace, CA 91342, sercel@transastracorp.com, philip@transastracorp.com, craig@transastracorp.com

Problem: NASA Advisory Council provided their "Recommendation Regarding Mismatch Between NASA's Aspirations for Human Space Flight and Its Budget, from the Council Public Deliberation, in July 31, 2014, and concluded that without a major change in strategy and approach, NASA's budget will not support the type of exciting missions that are needed to justify the existence of the human exploration program TransAstra has performed mission design and economic analysis of the potential benefits of space-derived propellant for human exploration beyond LEO. The results show that up to 80% of the cost of establishing and maintaining a human outpost in deep cislunar space is in launching and transporting propellant from the surface of the Earth. If plentifully available in cislunar space, water could be electrolyzed into O_2 and H_2 and liquefied for use in cryogenic propulsion or used directly as propellant in solar thermal rockets to provide a breakthrough in affordable transportation.

Historically the lunar surface has been viewed as an unpromising source of propellant feedstocks. However, recent work has shown that in lunar polar regions there may be vast areas with large quantities of frozen water and peaks that are perpetually in sunlight. This promises near continuous solar power for ISRU and other operations. Unfortunately, the multi-kilometer geographic separation between the perpetually lit peaks and the icy regolith on the bottom of large craters creates significant power distribution challenges. If the power distribution challenges can be circumvented,

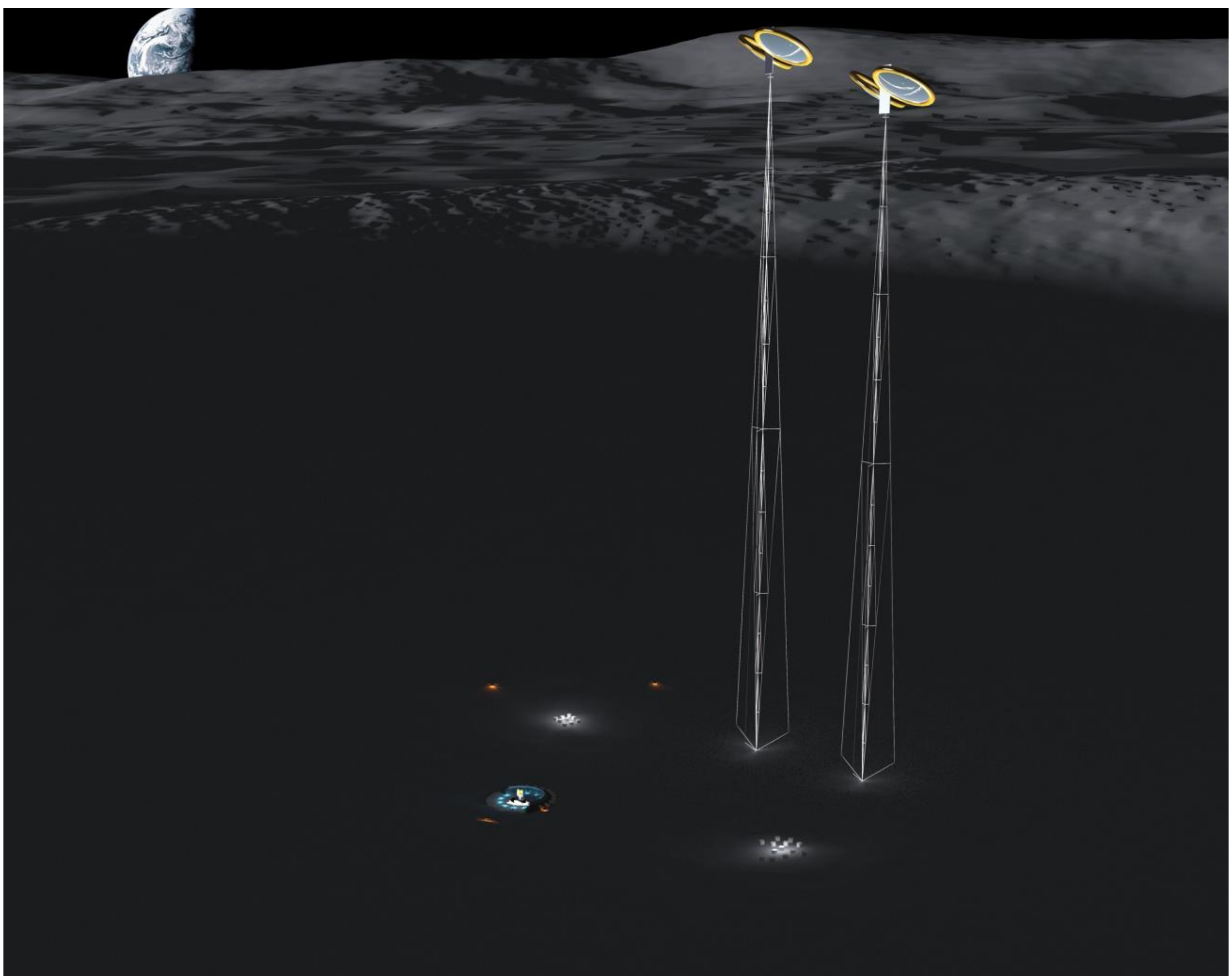

Figure 1- Lunar Polar Propellant Mining Outpost

it will obviate the need for massive and expensive nuclear power systems and it will greatly reduce the cost of ISRU for the lunar water needed to reduce the cost of developing and maintaining a lunar outpost.

Solution: The Lunar Polar Propellant Mining Outpost (LPMO) is a breakthrough mission architecture which greatly reduces the cost of human exploration, habitation, and industrialization of the Moon. LPMO will be humanity's first permanent beachhead on another planetary body and it will be economically sustainable based on two new innovations that together solve the problem of affordable lunar polar ice mining for propellant production. The first innovation is based on a new insight into lunar topography: our analysis suggests that there are suitable (10^4 m^2) landing areas in small (1 to 2 km) near-polar craters on which the surface is icy regolith in perpetual darkness but with nearly perpetual sunlight available at altitudes of only a few 100 m above ground.

In our proposed landing sites, our Sun Flower™ consisting of rotating light weight deployable reflectors held diagonally at the top of tensegrity masts only ~800 m in length (lightweight and feasible in lunar gravity), that can provide illumination to ground based solar arrays, provide nearly continuous power Therefore, large landers such as the Blue Moon proposed by Blue Origin (2), or the SpaceX Starship (formerly BFR) can feasibly deliver the power systems needed to both extract water (using the breakthrough Radiant Gas Dynamic (RGD) Rover approach) and process it into propellant via electrolysis and liquefaction. Perpetual darkness at ground level provides a naturally cold environment for easy radiation of waste heat to space for liquefaction and cryogenic storage of the produced propellants.

ISRA: Lunar Regolith Sample Excavation Company - A Space Resource Business Plan. Shanley, C.[1], Coto, M.[1], Pazar, C.[1], and McKeown, B.[1]. [1]Colorado School of Mines Center for Space Resources ***(47B Ravenswood Drive, Nollamara, 6061, Western Australia; cshanley@mymail.mines.edu)***

Abstract: This report presents a space resource business plan with an engineering framework and robust financial analysis for the development of a lunar regolith sample excavation, storage and data collection company, henceforth referd to as ISRA (the Interplanetary Space Resource Alliance).

ISRA provides services on the Moon that range from geochemical analysis to ownership transfer of lunar regolith, and future site preparation for surface operations. ISRA has shown there exists a strong business case for the robotic excavation of lunar regolith based on market potential combined with potential resource availability. There is a strong geological case for the accumulation of large reservoirs of volatiles (particularly water-ice) at the lunar poles, supported by limited quantitative data points collected over the past 50 years, from Apollo to LCROSS [1,2].

The purpose of ISRA is to provide viable commercial sample collection and resource excavation, together with the provision of reliable geologic information for specific locations thereby facilitating sustainable and equal opportunity cooperative space infrastructure development, towards the advancement of the cis-lunar economy and beyond.

The long term goal of ISRA is to provide equal opportunity services for the collection, analysis, and storage of space resource samples, together with the provision of scientific and economic information, thereby facilitating sustainable and cooperative space infrastructure development and construction.

The mission of ISRA is to pioneer sustainable space exploration, resource identification, and settlement through the profitable deployment of science and technology in order to facilitate the transition of humanity to a space-faring civilization.

The vision of ISRA is to create new exploration opportunities for space agencies and commercial companies in the field of space resources by enabling the collection and analysis of samples through the use of robust and reliable currently available technologies.

Products. ISRA offers the ability to purchase scientific information on the geological and geochemical characteristics and water-ice percentage of lunar regolith to customers who want to learn more about a particular location, or group of locations on the surface. Such information will be essential to project de-risking through the generation of robust 3D resource models in line with the terriestrial JORC code and the upcoming LORS (Lunar Ore Reserves Standards) code, currently in development by ispace.

As a byproduct of prospecting, we offer excavated bulk regolith for sale on the lunar surface. In our extended future campaigns, we will use our experiences from the Moon to provide an unparalleled landing site selection consulting service. ISRA plans to eventually offer a service that provides cleared flattened areas with the unconsolidated bulk regolith nearby for the future construction of rocket launch and landing pads.

Our customers are primarily established national space agencies such as NASA, ESA, JAXA, CNSA, ISRO, ROSCOSMOS, and UAESA. We also consider the growing potential of both large and small commercial space companies as our future customers who will need our prospecting data and regolith to establish their sustainable presence on the Moon.

Technology. There are a robust set of technologies [3,4] currently at TRL 5 or higher that can be deployed at relatively low-cost to the lunar surface that would enable both the acquisition of ground truth scientific data, and the collection of bulk-regolith as a saleable commodity. The primary technologies we will use to meet our goals and objectives include a third-party launch service and lander, state-of-the-art semi-autonomous excavation rovers (RASSORs), advanced solar power and energy storage systems, geochemical analysis instrumentation, orbital communications, and rover-rover/lander communications.

ISRA's lunar operations are focused on excavation of the upper 10–100cm of regolith using rovers integrated with excavation bucket drums, lights, cameras, and modularity (to permit future instrumentation changes, upgrades, and repairs), that are capable of recharging with a solar PV powered battery bank system at the lander. One of our founding goals is to develop a client-vendor relationship with lunar lander and launch vehicle companies for the development and deployment of technologies on the lunar surface.

Our team chose the lunar landing services provided by Astrobotic for our analysis based on reliability, integrated communications, and delivery payload mass capability. We will consider other launch and lander services and options on a case-by-case basis and will ultimately choose the lowest cost option with the highest reliability that is able to meet the technological requirements of each mission.

Justification. ISRA believes that given the recent surge in interest for lunar polar water-ice exploration and extraction, in conjunction with the NASA led Artemis program and other commercial interests, that there is sufficient justification to attempt to capture a 'first-mover' advantage by developing and deploying a lunar regolith excavation architecture in anticipation of significant development in the cis-lunar space economy.

ISRA will use science, technology, and business to capture the opportunity to become a key player of this rapidly evolving field and address the needs of multiple customers with an equal opportunity service toward the benefit of all of mankind, paving the way for future expansion of sustainable human existence throughout the solar system and beyond.

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Planetary Surface Technology Development Lab Inauguration P. J. van Susante[1], [1]Michigan Technological University, 1400 Townsend Dr. Houghton, MI 49931, pjvansus@mtu.edu.

Introduction: The Planetary Surface Technology Development Laboratory (PSTDL) is a new research facility designed and led by Dr. van Susante at Michigan Technological University (MTU) and consists of several spaces with various equipment and supporting labs. The goal of the PSTDL is to prototype, build, test and quickly increase the Technology Readiness Level (TRL) of technology being developed for lunar and mars missions.

Major facilities: The central piece of the PSTDL is a custom built rectangular 60inchx60inchx80inch Dusty Thermal Vacuum chamber (DTVAC) with a usable volume inside the thermal shroud of 50x50x70 inches, that can be cooled as low as -196˚C and heated as high as 150˚C, reach a vacuum of 10^{-6} Torr and contain a box with up to 3000 lbs. of regolith simulant. Outside the lab, a dedicated 3,125 Gallon Bulk LN2 tank supplies the liquid nitrogen to the DTVAC thermal shroud and plate and allows for long duration testing at cryogenic temperatures. The chamber has two 10-inch viewports, 16 smaller ports for power and data feed throughs. A 20-inch diameter expansion port is available if vertical expansion of the vacuum space would be required (this would require major modifications though).

The DTVAC facility is now operational as of January 15, 2021. The chamber will have a regolith bin that can hold up to 3000 lbs. of simulant and can be rolled into and out of the chamber. There will be two regolith bins so one can be prepared while the other is being tested. Water, compressed air, and high voltage power are available to the chamber as needed.

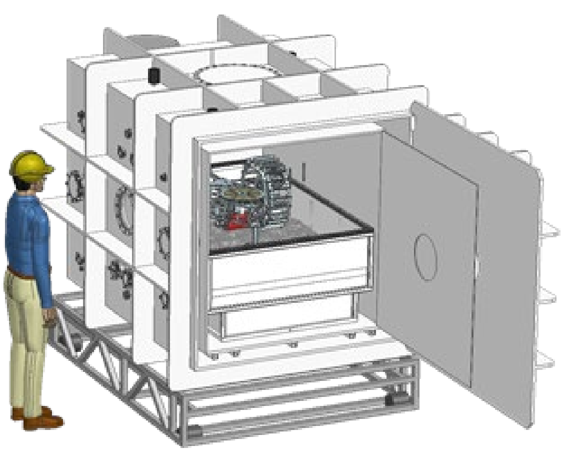


Figure 1: DTVAC loaded with regolith bin and experimental rover

Figure 2: DTVAC operational

A small 18-inch sided cube acrylic vacuum chamber is available for small scale testing in the PSTDL. It is connected to the LN2 supply for cooling of ice blocks or other hardware.

The other part of the PSTDL is a new 1100+ ft^2 lab that contains a 6 axis Fanuc m-710iC/50 industrial robotic arm with a reach of 2m and a 50 kg load capacity. In the robot's reach is a 14 ft^3 chest freezer in which lunar simulant can be mixed with water and frozen for excavation and measurement testing. The arm can support end-effectors and payloads for operation on the lunar surface (or on Mars or other planetary surfaces). An augmented reality sandbox system is installed to function together with the excavation sandbox filled with regular play sand and the robotic arm.

Figure 3: FANUC robotic arm and AR sandbox

Another major piece of the lab is a 14ftx6ftx1ft regolith simulant filled sandbox that is enclosed, kept under slight negative pressure for dust control as well as an 'airlock' to mitigate dust, has an overhead rail system that has as a gravity off-loading system (up to 200 lbs. total load) installed. Slopes up to 45˚ are possible to be built into the box. PPE and respirator certification are maintained for use with the facility.

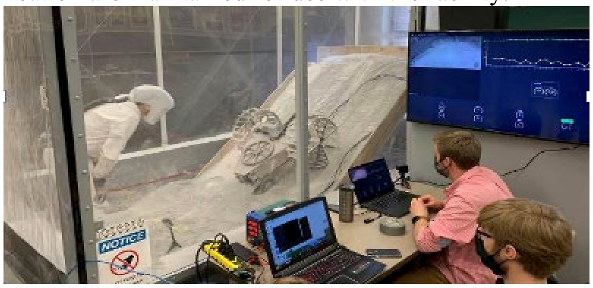


Figure 4: Regolith sandbox with slope testing

In addition to the test facilities, the PSTDL space contains mechanical build aeras, electrical workbenches, and several computational systems dedicated to modeling (CAD, FEA, DEM, CFD, etc.) the systems under development. Several groups of students under Dr. van Susante's supervision have access to the PSTDL. Students received extensive safety training to be allowed to work in the lab. Personnel working with specific hazards and PPE receive additional trainings as needed (robot, regolith simulant extended exposure, DTVAC, LN2), in coordination with our environmental and safety staff.

The PSTDL facilities are a shared space between several research groups. Dr. van Susante's Mining INnovation Enterprise is building a robot for the NASA Lunabotics Mining Competition. 35 students design, build, and test their robot for the competition. Additionally, they are fabricating a a trencher for operation in the DTVAC. Five graduate students will be working on more advanced design, modeling, building, and testing of space qualified hardware for the DTVAC and hopefully future CLPS payloads. A total of 15 full time undergraduate (12) and graduate students (3) worked on 4 funded NASA projects in the PSTDL during summer 2020. One of these inaugural projects the student team participated in was the NASA 2020 BIG Idea Challenge. The PSTDL team won this competition with the T-REX rover: a system built to deploy over 2km of superconducting power and communication cable into lunar PSRs.

Figure 5: T-REX won the Artemis Award

17 students will work on 5 funded NASA grants 2021 including the recently awarded NASA LuSTR grant.

Simulant and Ice: 35,000kg of lunar simulant will be required for use in the sandbox, the DTVAC and for use in the field tests for LuSTR. We have created our own lunar simulant named MTU-LHT-1A to support these large-scale tests. Our simulant consists of crushed glassy basaltic scoria mixed in appropriate ratio with Greenspar 90 and Greenspar 250 (which are both pure crushed anorthites). This created a lunar simulant that is similar in particle size distribution and mineral composition to Apollo Highlands material, but for a price of $1 to $2/kg.

To study ice/water extraction under cryogenic and vacuum conditions, it is required to pre-freeze all components: ice, lunar simulant, and any additional process component. In Michigan, chilling can be done outside in the winter. Year-round cold processing will be supported by a 40ft freezer container and a 40ft dryer container to dry the lunar simulant after use with ice/water. A process using ice-shavers, buckets of regolith simulant and a poly-ethylene cement mixer was devised to precisely mix the simulant and ice without melting. The simulant/ice mixture is then placed in the

Figure 6: Icy Regolith Manufacturing Process

bin by hand and compacted as desired. For quality control purposes, the temperature of the ingredients at different steps is measured with a ThermoWorks thermopen. Temperature did not exceed 17F during test runs. It is crucial to ensure a very quick loading procedure in the DTVAC to keep cart contents frozen. Quick connect couplings for power and sensors are required to speed up the installation and loading procedure.

Conclusion: The PSTDL is a new, versatile facility with a capability to test TRL-1 to TRL-6 technologies for use on the Moon, Mars or asteroids and is sized for CLPS and other missions. We would be happy to discuss collaboration or testing and look forward to serving the needs of the community.

SIMULATIONS OF LUNAR THERMAL MINING: EXPERIMENTS AND MODELS. T. G. Wasilewski[1]
[1]Space Research Centre PAS, Bartycka 18A, 00716 Warsaw, PL

Introduction:
Using dusty thermal vacuum chamber experiments and Finite Elements Method modellings, I was able to simulate the behaviour of icy regolith analogues in a PSR-relevant environment. The investigations focused on combined heat and mass transfers within the deposits with a special focus on phase change interface movement, which can be easily translated to the water production. The investigations showed interesting similarities to terrestrial production systems and allow for a redesign of thermal mining architecture and its business case.

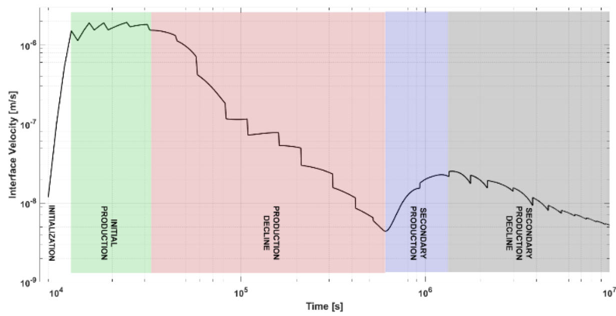


Figure 1: A typical movement rate of sublimation interface with distinct process phases

Icy regolith heating:
If a necessary heat input is provided to the icy deposit on the Moon, water ice starts sublimating from the deposit creating a sublimation lag. The lag acts as a thermal insulator and damps further production. This is reflected in distinct process phases seen in Figure 1. Temperature- and pressure-dependent material properties also damp the production. Multiple other nonlinearities and negative feedbacks exist in the system, which further lower the performance of the process, but need further research. Those include the inability to capture vapour resulting in pressure gradients directed towards the deposit and subsequential redeposition of water, as well as dust uplifting, which refracts light and lowers heat input to the deposit.
The investigations [1], [2] allowed for validation of state-of-the-art equations governing this process but also allowed for development of simple tools to predict the production rate and yields on the Moon. Those prediction tools are similar to Decline Curve Analysis methods [3] used successfully in the petroleum industry for over 70 years. It was found that there is an identity between terrestrial reservoir pressure decrease and lunar thermal conductivity decrease in those parameter's influence on production performance.

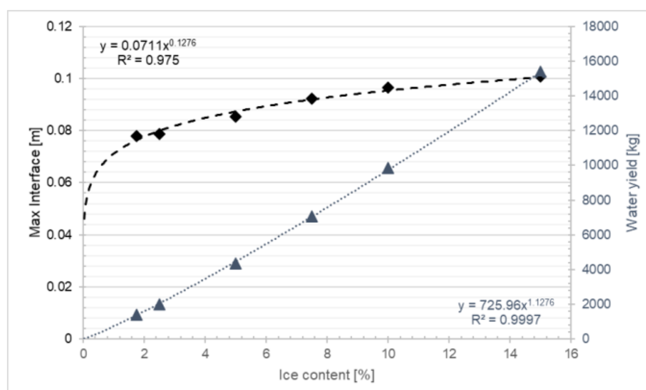


Figure 2: Total yields during 10^6 second heating operations at various ice contents

References:

[1] T. G. Wasilewski, T. Barciński and M. Marchewka, "Experimental investigations of thermal properties of icy lunar regolith and their influence on phase change interface movement," *Planetary and Space Science,* 2021.

[2] T. G. Wasilewski, "Lunar thermal mining: phase change interface movement, production decline and implications for systems engineering," *Planetary and Space Science,* 2021.

[3] J. J. Arps, "Analysis of Decline Curves," *Transactions of the AIME,* pp. 228-247, 1945.

FUSED FILAMENT FABRICATION LUNAR 3D PRINTER USING IN-SITU RESOURCES

PARTENAIRES

POLYTECHNIQUE MONTRÉAL UNIVERSITÉ D'INGÉNIERIE

CEWIL CANADA*

PolyOrbite

DYZE DESIGN

CSA ASC

HEC MONTRÉAL

FACTS

The Moon is a hostile environment:
- Lunar dust (regolith) very abrasive;
- Extreme temperatures (-200°C to 100°C);
- Microgravity;
- Difficult to stock up resources;
- Radiation on electronic components.

The screw extruder allows us to create filaments, several meters long, from a mixture of lunar regolith and high-performance polymers at 400°C.

Adding a heating chamber allows testing high performance polymers on Earth. This design can be reused as protection on the Moon.

One of the main objective of the project is to print small objects (100mm x 100mm x 100mm) on the Moon. One possible application is to produce components to repair the rover in case of damage.

Figure 1 : Regolith Simulant

+

High Performance Polymers (PEI, PEEK, TPI)

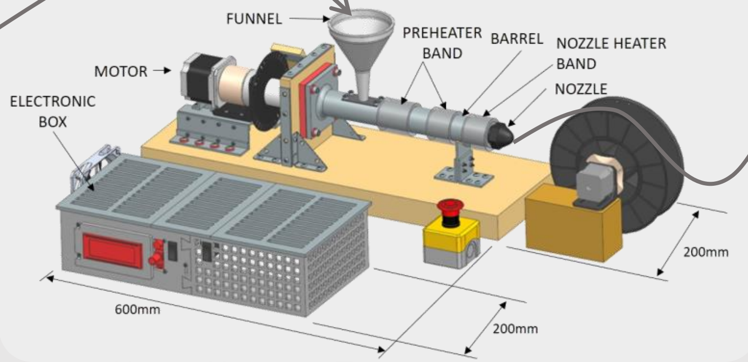


Figure 2 : Screw Extruder

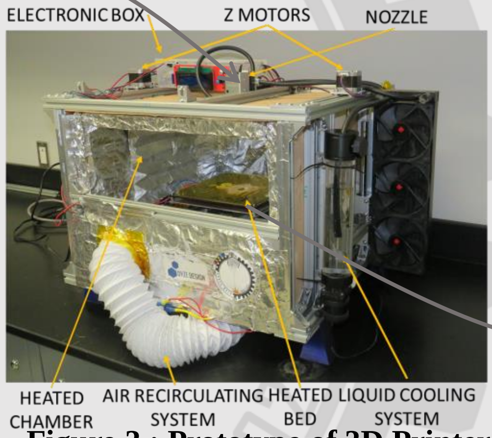


Figure 3 : Prototype of 3D Printer of dimension 510mm x 565mm x 385mm.

Figure 4 : Gear Ø20 mm 3D printed with 20% Regolith + 80% PEI wt %

RESULTS

We created filaments with up to 25% lunar regolith and 75% PEI (mass %). At 30% regolith, the Screw extruder system breaks down.

3 different mixtures (wt%) have been printed.
- 5% regolith / 95% PEI
- 10% regolith/ 90% PEI
- 20% regolith / 80% PEI

WHAT'S NEXT?

All the mixtures have been successfully printed. 2 major problems have been identified :
1. The diameter of the filament is not uniform and causes some complications during printing;
2. PEI is hygroscopic and creates bubbles during filament fabrication and printing.

*This project is funded in part by the Government of Canada's Innovative Work-Integrated Learning Initiative (IWIL) and Co-operative Education and Work-Integrated Learning (CEWIL) Canada's Innovation Hub (iHUB).
The opinions and interpretations in this publication are those of the authors and do not necessarily reflect those of the Government of Canada or Co-operative Education and Work-Integrated Learning Canada.

Raphael Alçufrom, Tamir Aljindi, Étienne Allaire, Frédéric Baumelle, Gabriel Berestovoy, Feng Yang Chen, Inès Couder, Raphael-Alexis De Luca, Sélène De Spiegeleer, Tommy Deschênes, Jean-Christophe Desmarais, David Diffo, Eliott El Hoayek, Eric-Aimé Izere , Jean-Sébastien Giguère, Jovan Kostenov, Baptiste Langlet, Alice Lemieux-Bourque, Junior Moukam, Alexandrine Plante, Charles-Olivier Poirier, Alexandre Zahlawi. Supervisé par : Pr. Frédérick Gosselin, Andrew Hayes (Ing., CSA), Olivier Duchesne.

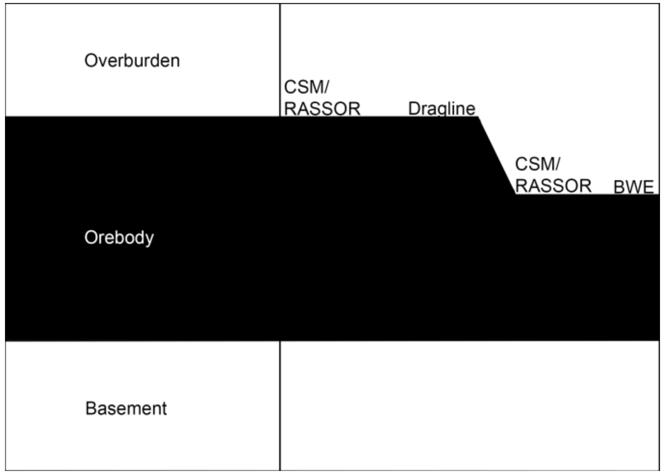
COLLEGE OF ENGINEERING
Mining & Geological Engineering

A Good Look Back: Implementing Coal Mining Techniques for Water Ice Extraction in Permanently Shaded Regions of Lunar Regolith

KW Brown, UArizona Department of Mining and Geological Engineering

1900s: Dragline → High volume, low cost. Longtime equipment of choice in North America.

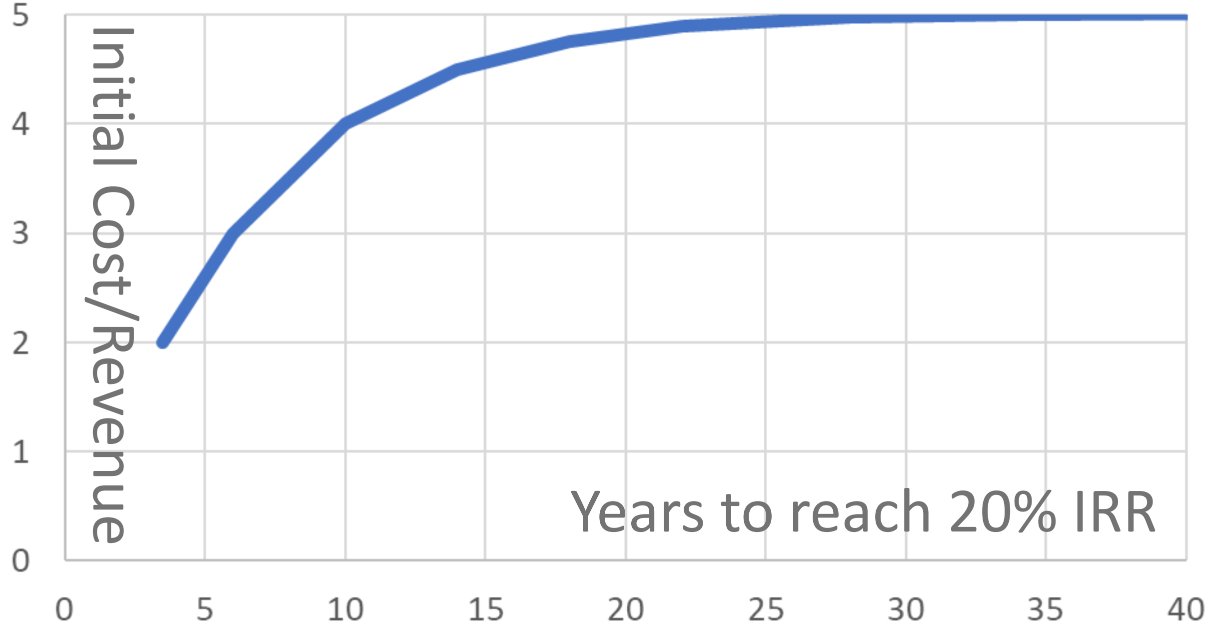
Please click to start audio!

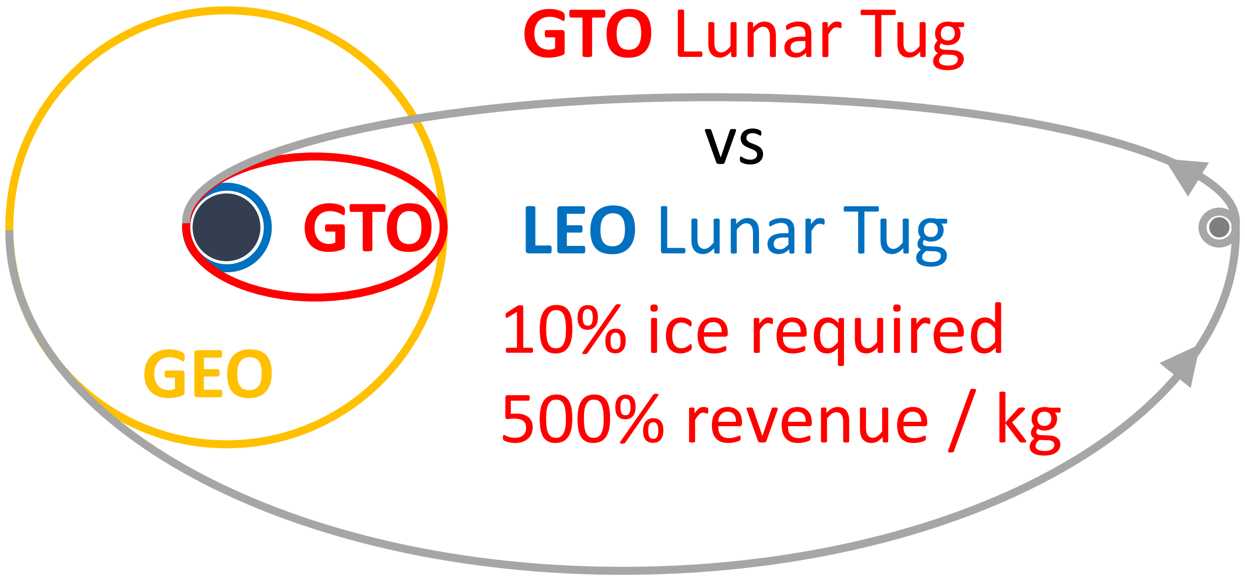


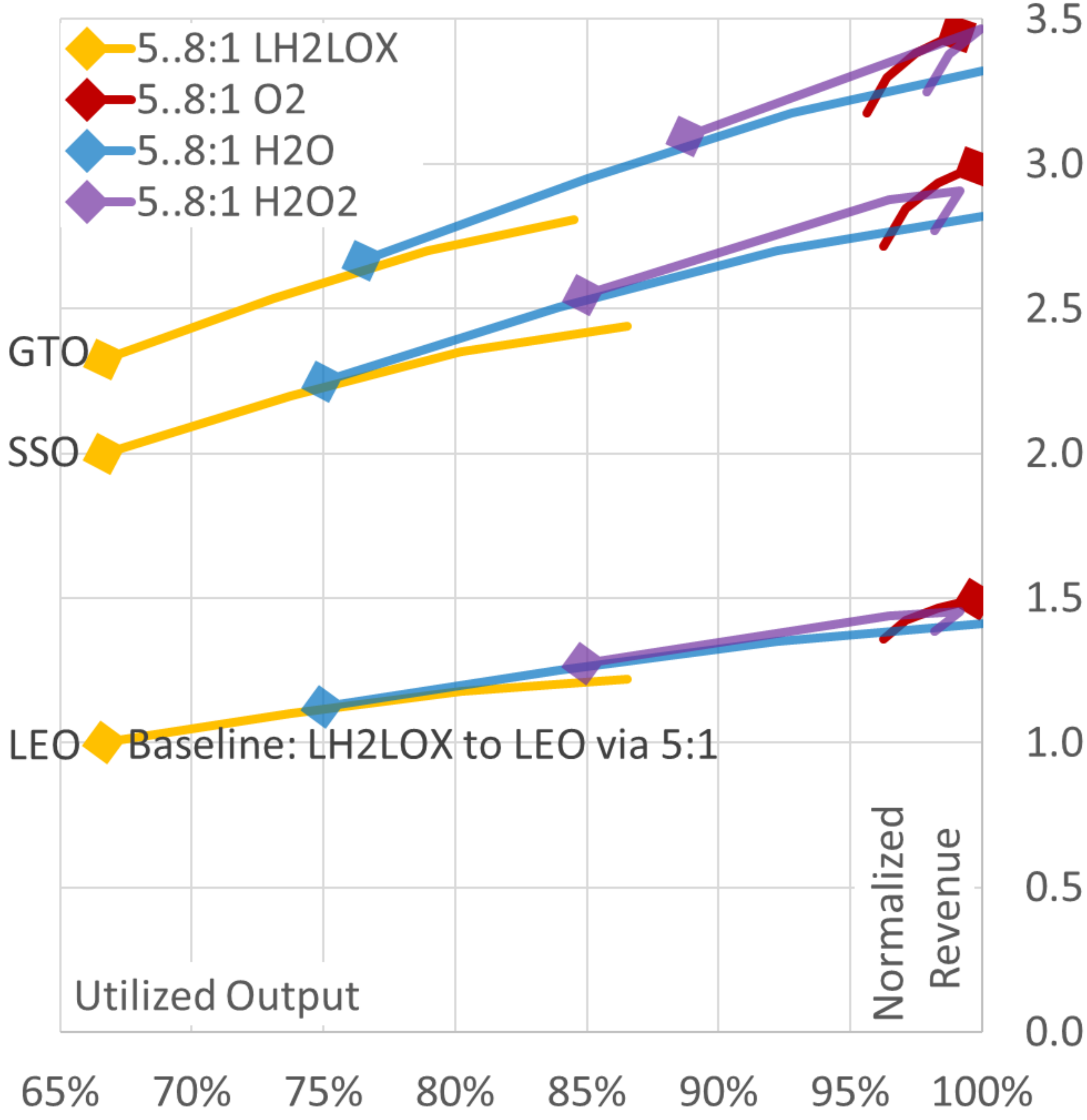
1920s: Bucket Wheel Excavator (BWE) → Increased volume, decreased selectivity. Longtime equipment of choice in Central Europe.

1990s: Continuous Surface Miner (CSM) → Low volume, high selectivity. Growing in popularity in India, South Africa and Australia

2010s: NASA RASSOR → Very low volume, good opportunity for autonomy. Will be the initial technology of choice for lunar regolith excavation

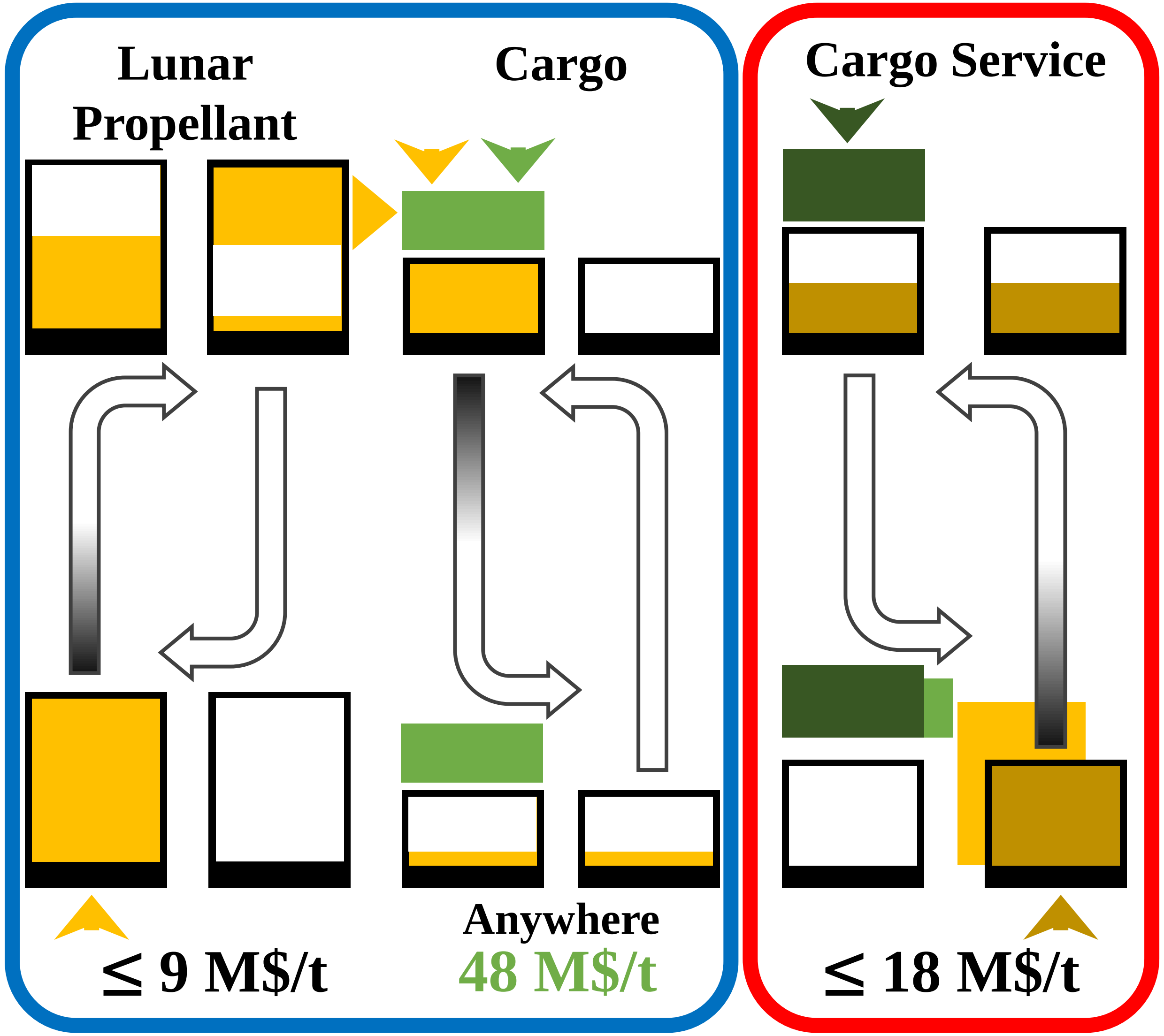




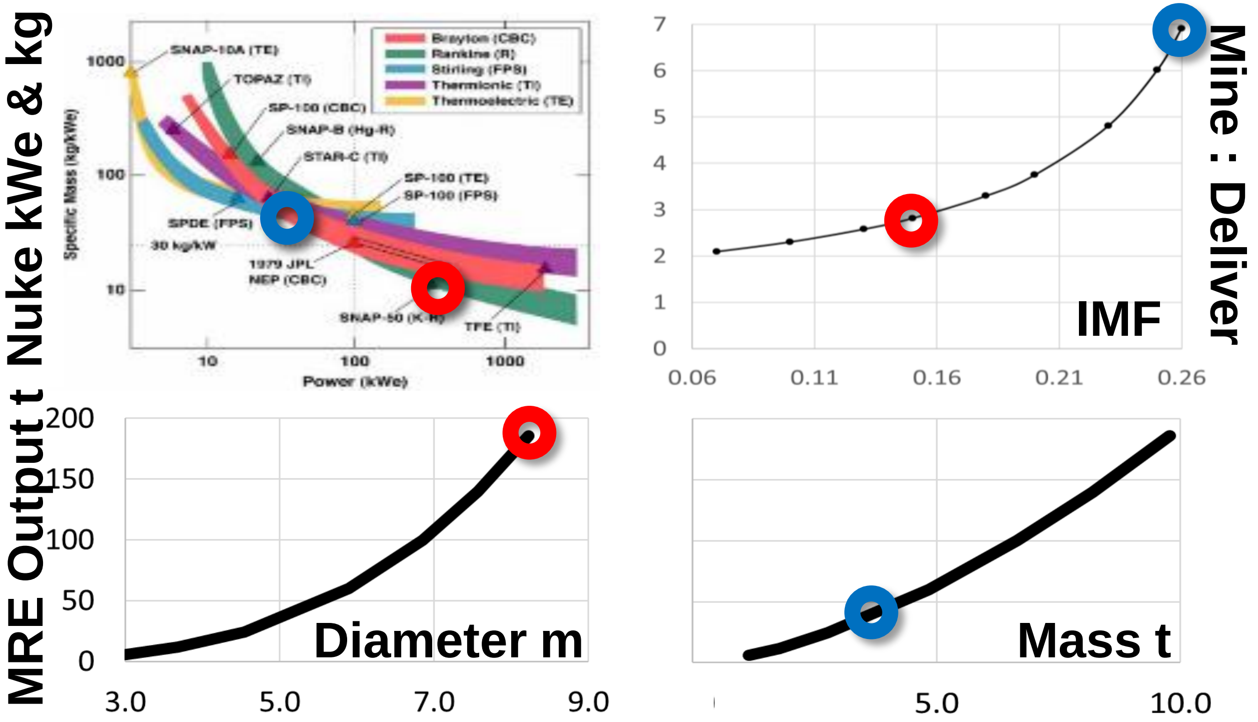


nicholas.j.bennett@student.unsw.edu.au

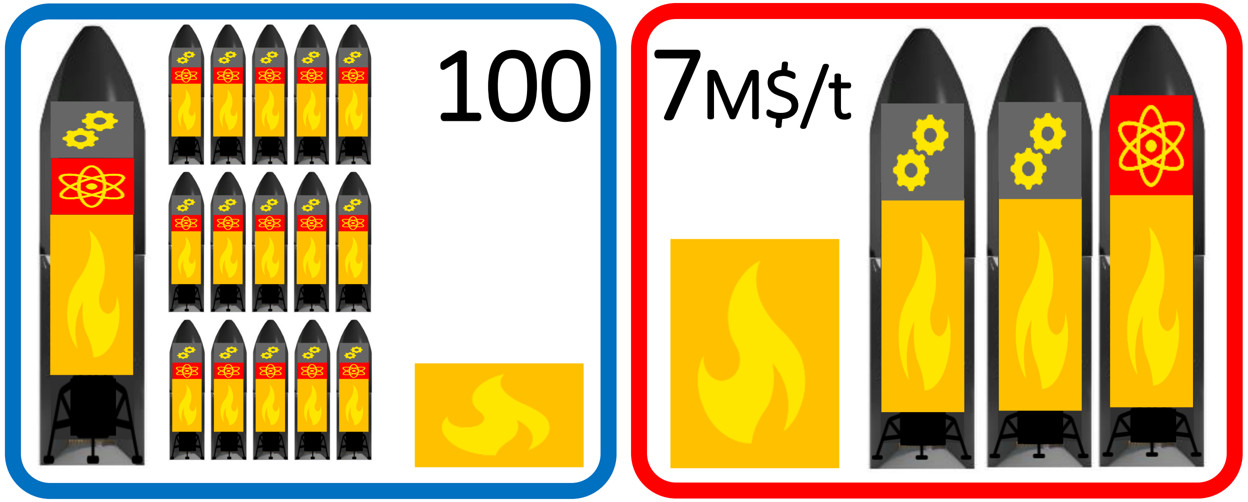
LLO — Earth Propellant 20 M$/t



Lunar Surface Viable Propellant ≥ 27 M$/t



Compounded Nonlinearities



UNSW SYDNEY Australian Centre for Space Engineering Research
nicholas.j.bennett@student.unsw.edu.au

Space Resources and Social Acceptance

Y. Isabel Casasbuenas
M. Nakagawa

June 2021

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How to make the earth-off mining activities sustainable?

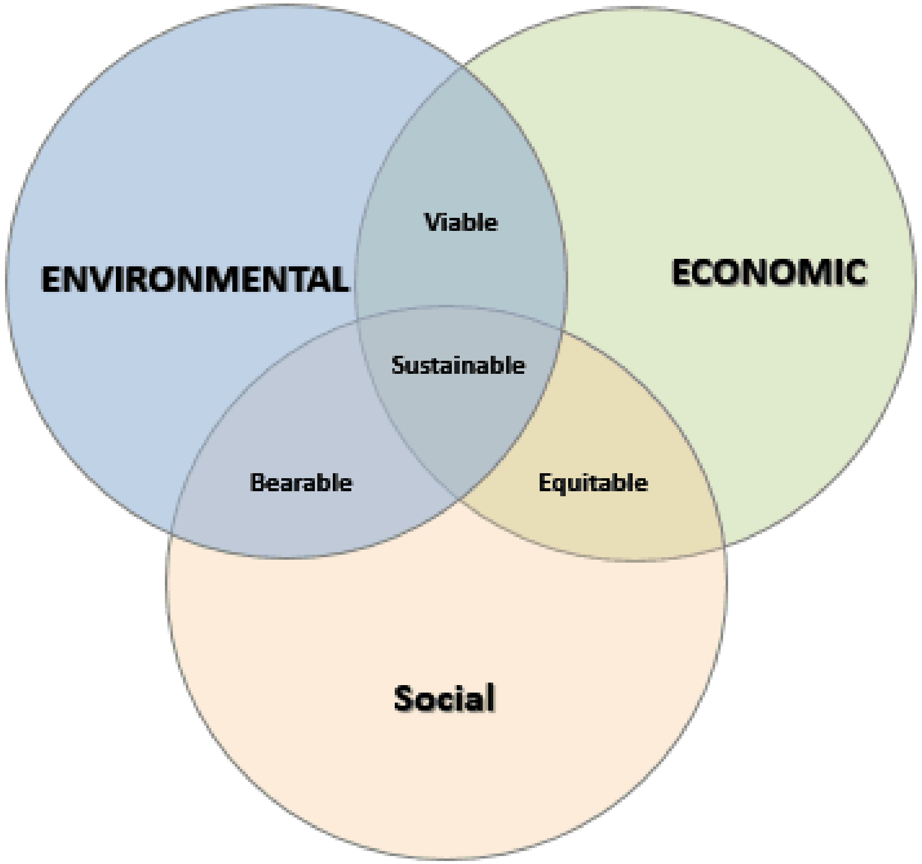
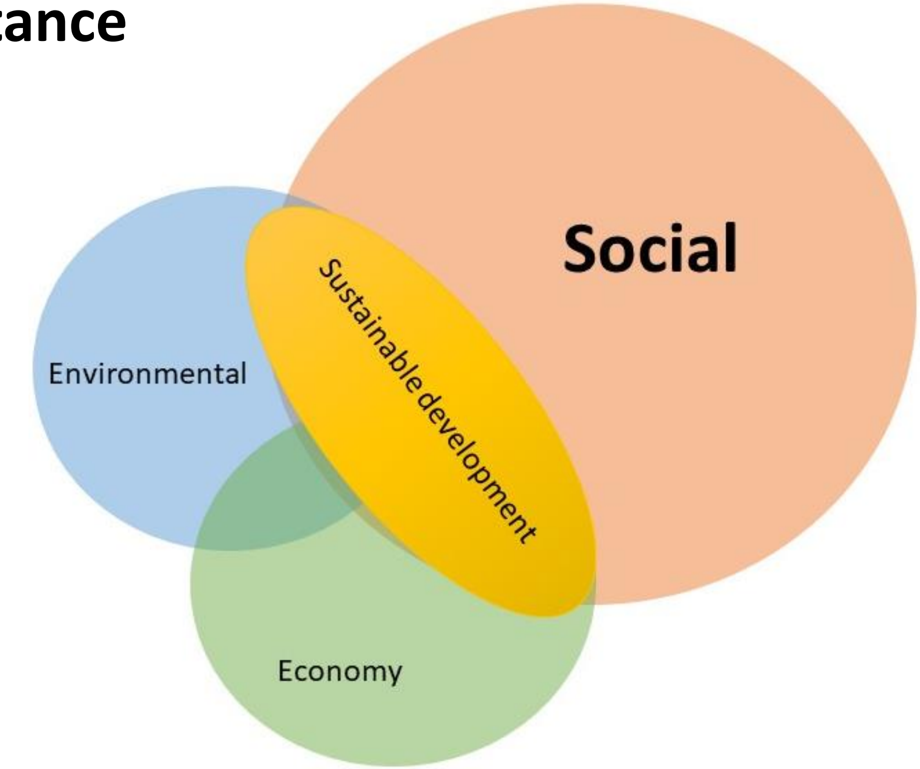


Figure 1: Sustainable development pillars [1]

Social acceptance



- The sustainable development concept for space resources would contribute to mitigate different challenges.
  - Stakeholders Conflicts, inequalities, and environmental issues.
- Social acceptance will become in a high priority.
  - Community perception will have an important role in the development of future space activities
- It is necessary to start to think about potential impacts.
  - A new concept of sustainability needs to be applied.

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Framework for Lunar Site Investigations

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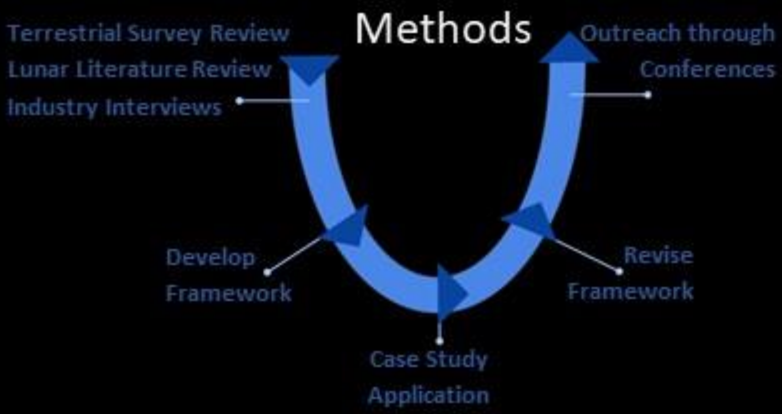
H. A. Danque[1], E. Butler-Jones[2], J. Hinton[3], E. C. Luken[4], and J. M. Sangree[5], [1,2,3,4,5]Center for Space Resources, Colorado School of Mines, 1500 Illinois St, Golden, CO. 80401. hdanque@mines.edu

Goals: Reduce operational, technical, and financial risk by adapting current terrestrial site investigation standards to proposed lunar operations [1],[2]

- Consider the unique aspect of the lunar environment
- Determine the key missing data to perform a detailed lunar site investigation

Desk Study Outline

Report Section	Subsection
Introduction	• Project Description • Background (previous investigations completed)
Site Surface Location & Conditions	• Site Location Overview • Surface Topography
Subsurface Conditions	• Geology, Geophysics, Geochemistry • Geotechnical Concerns
Hazard Analysis	• Operational Hazards • Seismic Environment



Detailed Study Outline

Report Section	Subsection
Project Description	• Project Description • Investigation Methods
Surface Conditions	• Local Environment (confirmation of desk assumptions) • Detailed Surface Topography
Subsurface Conditions	• Geotechnical assessment • Volatile/Chemical Assessment
Design & Construction	• Site Preparation, Subgrade Preparation • Fill Specifications & Grading • Groundwork Construction • Recommended Bearing Capacities • Seismic Requirements • Dust Considerations • Electrical Grounding
Access Preparation	• Launch/Landing Site • Travel Route Slope and Wall Stability
Hazard Analysis	• Detailed Hazard Analysis

Image Credit: LPI, Apollo Surface Panoramas

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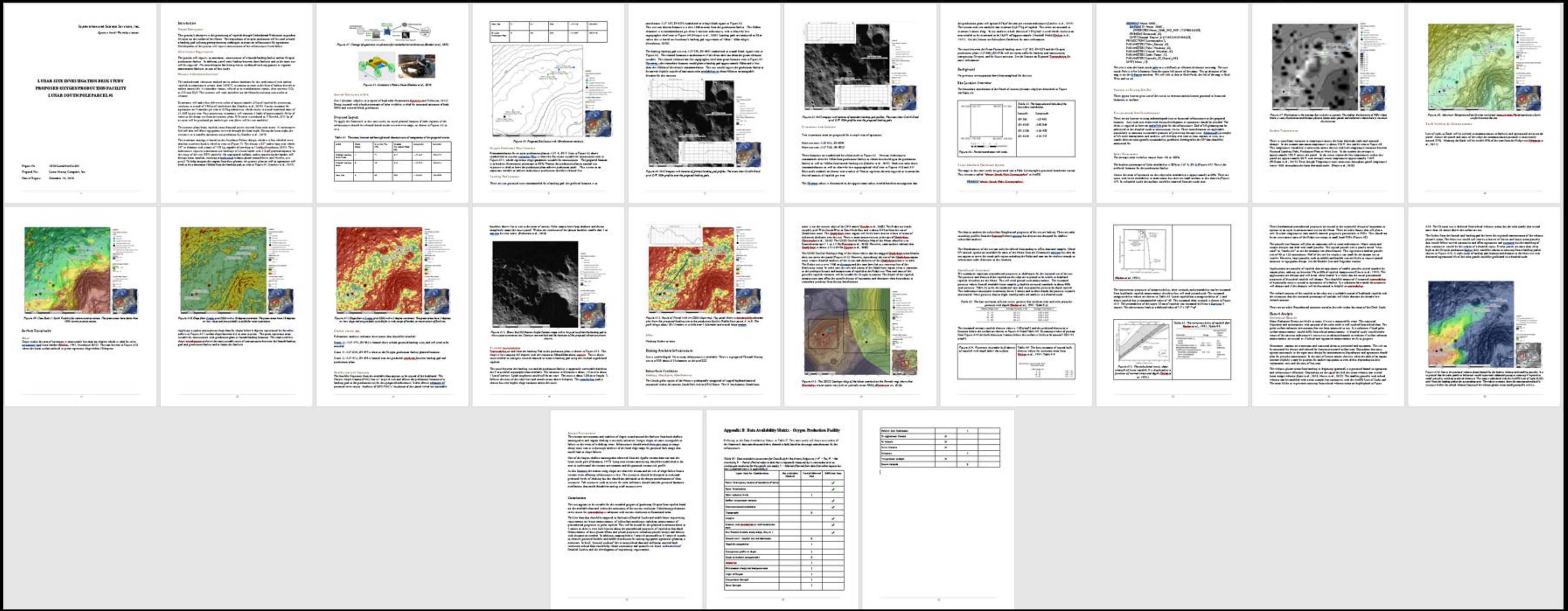

[1] Clayton, C. R. I., Matthews, M. C., and Simons, N. E. (1995). *Site investigation*. Blackwell Science. [2] The British Standards Institution. (2015). *BS 5930:2015 Code of practice for ground investigations*. [3] Kornuta D., *et al.*, (2019) "Commercial lunar propellant architecture: A collaborative study of lunar propellant production," *REACH*, vol. 13, p. 100026. [4] Heiken, G. H., Vaniman, D. T., and French, B. M. (1991). *Lunar sourcebook - A user's guide to the Moon*. Cambridge University Press. [5] Sanders, G. "NASA Lunar ISRU Strategy," Luxembourg, Oct. 10, 2019, Accessed: Apr. 02, 2021. [6] NASA, "NASA's Plan for Sustained Lunar Exploration and Development," National Space Council, Mar. 2020. Accessed: Apr. 03, 2021.

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Image Credit: LPI, Apollo Surface Panoramas

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[5], [6]	Case Study #1	Case Study #2
Product	Oxygen, Launch Landing Site	H2 and O2 Propellant
Resource	Regolith	Water Ice
Region	South Pole	South Pole
Location	Artemis Ridge	Artemis PSR #4
Process	Carbothermal Reduction	Thermal Mining

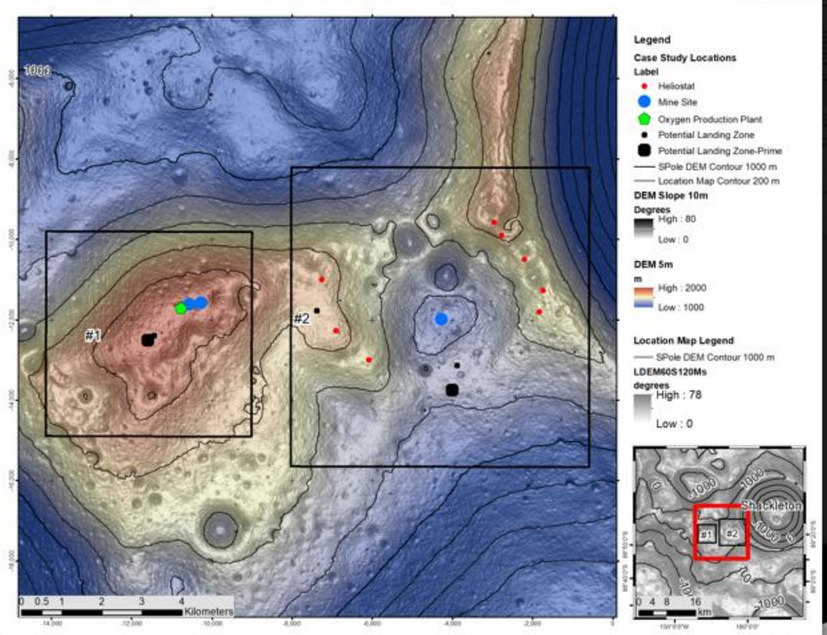

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Image Credit: LPI, Apollo Surface Panoramas

Framework for Lunar Site Investigations

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Key Lunar Considerations [3], [4]

- Reduced gravity
- Solar illumination
- Landing and launch operations
- Thermal management
- Electrostatic properties
- Behavior of disturbed regolith
- Dilatancy and bulk density variation
- Compaction profile
- Agglutinate % content
- Surface dust
- Temperature variation
- Geologic and Geotechnical variability
- Regolith volatile content
- Radiation
- Lunar seismic environment

[5], [6]	Case Study #1	Case Study #2
Product	Oxygen, Launch Landing Site	H2 and O2 Propellant
Resource	Regolith	Water Ice
Region	South Pole	South Pole
Location	Artemis Ridge	Artemis PSR #4
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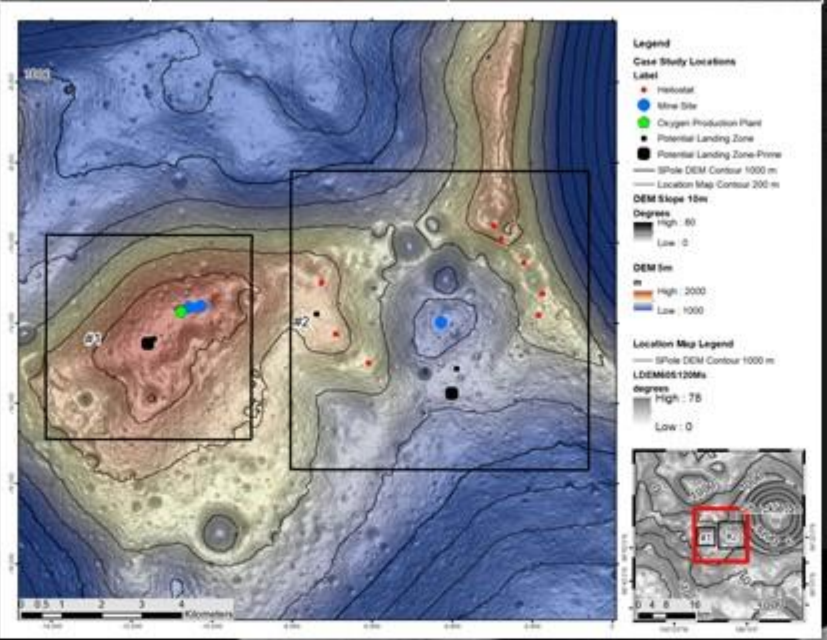

Conclusion:

- This framework can reduce or identify risks to future lunar development
- It identifies critical site conditions that must be measured
- It is a solution to organize site investigation data acquisition and reporting
- Most locations on the Moon will require
  - Project Description
  - Surface Conditions
  - Access Preparation
  - Hazard Analysis
- Other project locations will also require a
  - Detail Surface Analysis
  - Detailed Subsurface Analysis
  - Design and Construction Guidelines

[1] Clayton, C. R. I., Matthews, M. C., and Simons, N. E. (1995). *Site investigation.* Blackwell Science. [2] The British Standards Institution, (2015). *BS 5930:2015 Code of practice for ground investigations*. [3] Kornuta D., *et al.*, (2019) "Commercial lunar propellant architecture: A collaborative study of lunar propellant production," *REACH*, vol. 13, p. 100026. [4] Heiken, G. H., Vaniman, D. T., and French, B. M. (1991). *Lunar sourcebook - A user's guide to the Moon.* Cambridge University Press. [5] Sanders, G. "NASA Lunar ISRU Strategy," Luxembourg, Oct. 10, 2019, Accessed: Apr. 02, 2021. [6] NASA, "NASA's Plan for Sustained Lunar Exploration and Development," National Space Council, Mar. 2020. Accessed: Apr. 03, 2021.

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Image Credit: LPI, Apollo Surface Panoramas

Environmental Impact Analyses for Space Resources Activities

EIAs can be conducted by government or industry bodies; for many mining activities, they are usually required by governments

Under U.S. Law (NEPA), Federal agencies must issue an environmental impact statement for "major federal actions significantly affecting the quality of the human environment"

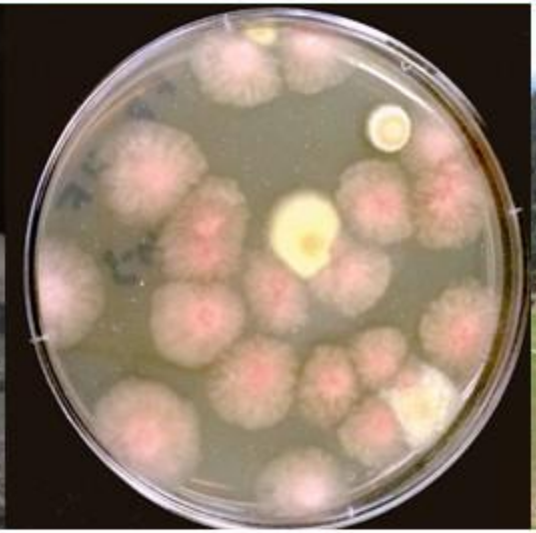
Most nations have adopted or adapted the US process; there is even a Convention for EIAs on Transboundary Pollution

Government EIAs are not substantive regulations, they are disclosure processes

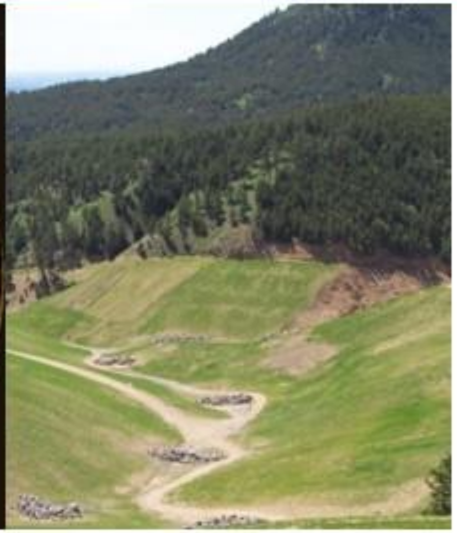
An Early EIS for Space Resources

Launch

Operations



Planetary Protection



Remediation/ Decommissioning

For more information, you can reach Alex at
alex.gilbert@powerandresources.com
See also: Gilbert, A. G, and Vidaurri, M. "Major Federal Actions Significantly Affecting the Quality of the Space Environment: Applying NEPA to Federal and Federally Authorized Outer Space Activities." *Environs* (2021) (Forthcoming).

Image sources: SpaceX, NASA

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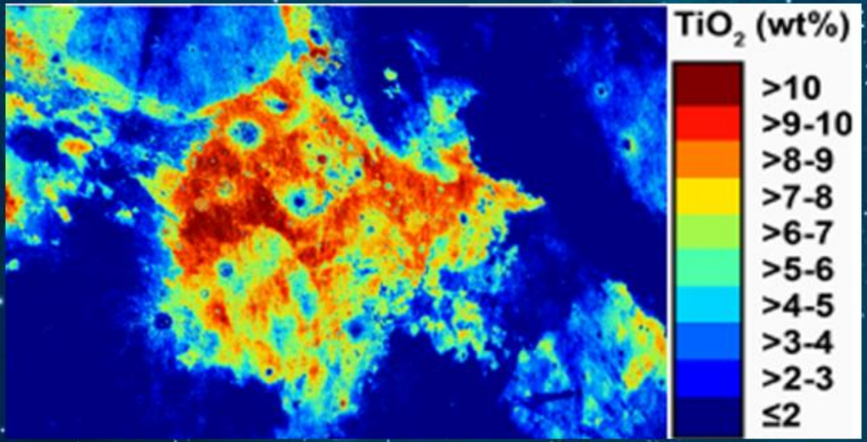
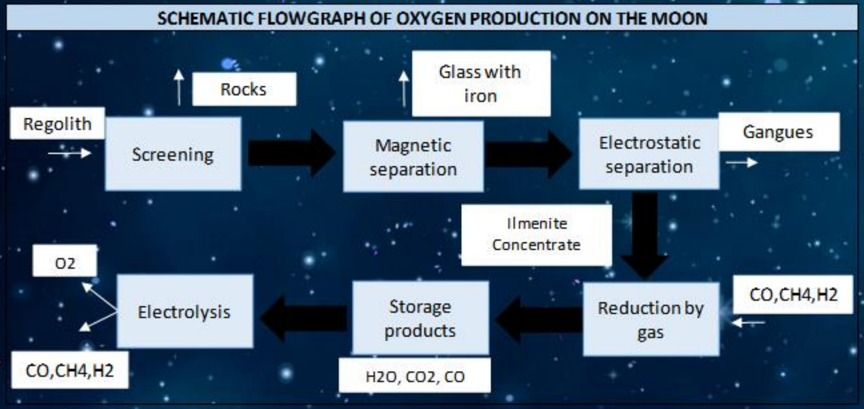
A Geometallurgy Approach of the Exploration of Lunar Ilmenite for Oxygen Production on the Moon

Gustavo Jamanca-Lino | Space Resources Program – Colorado School of Mines

Many researchers have developed metallurgical processes to concentrate lunar ilmenite and produce oxygen on the Moon. However, the successful is limited in terms of recovery and purity grade. This study reviews the geological data of the regolith and breccias sample brought by Apollo 11 to verify ore features that affect the metallurgical behavior. This approach is known as geometallurgy and intends to combine geology with metallurgical engineering to solve the lunar context's mining problems. The author review the characteristics of the "degree of liberation" and "chemical composition" of ilmenite on Mare Tranquillitatis and their impact on concentration and extractive processes

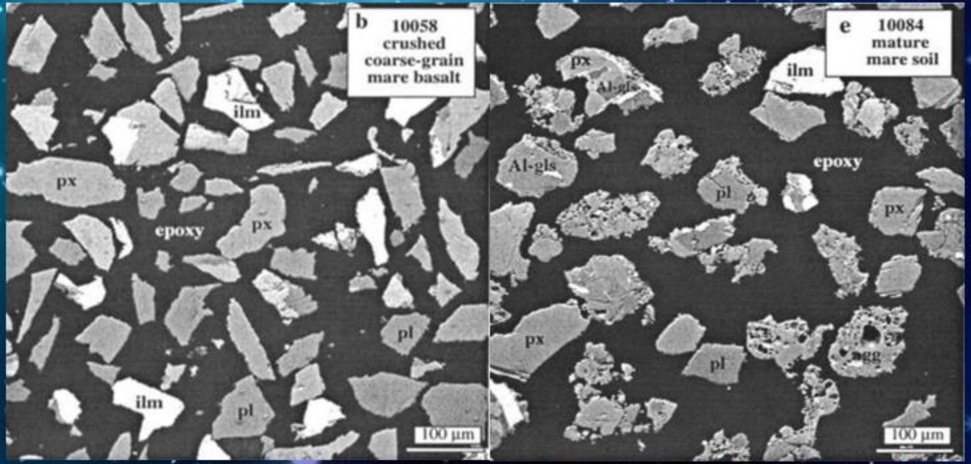


Map of Mare Tranquillitatis with TiO2 distribution



Possible unit operations and processes in a future production plant

The degree of liberation (D.L.) is a quantitative measure of a mineral in a single particle. If the particle contains a single mineral, the D.L is 100, and it decreases with the association with other phases. Mare Tranquillitatis is an excellent soil to be processed since it is a fine grain size material. However, the fine ilmenite is hard to concentrate from the regolith up to an acceptable grade because other minerals lock its particles. It is really hard to increase the ilmenite content from 6% in the regolith to about 90%. There are no data that describe the whole size distribution, but the size ranges analyzed by direct and indirect methods show less than 40% free ilmenite. This information should lead us to evaluate other ilmenite sources, such as the rocks and breccias mixed with the regolith, which have a higher content of free ilmenite (greater than 75%).

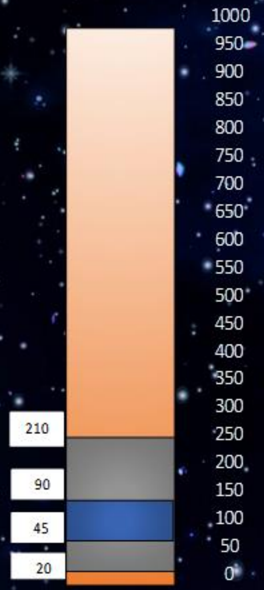


Microscopy of the basalt rock and regolith from Ti distribution in grain-size fractions of Apollo soils 10084 and 71501

The results will be directly influenced by the degree of liberation, and it would not be feasible to apply current grinding technologies to increase it.

Sample	Technique	Size	Feed %w Ilmenite	Grade %w Ilmenite	Recovery (%)	DL
A. Basalt 10058	Magnetic	45-90	18.5	62	39	78
B. Regolith 10084	Magnetic	45-74	10.2	24	8.8	37
C. Simulant	Electrostatic	90-150	10	95	68	100
D. Regolith 10084	Electrostatic	90-150	10	45	24	No data
E. Regolith 10084	Magnetic + Electrostatic Air	90-150	7	37	60	No data
F. Regolith 10084	Magnetic + Electrostatic (Nitrogen)	90-150	7.3	51	48	No data

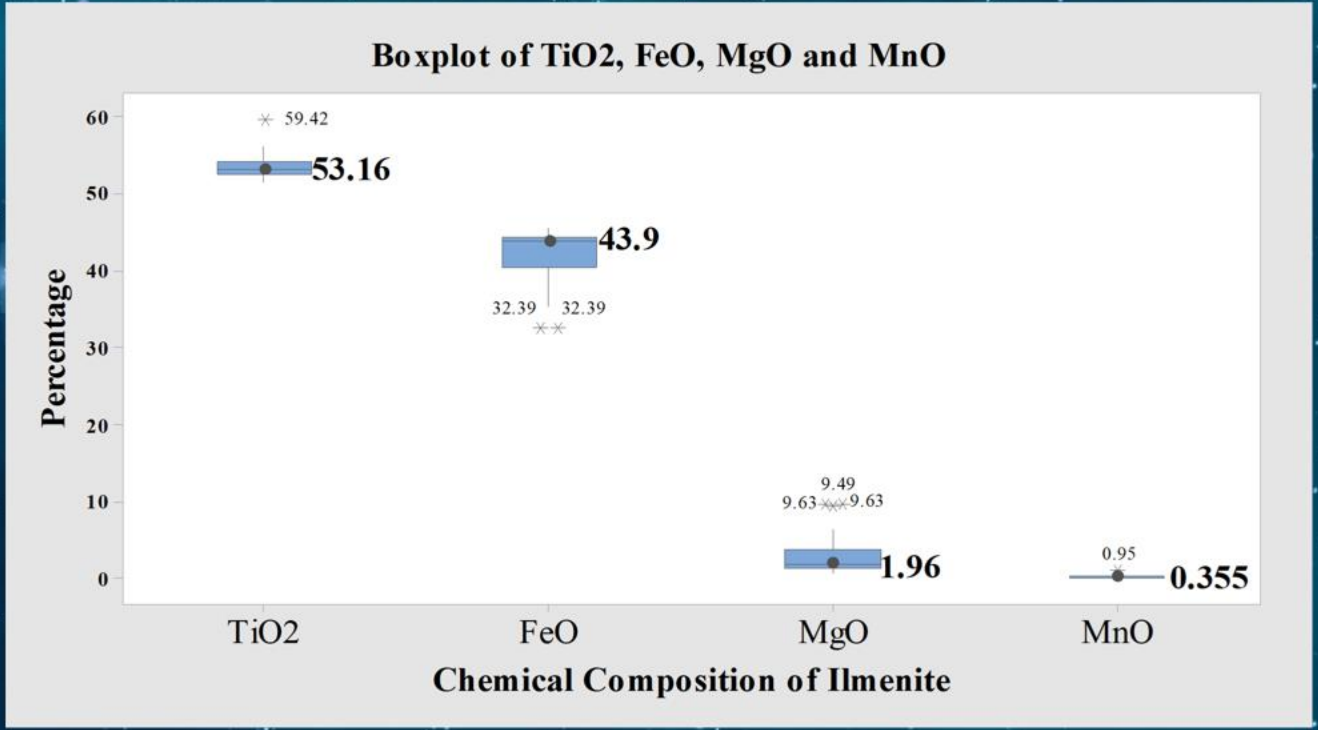
Results summarized and calculated by the author. Data from Test A y B ,
; TEST C,E, F and TEST D]. Lunar simulant has anorthite, Ilmenite, olivine, and pyroxene in the weight ratio of 4/1/1/4



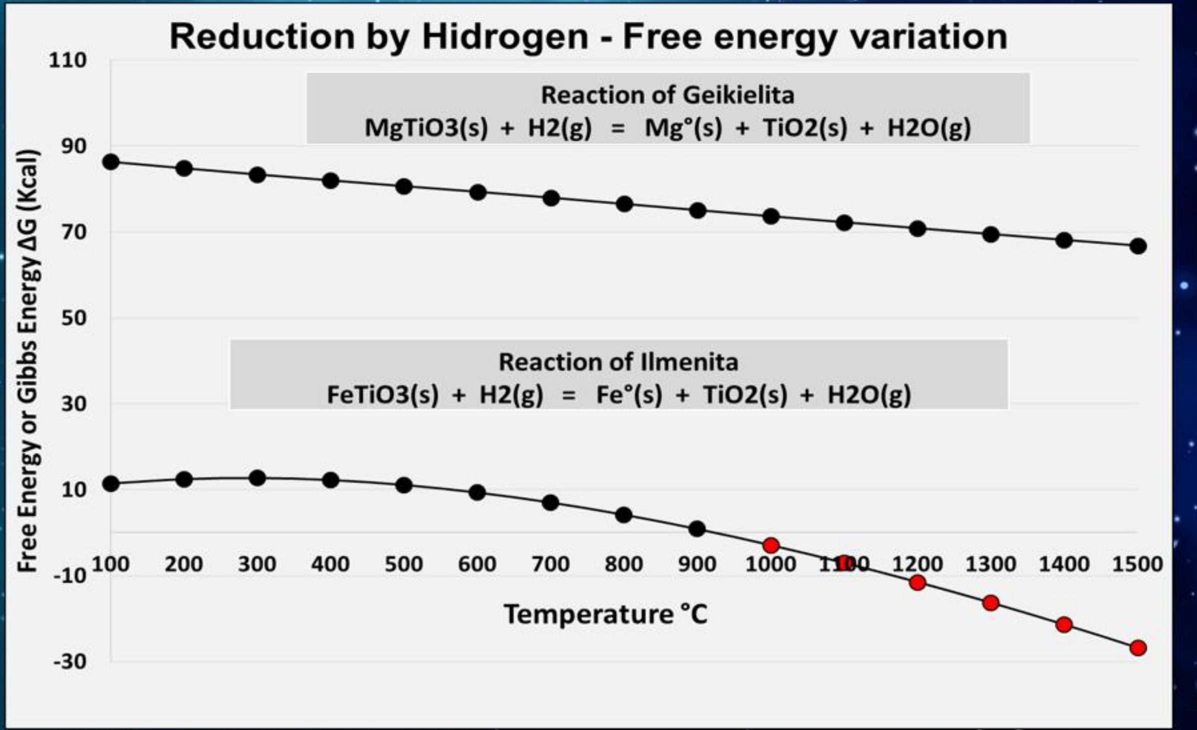
Size range (microns) characterized by D.L.
Blue: direct, Gray: indirect
Orange, no data

A Geometallurgy Approach of the Exploration of Lunar Ilmenite for Oxygen Production on the Moon

Gustavo Jamanca-Lino | Space Resources Program – Colorado School of Mines

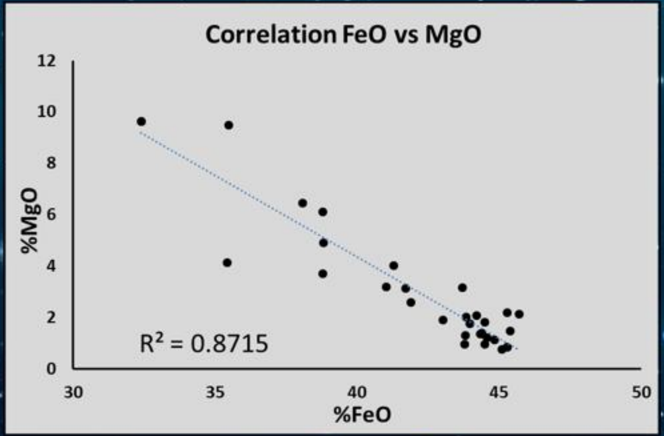


Statistical distribution of the chemical composition of ilmenite in the breccias and basalts in Mare Tranquillitatis. Data from lunar breccias



Energy free variation for both the minerals in the reduction by hydrogen. Calculated with HSC Chemistry V. 6.0

In the same context, only ilmenite with low magnesium should be processed with chemical composition to increase performance. The lunar breccia samples show that the magnesium oxide content is highly variable in the ilmenite with a statistical non-normal distribution of the MgO content. There are very high values, reaching up to three times more than average (over 9%). According to statistical and thermodynamic calculations, the presence of this oxide in ilmenite is detrimental to the process since it dilutes the iron content and reduces the process's efficiency. Future mining operations must identify high MgO and low MgO ilmenite as a correction factor in the economic evaluation of the deposit.



Linear correlation between %MgO - %FeO in ilmenite

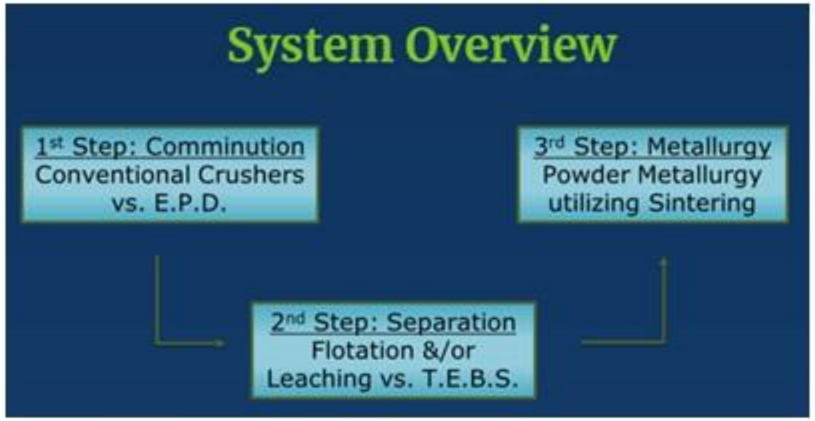
The ilmenite reaction will become spontaneous at temperatures over 1000°C; however, geikielite's reaction never achieves the spontaneous state; the free energy variation is always positive and never produces water. It means that ilmenite with a high MgO content will have less water production yield since MgO * TiO2 does not reduce even at very high temperatures

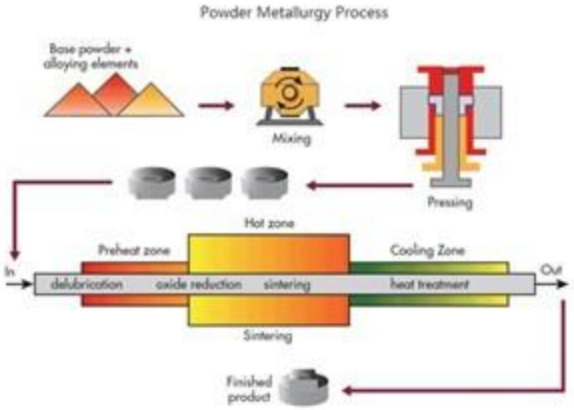
Conclusion

Chemically, the Mare Tranquillitatis is a high deposit of ilmenite to mine. Instead, considering geometallurgy, the ilmenite in the deposit must be classified according to their degree of liberation (free or mixed) and according to its magnesium oxide content. This knowledge will assist in selecting the right location in the deposit to mine, the right size range to process, and an accurate metallurgical architecture to maximize the operative results and, therefore, the profitability.

More information:

Space Resources Engineering: Ilmenite Deposits for Oxygen Production on the Moon





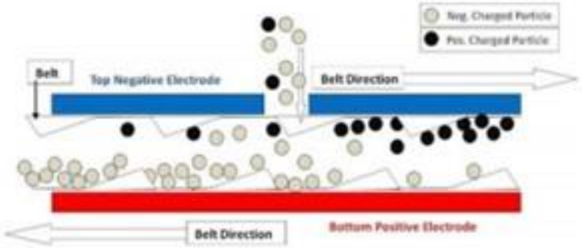


Figure 2. Detail of separation zone

Multi-Product Lunar Beneficiation System

- **Kerst J.H. Kingsbury, University of Arizona**
- Kerstk@email.arizona.edu
- 971-240-7406
- LinkedIn: Kerst Kingsbury

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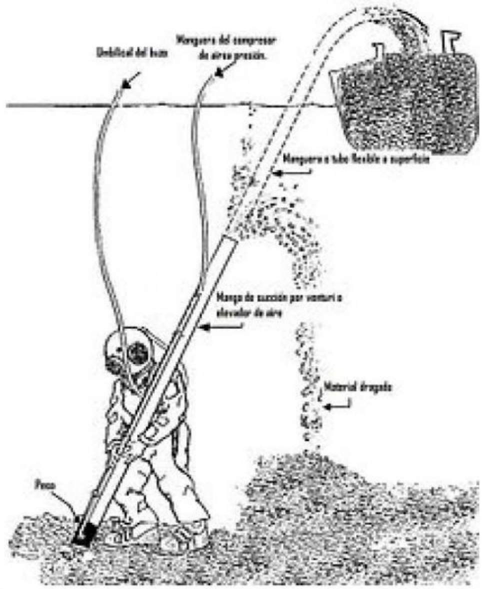
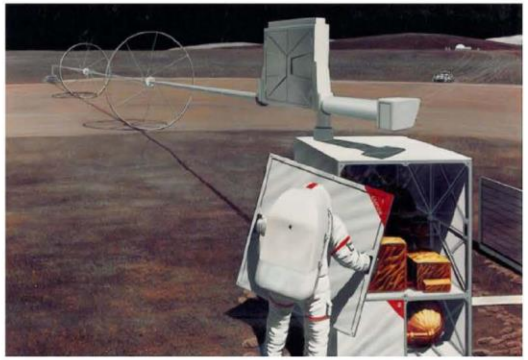
ICY LUNAR REGOLITH ROTARY MINING IMPLEMENT WITH PNEUMATIC CONVEYANCE FOR LUNAR (1) EXCAVATION AND (2) FRACTURING FOR ENHANCED WATER SUBLIMATION & RECOVERY

T. E. Loop[1], [1]Colorado School of Mines, 1310 Maple St., Golden CO 80401 – thomasloop@gmail.com



(Airlift (dredging device) – Wikipedia)



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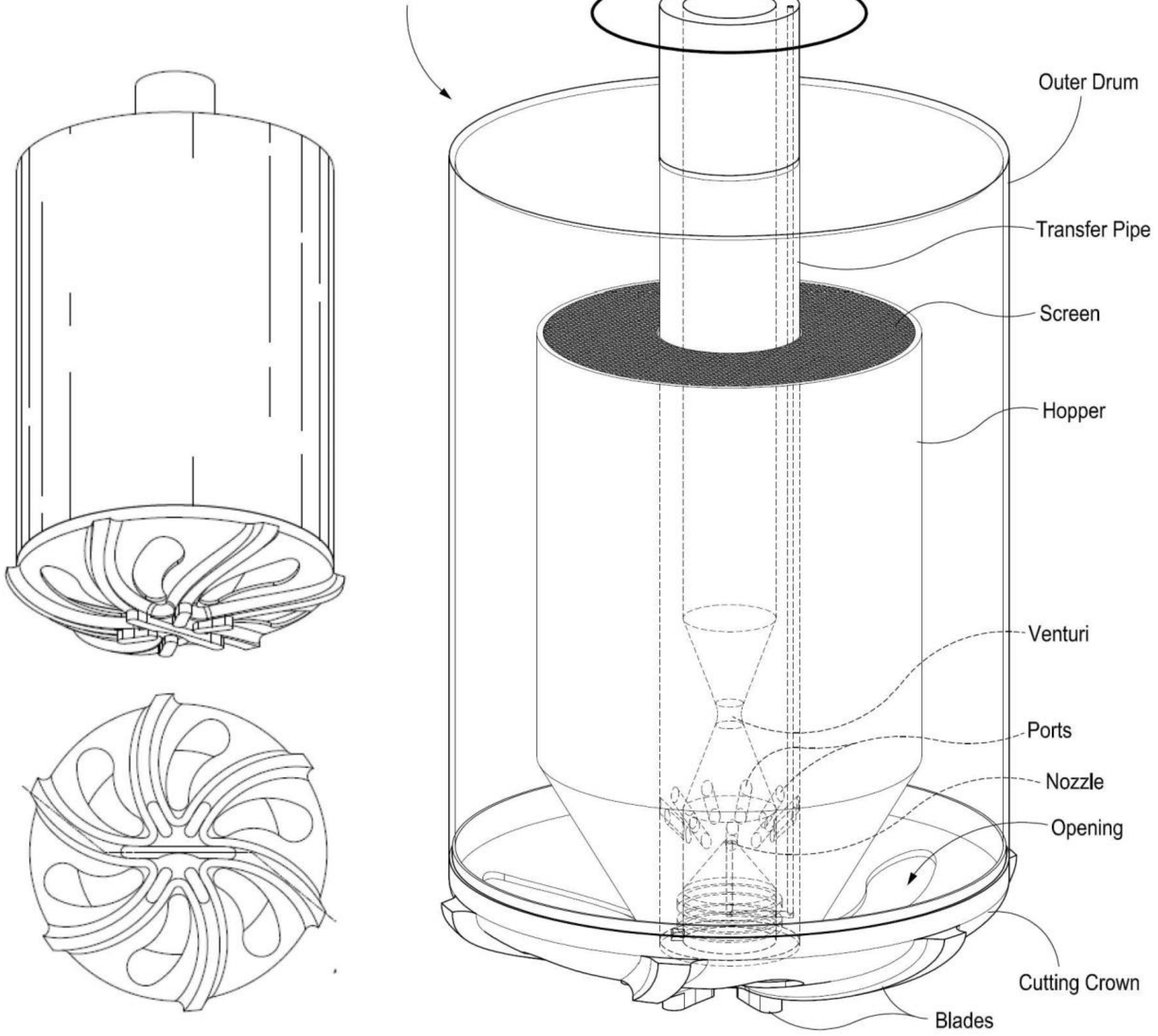
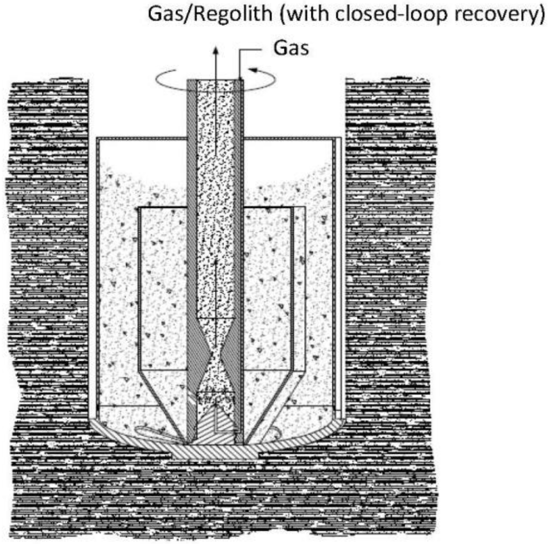
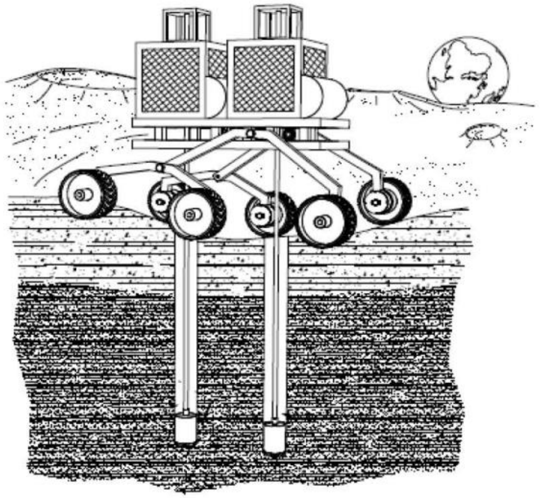
Nested Rotary Drag Bit





Rotary Drilling with Pneumatic Transfer

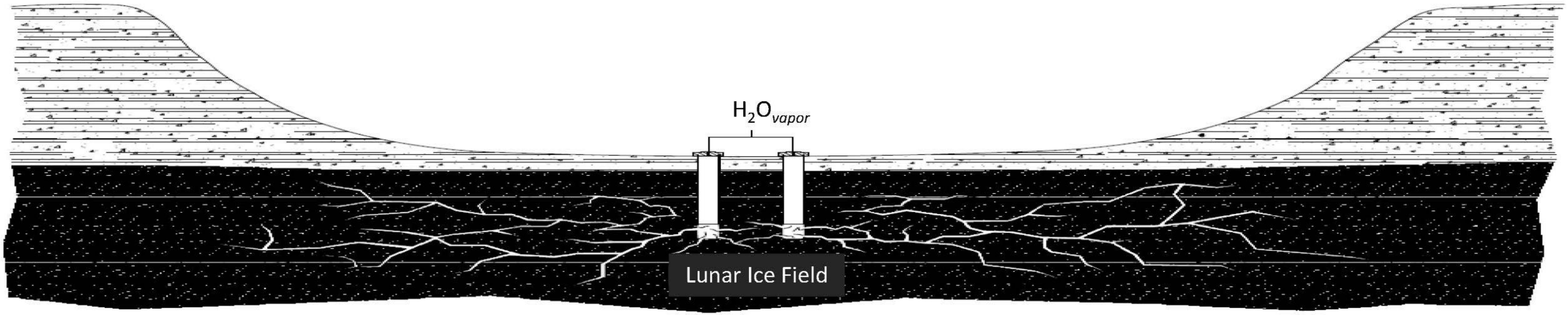


Lunar Drill Rig with Counter-Rotating Bits

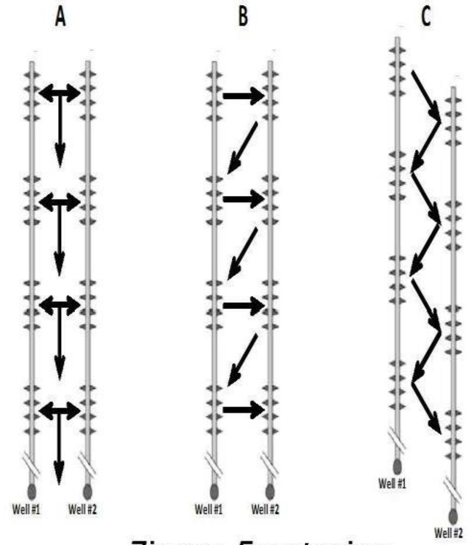
ICY LUNAR REGOLITH ROTARY MINING IMPLEMENT WITH PNEUMATIC CONVEYANCE
FOR LUNAR (1) EXCAVATION AND (2) FRACTURING FOR ENHANCED WATER SUBLIMATION & RECOVERY

T. E. Loop[1], [1]Colorado School of Mines, 1310 Maple St., Golden CO 80401 – thomasloop@gmail.com

Enhanced Water Sublimation via Lunar Fracking?



1. A method of mining water on the Moon, comprising the steps of:
   - drilling a borehole into a surrounding subsurface ice field located beneath the surface of the Moon a selected distance (e.g., 10s of meters deep);
   - detonating one or more explosives at one or more locations within the borehole to thereby fracture the subsurface ice field (e.g., “zipper-fracturing”); and optionally/preferably
   - exploding a thermal conductor into the subsurface ice field to thereby increase the rate of water gas extraction out of the borehole (by increasing the thermal conductivity of the ice field); and
   - extracting water gas out of the borehole for subsequent processing.



Zipper-Fracturing

Lunar Claim Optimization for ^{3}He and Other Solar Wind Implanted Volatiles

Stewart Ray, Colleen Olson, Lisa Robibero, Steven Coutts, & Maxwell Sissman

Planetary and Terrestrial Mining Sciences Symposium & Space Resources Roundtable

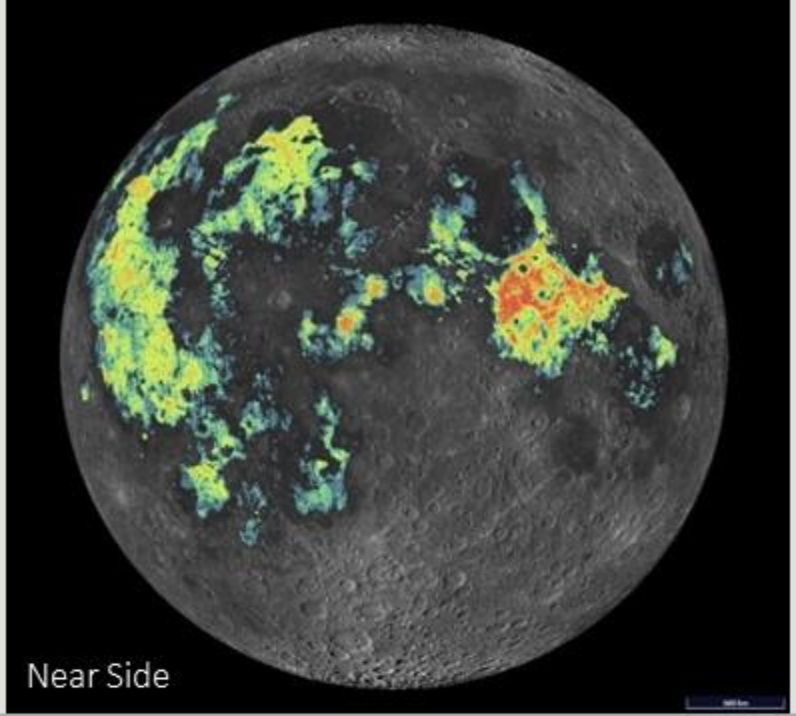
06/10/2021
Colorado School Of Mines

INTERACTIVE ^{3}HE CLAIM OPTIMIZATION MODEL: https://bit.ly/3c9Cxs2

- PROXIES:
  - Titanium Oxide (TiO_2) abundance
    - From Lunar Reconnaissance Orbiter's Wide-Angle Camera (WAC)
  - Optical Maturity Index (OMAT)
    - From Kaguya Lunar Multiband Imager (MI)
- ENGINEERING CONSTRAINTS:
  - Slope
    - From Lunar Reconnaissance Orbiter's Lunar Orbiter Laser Altimeter (LOLA)
  - Rock Abundance
    - From Lunar Reconnaissance Orbiter's Lunar Radiometer Experiment (DIVINER)
- LROC QUICKMAP MODEL:
  - Data Sets are pre-loaded
  - User-Friendly Interface
- EXPRESSION LAYERS:
  - User decides input parameters
  - Model is adjustable in the future
  - Can use different inputs to look for other resources
- NEAR SIDE REGIONS FAVORABLE:
  - Volcanic mare basalts rich in ilmenite (TiO_2)
  - Relatively old surface ages
  - Flat areas with low rock abundance

Variable	Name of Relevant Dataset	Range of Dataset	Likely	More Likely	Very Likely	Most Likely	Dig Here
TiO_2	"abundance_TiO_2"	2 – 10 (%)	> 3.0	> 4.5	> 6.0	> 7.5	> 9.0
OMAT	"lclem_omat"	0 - 0.3 (unitless)	< 0.25	< 0.225	< 0.20	< 0.175	< 0.15
Slope	"ldsm_16"	0° - 90° (degrees)	< 20	< 16	< 12	< 8	< 4
Rock Abundance	"Abundance_rock"	0-0.1 (%)	< 0.10	< 0.08	< 0.06	< 0.04	< 0.02

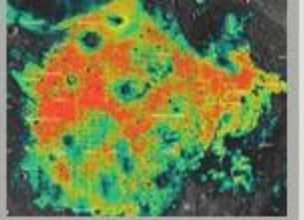
Initial input parameters used to create confidence level expression layers of likely ^{3}He abundance



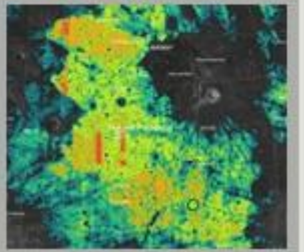
Likely Claim Sites

- 1) MARE TRANQUILLITATUS:
  - Largest Red "Hot Spot" region on Moon
  - Fairly large mare basin
- 2) OCEANUS PROCELLARUM:
  - Very large mare basin on Moon
  - Most places Yellow or Orange
- 3) MARE IMBRIUM:
  - Most places Yellow or Orange
  - Fairly large mare basin
- 4) MARE VAPORUM/SINUS AESTUUM:
  - Three smaller Orange/Red "Hot Sopts"

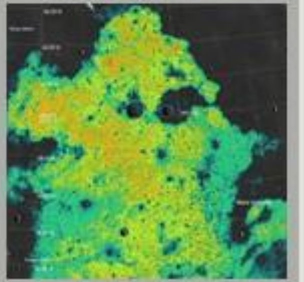
1)



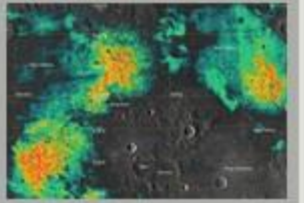
2)



3)



4)



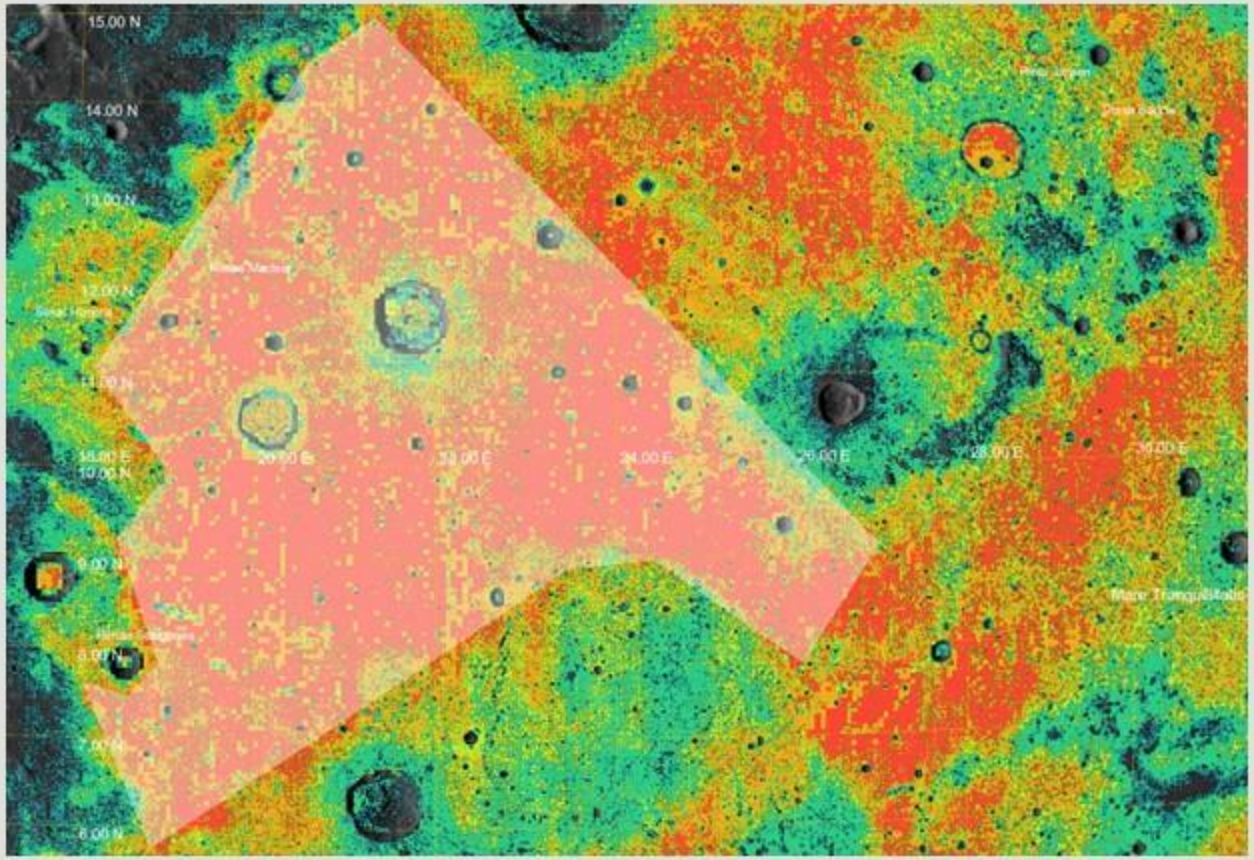
Apollo ^{3}He Abundance

Mission	Average ^{3}He abundance (ppm)	Location (°N)	Location (°E)	Map Output
Apollo 11	11.2	0.67409	23.47298	Most Likely
Apollo 17	10.2	20.18809	30.77475	Very Likely
Apollo 12	4.975	-3.01381	-23.41930	Not Likely
Apollo 15	3.075	26.13224	3.63400	Not Likely
Apollo 16	1.95	-8.97341	15.49859	Not Likely

Average Apollo Mission ^{3}He abundances from (Schmitt, 2006)

- SANITY CHECK:
  - Apollo ^{3}He abundances correlate with confidence levels in model

Resource Approximation



Parameter:	Value:	Unit:	Rationale:
Production Rate	100	kg/yr	Minimum viable quantity to sell to a terrestrial market
Mine Life	10	yrs	Needed to recover capital investment and close business case
Yield	33	kg/km^2	From (Schmitt, 2006), Table 7.1; confirmation needed by future samples
Area Mined	3	km^2/yr	
Minimum Site Area	30	km^2	3km^2 /yr for 10 years
Minimum Claim Size	38	km^2	25% margin of error

Minimum claim size based on 100 kg/yr production rate (Sowers, 2020)

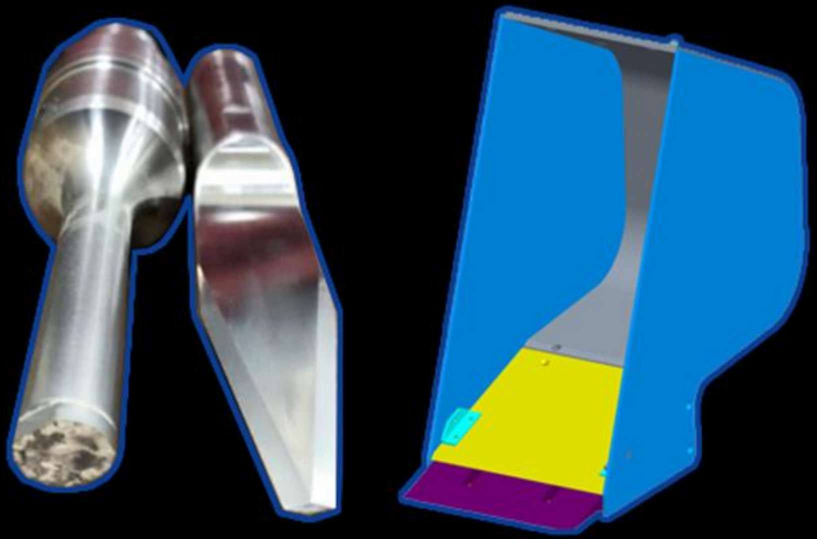
- MARE TRANQUILLITATUS HOT SPOT:
  - First order approximation made with Draw & Search Tool in QuickMap
  - Polygon is ~38,000 km^2
  - Yields ~1,000 Mines
  - 25% margin yields ~750 Mines
  - **Total Approximate Yield:**
    - **~75,000 kg/yr**

ULTRASONIC LEADING EDGE FOR LUNAR EXCAVATION TOOLS

E. T. Rezich, A. Schepelmann, D. J. Gotti, D. L. Linne - NASA Glenn Research Center

Heavy construction and excavation machinery.

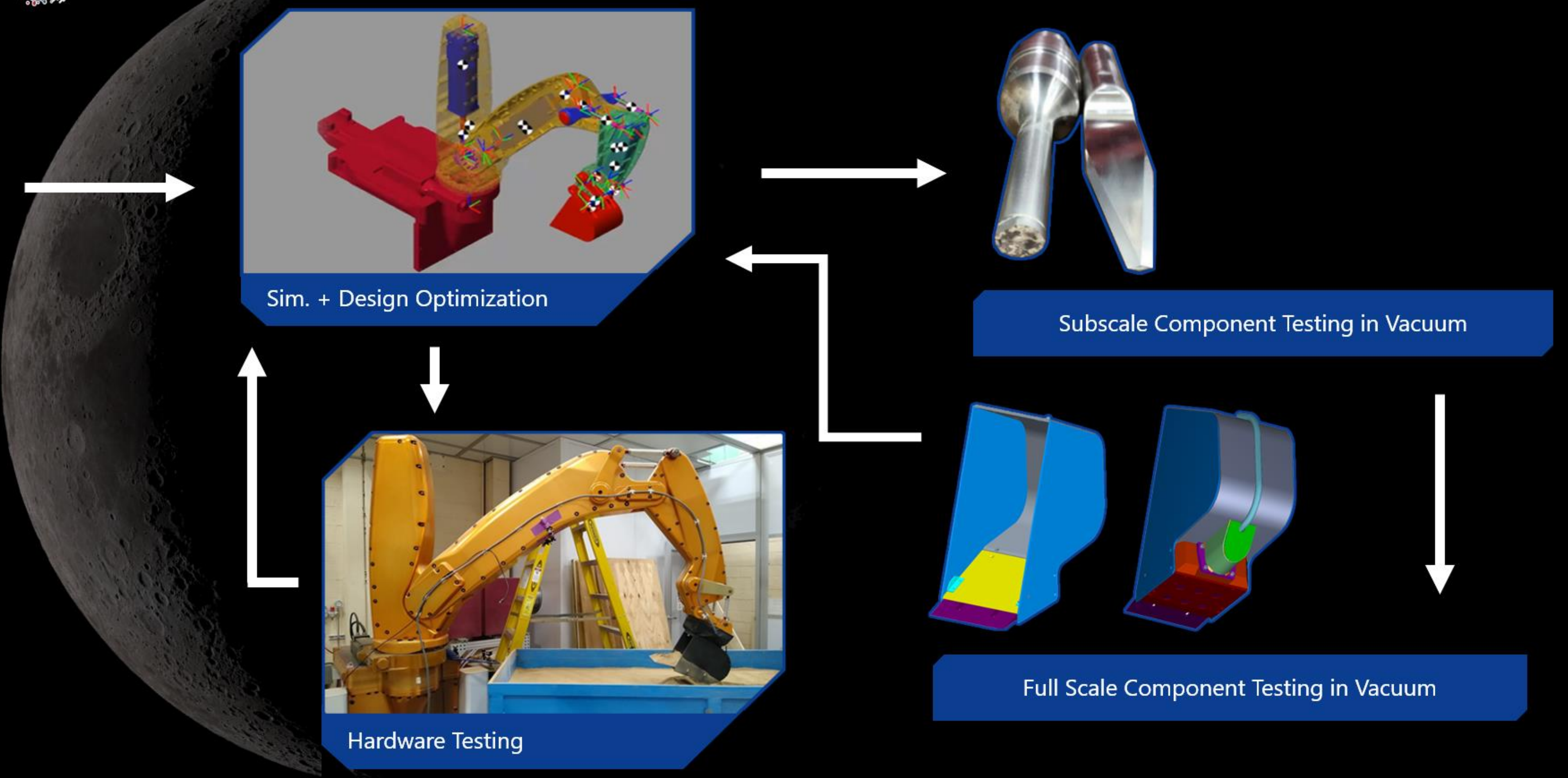
- Regolith and granular ice excavation is critical to produce resources on the lunar surface.
- Current terrestrial excavation equipment designs are not suitable for lunar applications.

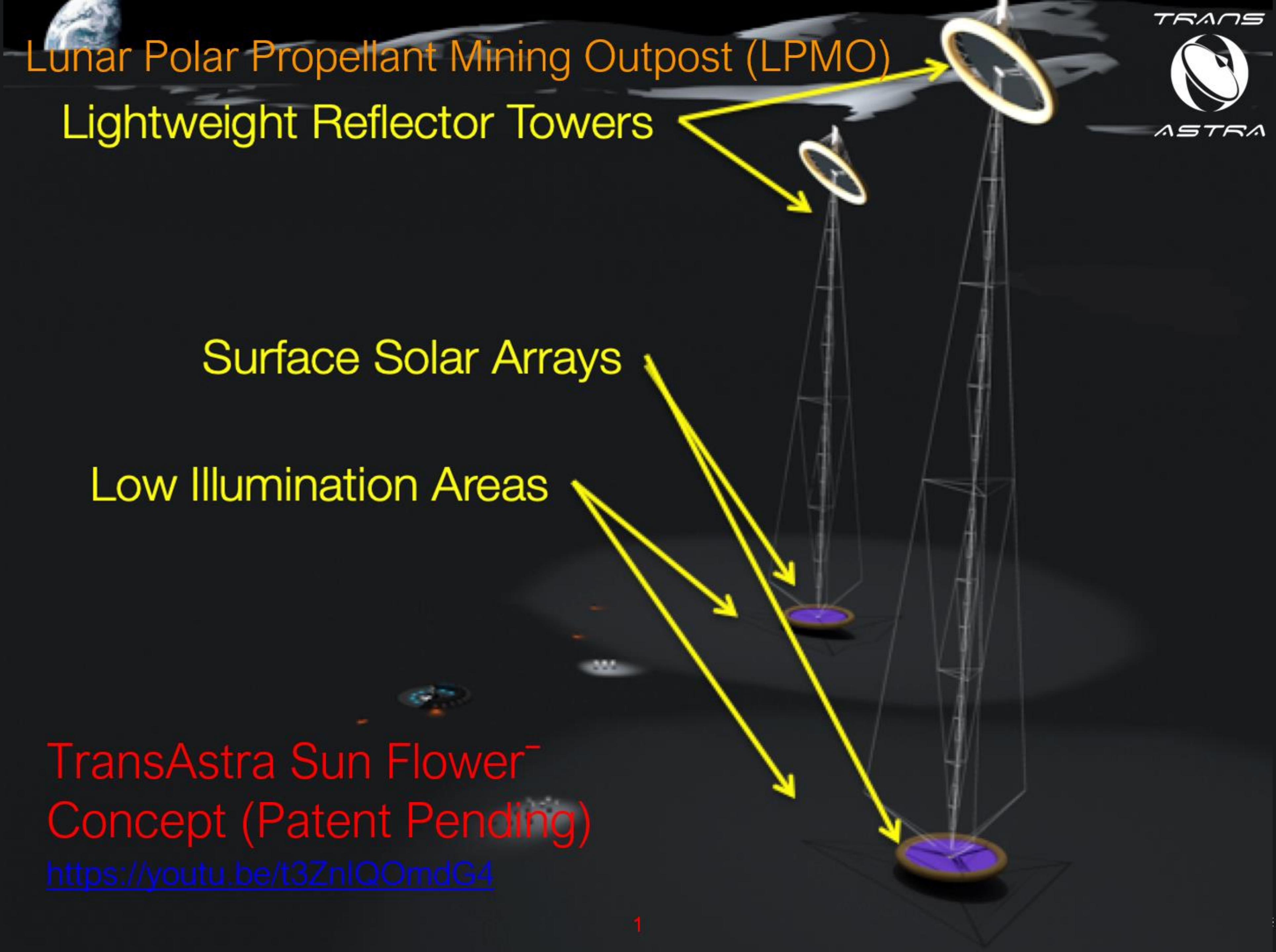


Ultrasonic forced vibration tools. L: Vibration probe. R: Bucket concept.

- Tools with resonantly vibrating leading edges could significantly reduce soil penetration forces.
- Such tools could decrease the power consumption and mass of lunar excavation systems.

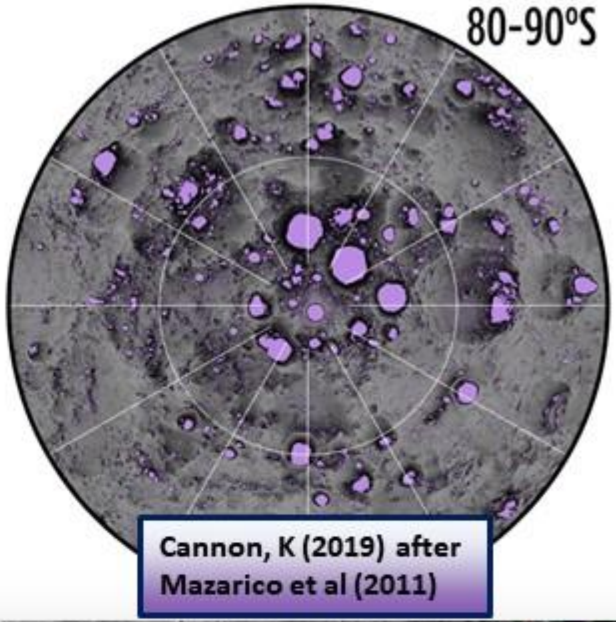
ULTRASONIC LEADING EDGE TOOL DESIGN PIPELINE

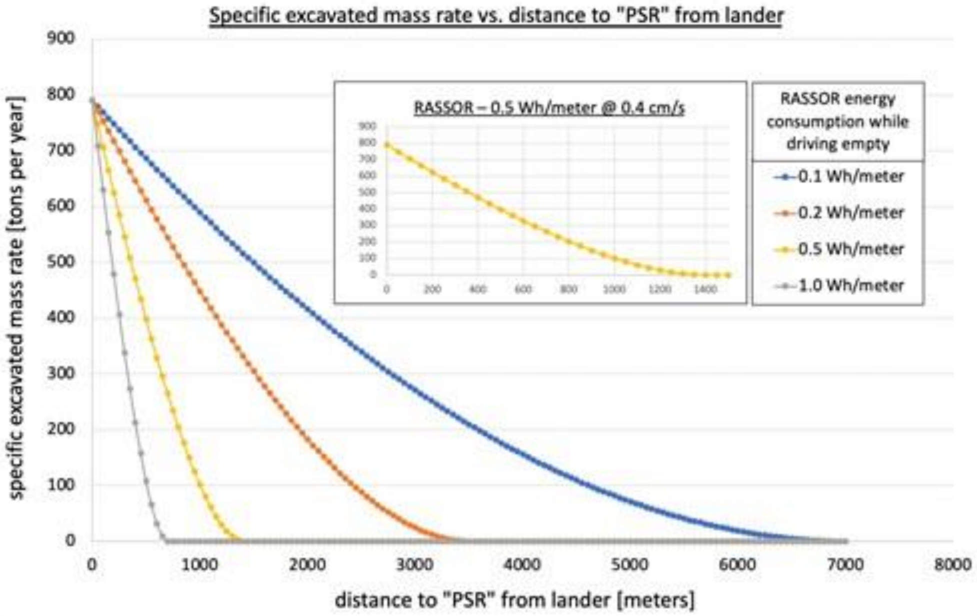


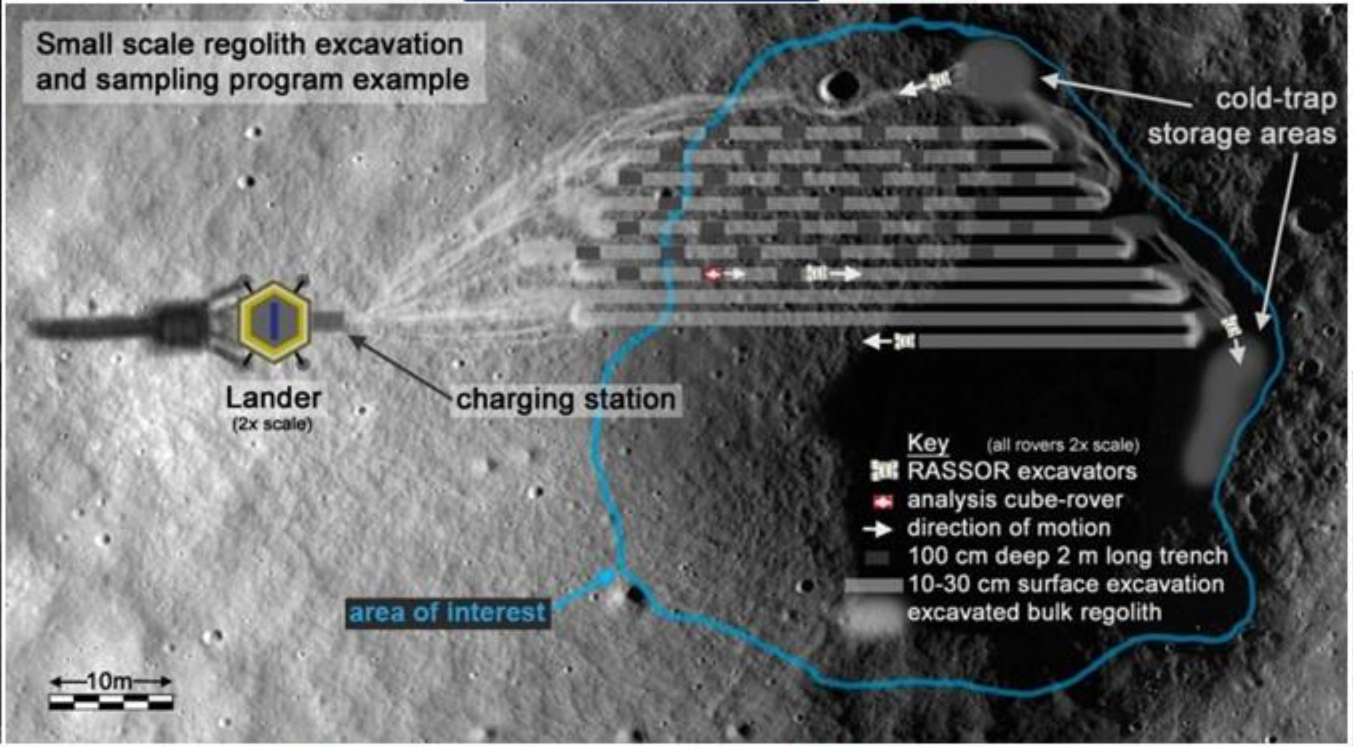

Lunar Polar Propellant Mining Outpost (LPMO)
Lightweight Reflector Towers
Surface Solar Arrays
Low Illumination Areas
TransAstra Sun Flower¯
Concept (Patent Pending)
https://youtu.be/t3ZnIQOmdG4
TRANS ASTRA
1

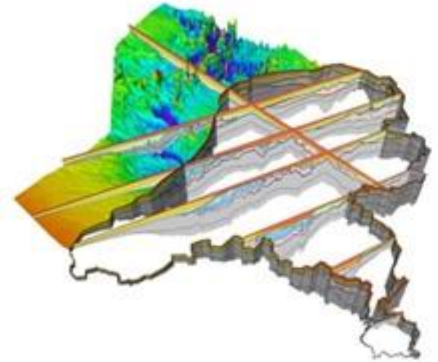
INTERPLANETARY SPACE RESOURCE ALLIANCE
ISRA

A BUSINESS CASE FOR A NEAR-TERM LUNAR EXCAVATION CAMPAIGN (2024-2028)









Miguel Coto | Ben McKeown | Cole Pazar | Chris Shanley

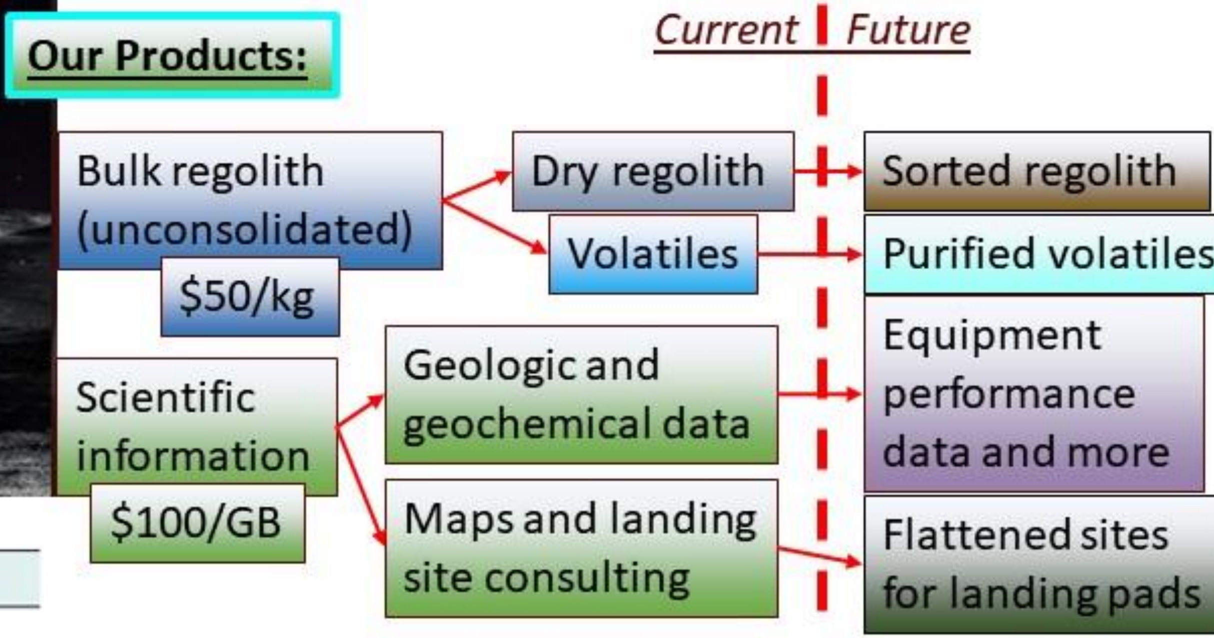


Table 16: Summary of financial model assumptions

Parameter	Basis	Value
No. Trench Metres Excavated / Yr	Based on 3 Rassors each excavating 100 two metre Trenches / Yr	600m
Sample Mass Excavated / 1m of Trench	Basis described in Tables 3,4 and Fig. 15	~3000 kg
Excavated Sample Price	Basis described in Section 6.4	$50/kg
Total Mass of Equipment	Basis described in Table 1 and on Max Griffin Lander Payload [Ref. 29]	475 kg
Unit Capex	Based on literature [e.g. Ref. 5 and checked with Rob Mueller]	$30,000/kg
Launch & Landing Costs	Based on Viper Rover to Lunar surface cost	$200m
Annual Operating Costs	Basis described in Table 14	$10m pa
Equipment Replacement Frequency	Based on conversation with NASA (RM) & [Ref. 36]	Every 5 years

Figure 26: Cumulative pre-tax free cash flow

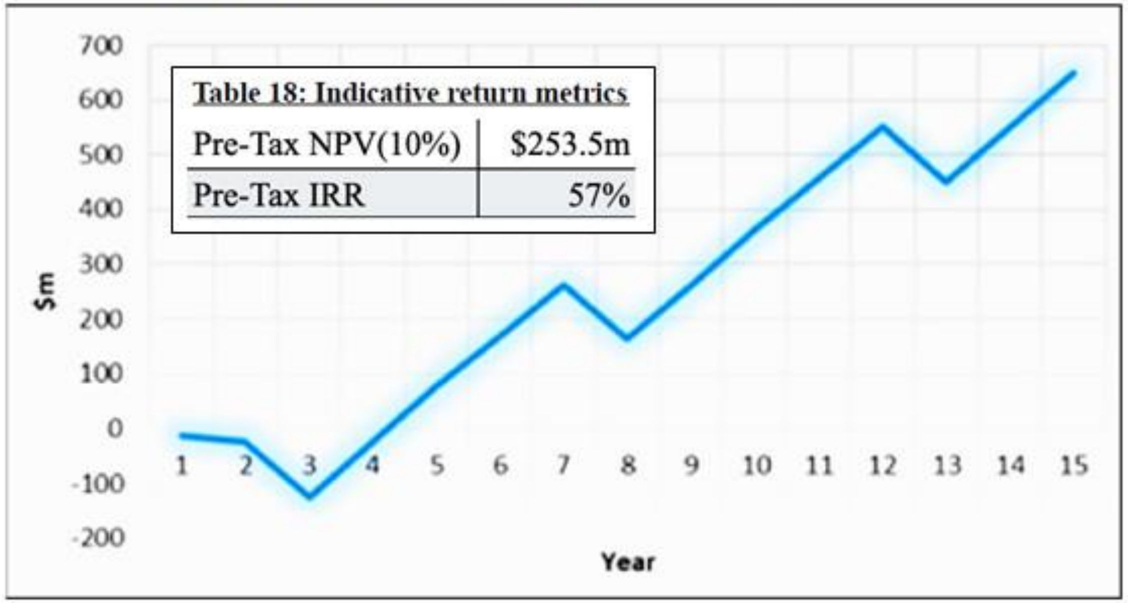


Table 18: Indicative return metrics

Pre-Tax NPV(10%)	$253.5m
Pre-Tax IRR	57%

https://www.researchgate.net/publication/344707509_Lunar_Regolith_Sample_Excavation_Company_-_A_Space_Resource_Business_Plan

Miguel Coto Ben McKeown Cole Pazar Chris Shanley

BACK UP SLIDES

Figure 3: A) Theorised water-ice depth distribution (after LMIS 2020) and Regolith density variation assumptions (adapted from Lunar Sourcebook)

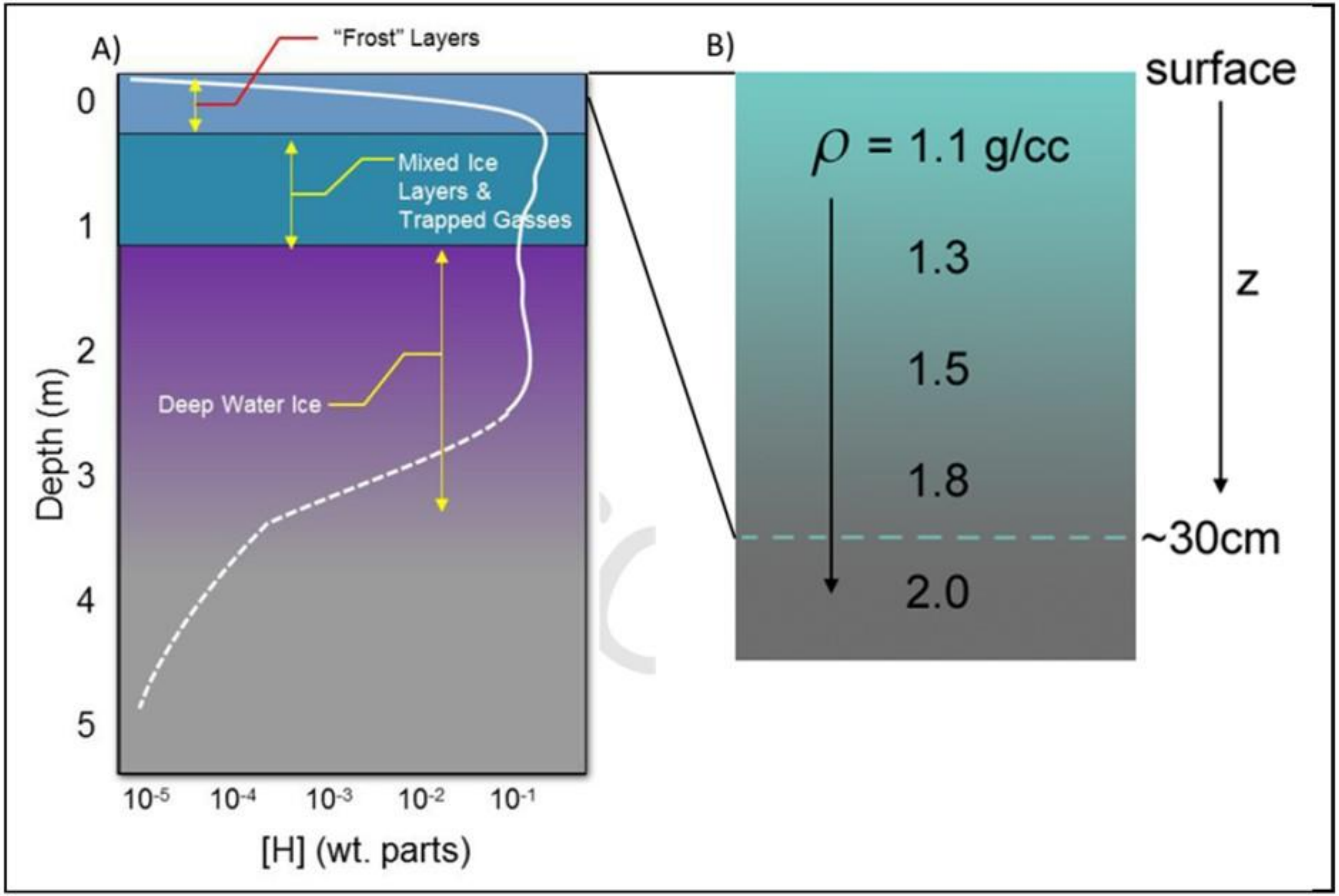


Figure 4: Expected geologic distributions of ice in Lunar regolith[10]

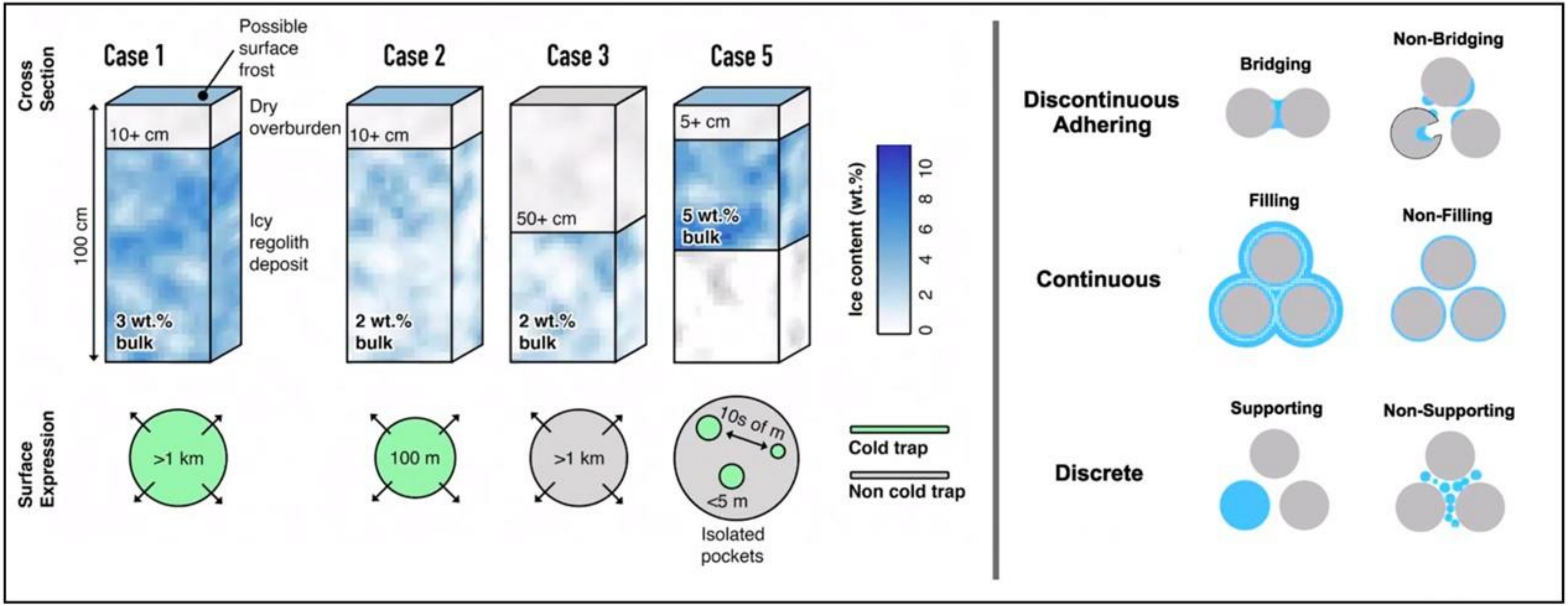
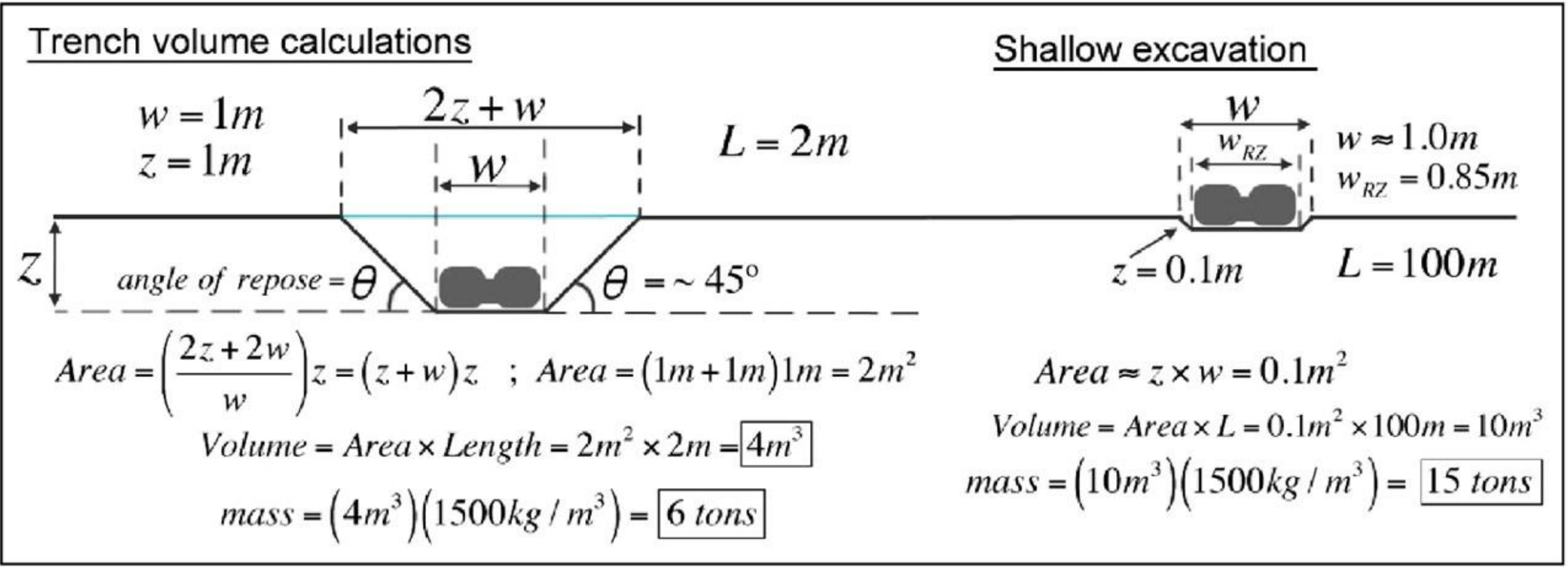


Figure 15: Excavated mass calculations and geometries used for trench volumes (ISRA)



Interplanetary Space Resource Alliance

ISRA

SPACE TECHNOLOGIES

Deployable 15 m^2 Lunar solar array Schematic (to scale)

Center *for* Space Resources

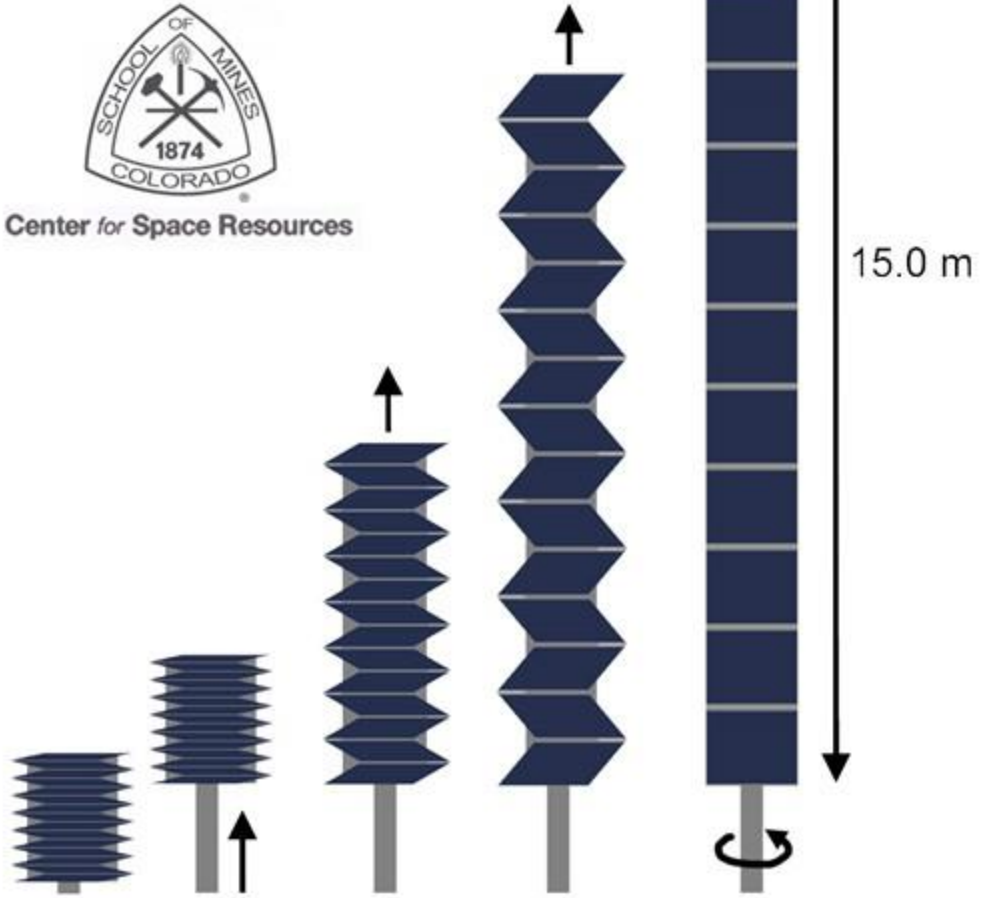
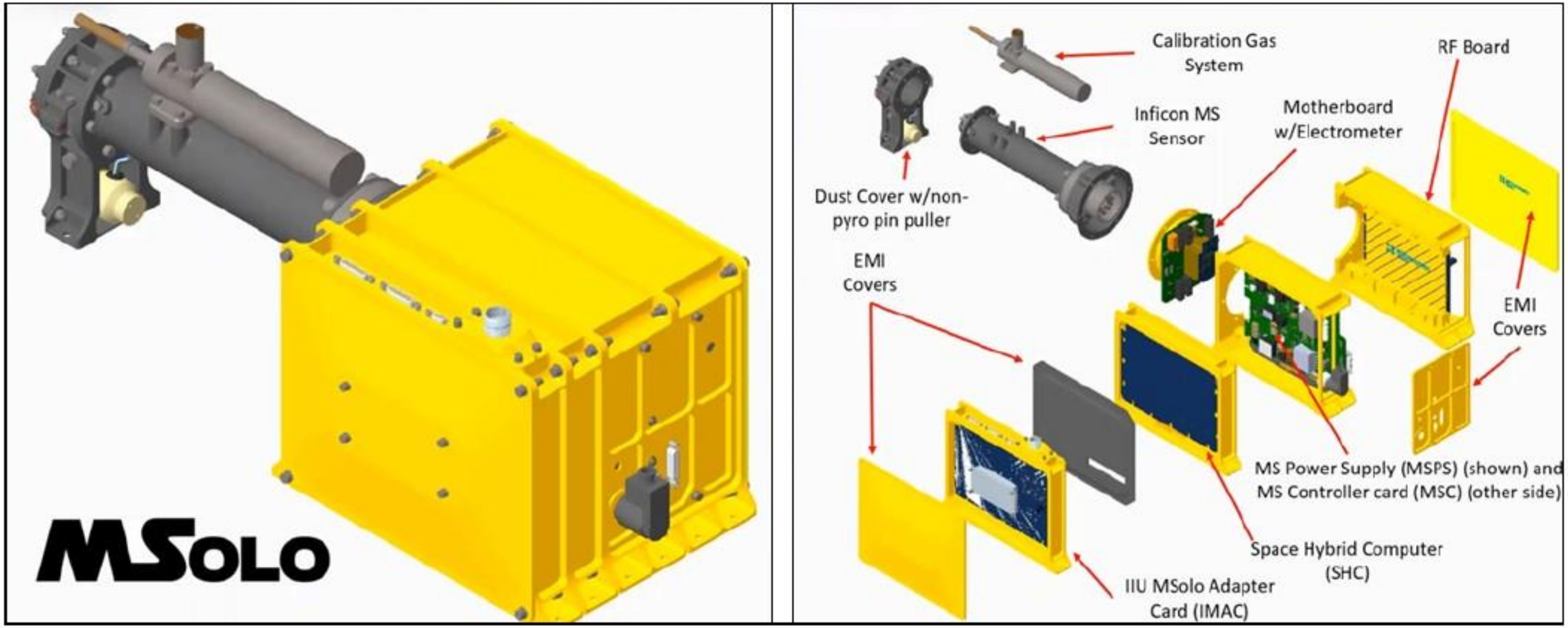
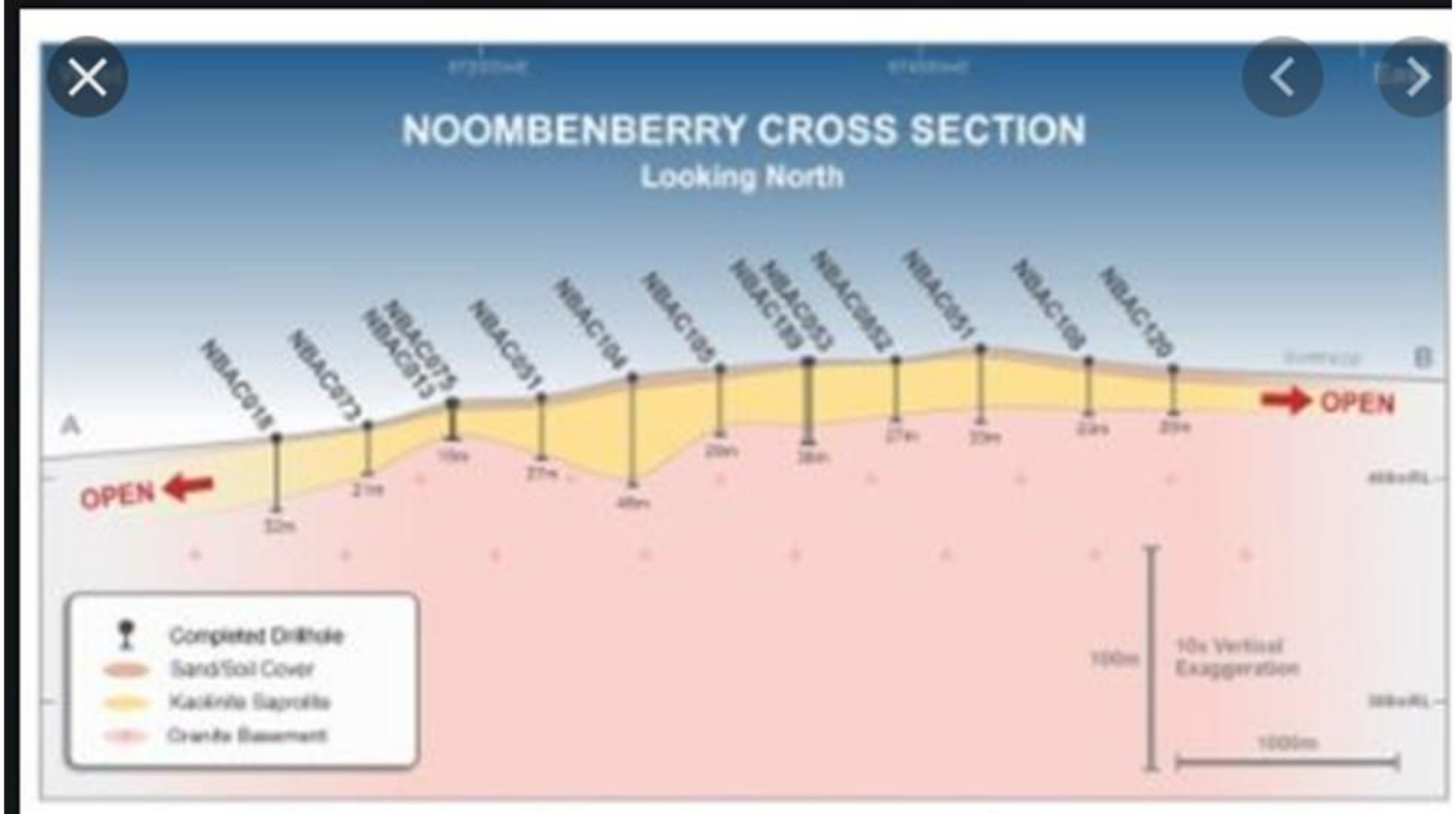


Figure 24: MSolo detailed visual schematic and CAD model modular diagram[45]



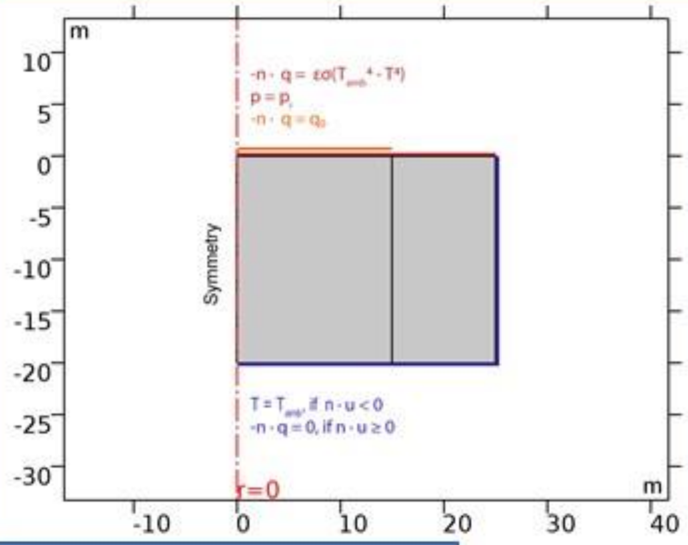


Cross Section 6,494,000mN, showing a representative simplified geological interpretation across the project area.

Poss terrestrial application of RASSOR tech –Kaolinite/Halloysite deposit Western Australia

Two models:
Experimental: 3D, small geometry, 4-5 hrs timeframes, validation of data, low vacuum, >93K

Theoretical: 2D-axisymmetrical, large geometry, week-long timeframes, ultrahigh vacuum, >40K

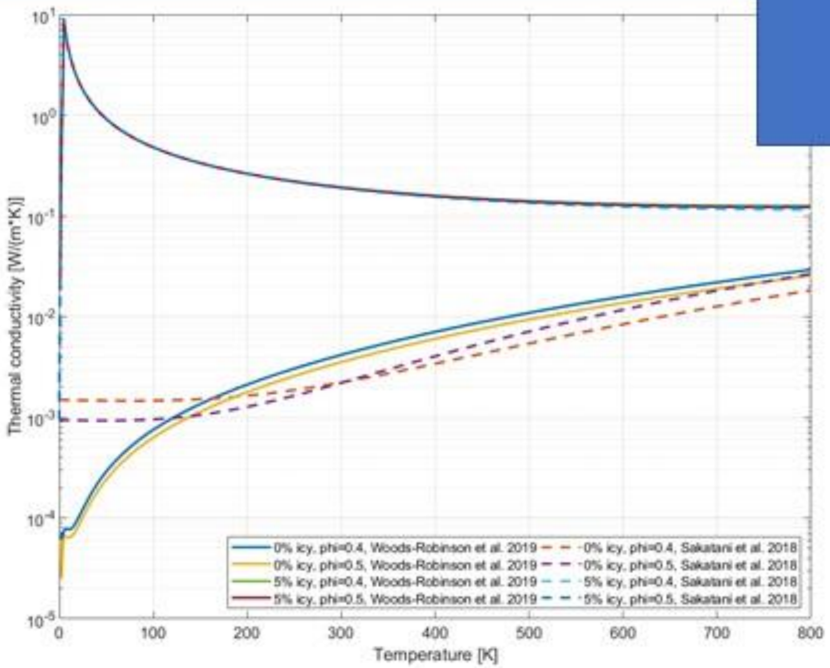


T. G. Wasilewski, et al., 2021, "Experimental investigations of thermal properties of icy lunar regolith and their influence on phase change interface movement," Planetary and Space Science 200

T. G. Wasilewski, 2021, "Lunar thermal mining: phase change interface movement, production decline and implications for systems engineering," Planetary and Space Science 199

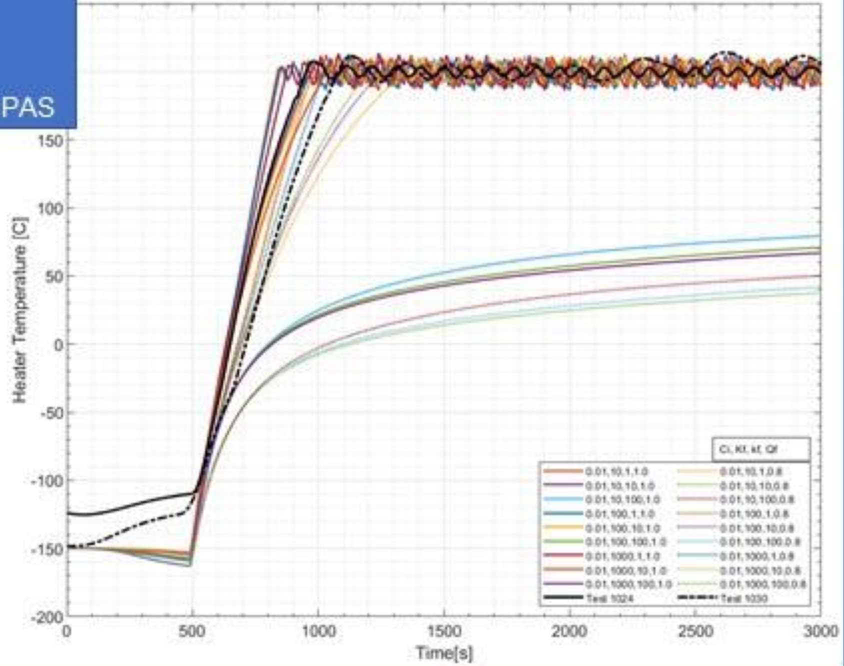
Simulations of lunar thermal mining
experiments and models

T. G. Wasilewski, Space Research Centre PAS

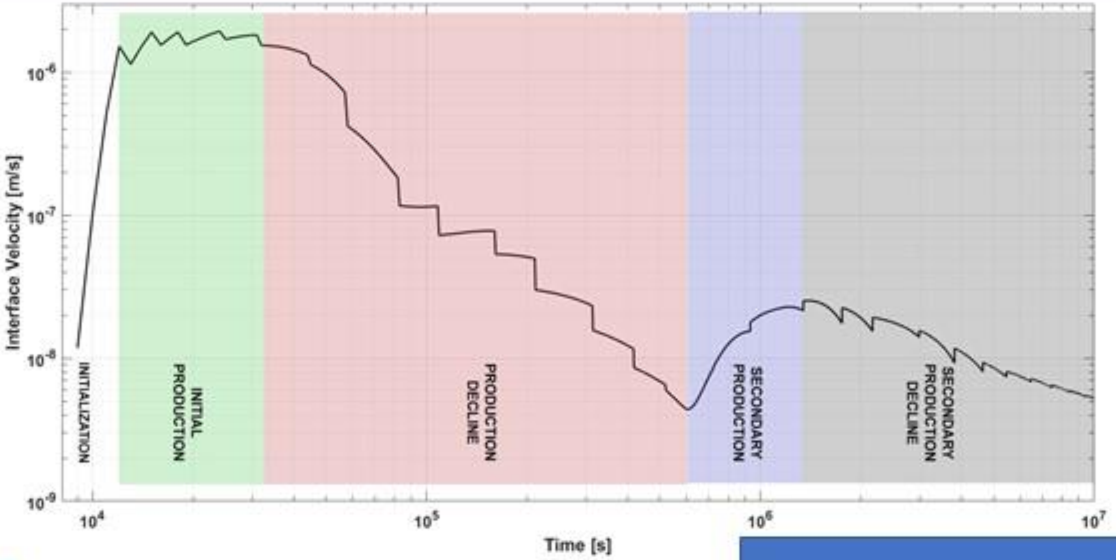


Each physical property of materials in the model is highly variable, which renders solution non-linear. Most previous studies use averaged values.

Highly variable results, very sensitive to changes in **ice content**, **permeability**, **dry conductivity** and **heat input**

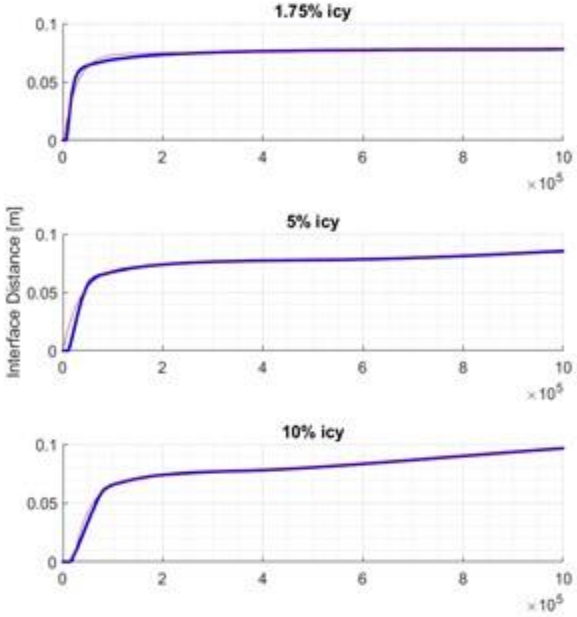


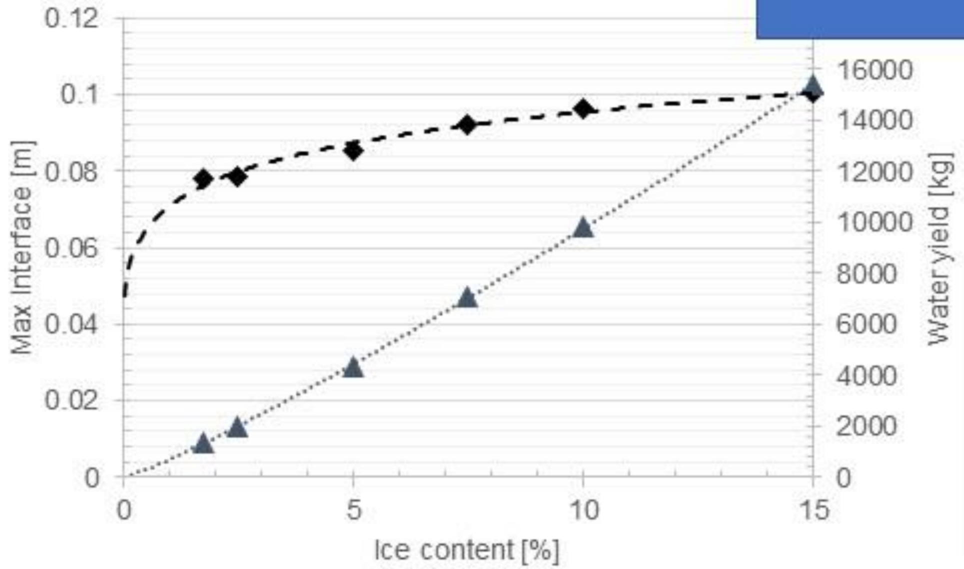
Simulations of lunar thermal mining
experiments and models



5 distinct production phases similar to terrestrial production systems

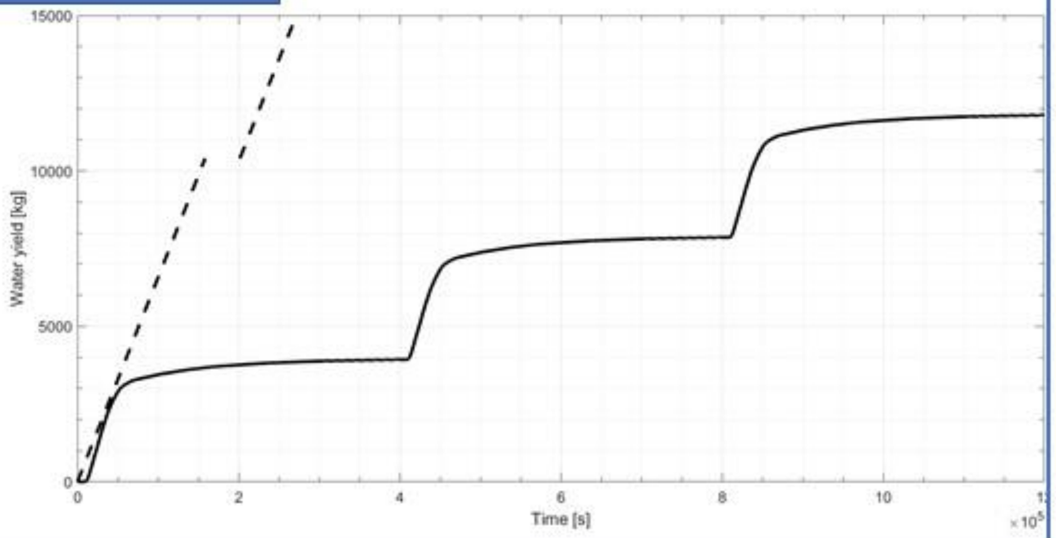
Change of rate of production in terrestrial systems is caused by **decline of reservoir pressure**. In case of lunar thermal mining, similar change is caused by **decline of thermal conductivity**





Thermal mining business case requirements are hard to reach

Sublimation lag removal is a reasonable strategy to improve process performance



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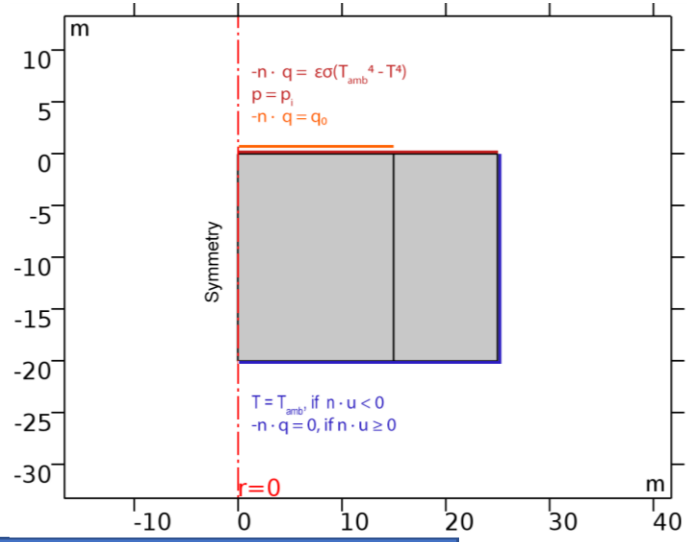

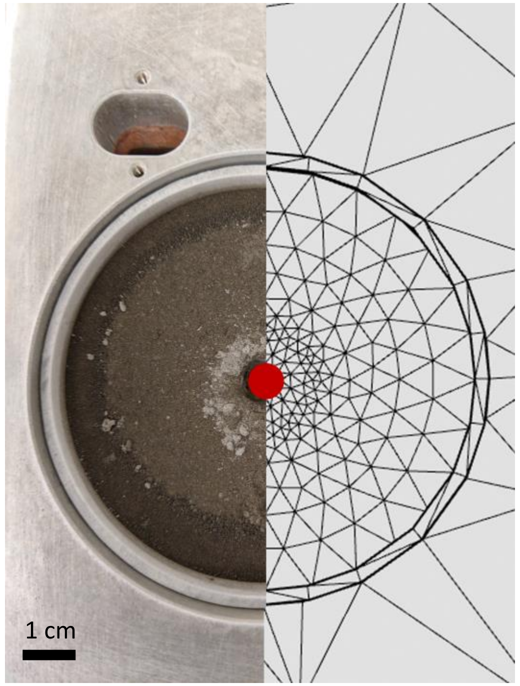

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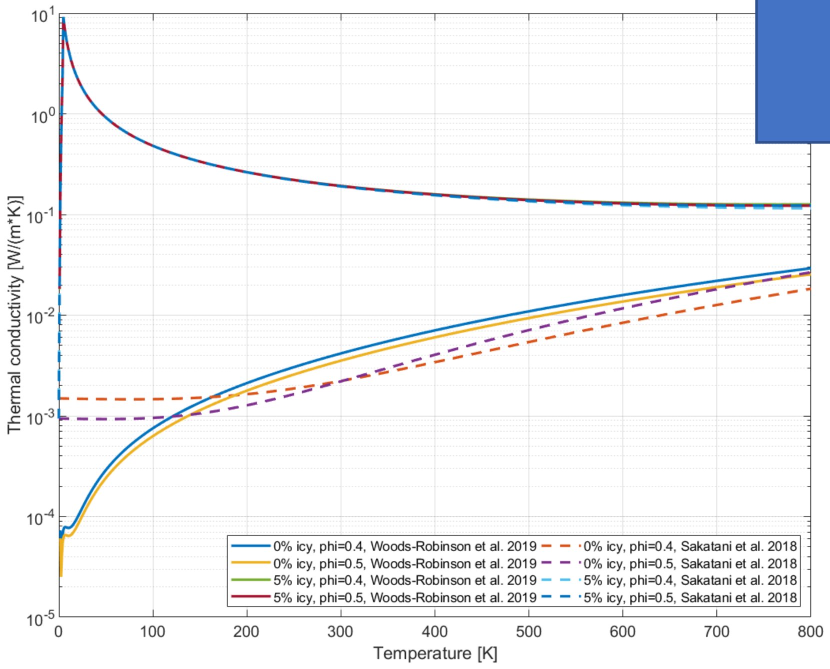

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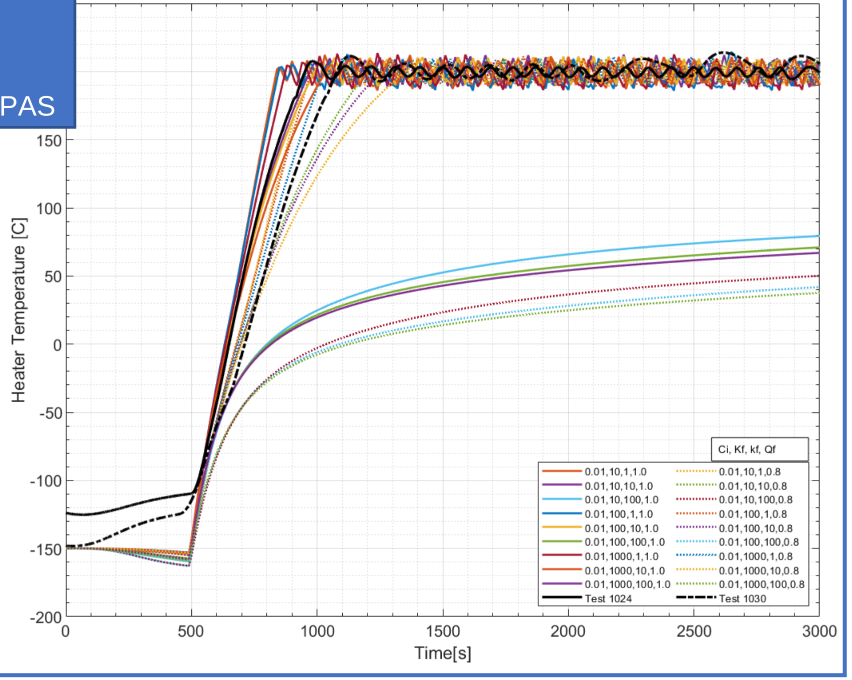

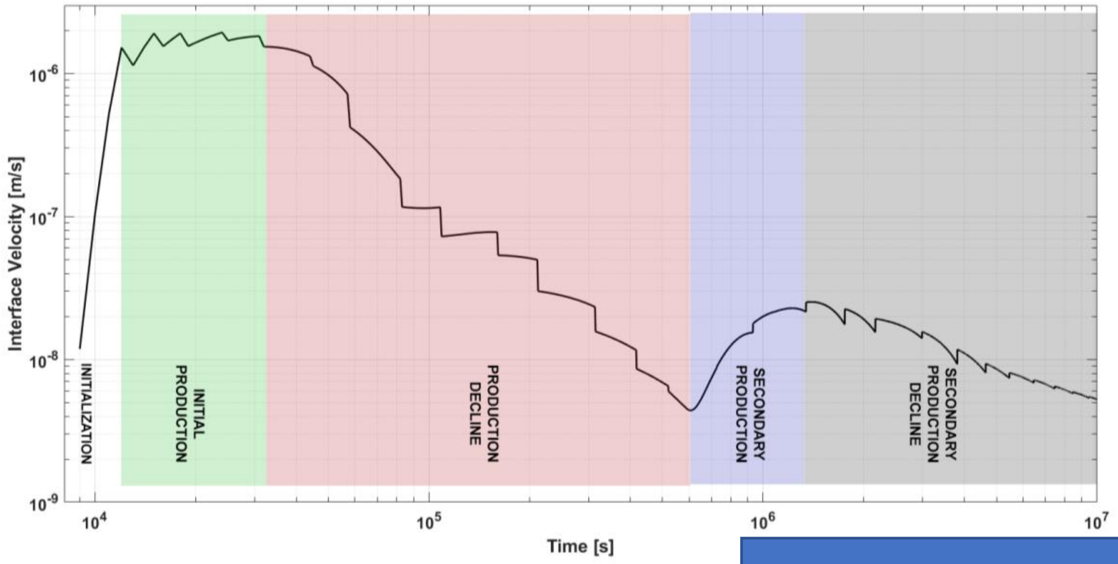

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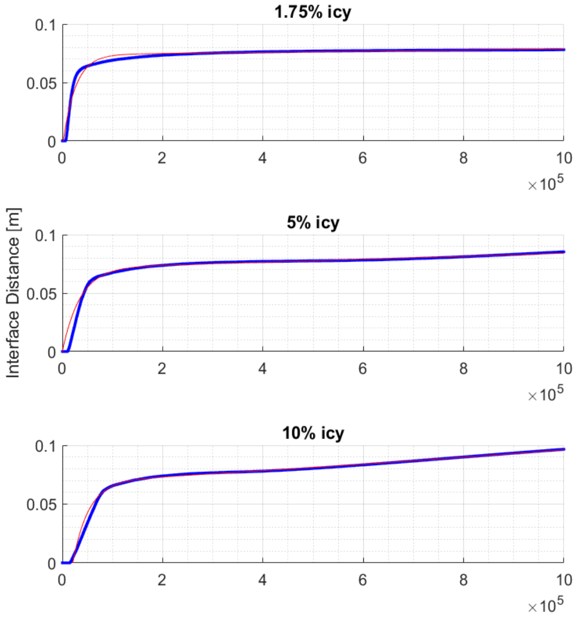
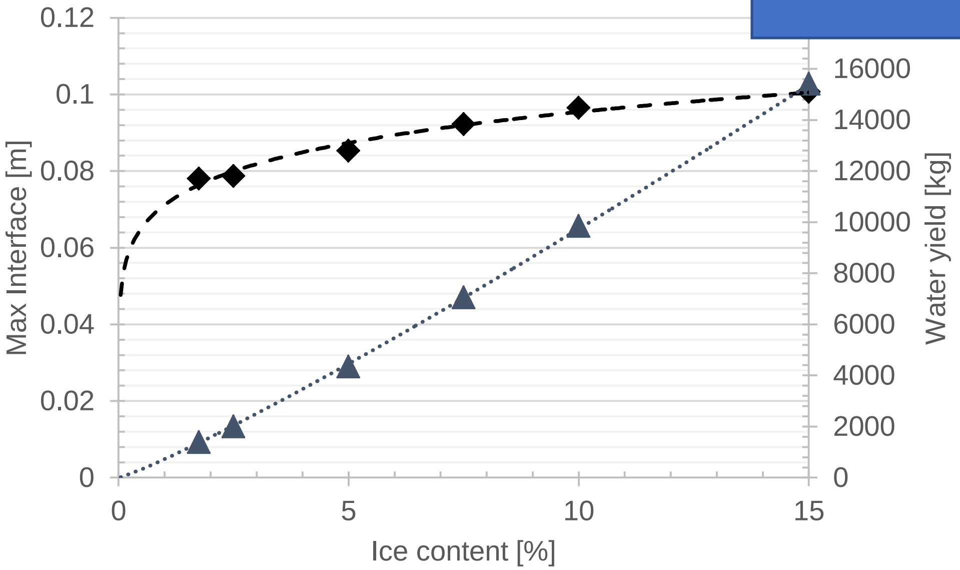


Simulations of lunar thermal mining
experiments and models

Sublimation lag removal is a reasonable strategy to improve process performance



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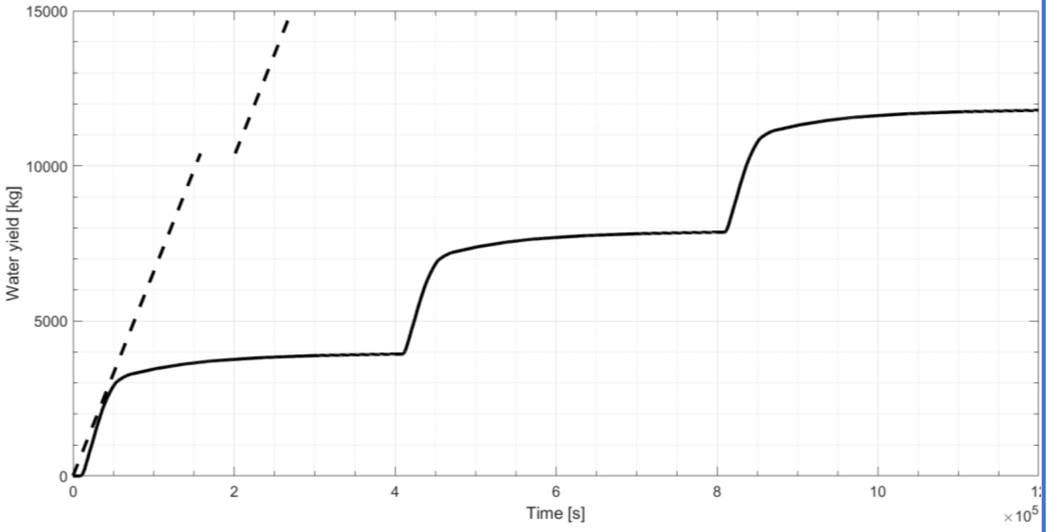


PTMSS Planetary & Terrestrial Mining Sciences Symposium & Space Resources Roundtable

Hosted by the Canadian Minerals and Metals Plan Secretariat

The Canadian Minerals and Metals Plan | Le Plan canadien pour les minéraux et les métaux

Financé par Ressources naturelles Canada | Funded by Natural Resources Canada | Canada

Virtual 2021

Lunar Construction

THE BASICS OF CREATING A MICROWAVE-BASED CONSTRUCTION SYSTEM FOR THE MOON.

Doug Rickman[1], Martin B. Barmatz[2], Ralph W. Bruce[3], Michael R. Effinger[4], William F. Kaukler[5], and Holly S. Shulman[6], [1]Jacobs Space Exploration Group/NASA Marshall Space Flight Center, Huntsville, AL, 35812 USA. <doug.rickman@nasa.gov>, Corresponding author, [2]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, M/S 79-24, Pasadena, CA 91109-8099 <martin.b.barmatz@jpl.nasa.gov>, [3]RWBruce Associates, LLC, Joelton, TN 37080, <ralph.w.bruce@Vanderbilt.Edu>, [4]NASA Marshall Space Flight Center, ST14, Huntsville AL 35812 <michael.r.effinger@nasa.gov>, [5] Univ. of Alabama in Huntsville, Huntsville, AL 35899 <william.f.kaukler@nasa.gov>, [6] DrHollyShulman, LLC, Belmont, NY 14813 USA <shulmanh@alfred.edu>.

Introduction: As a lunar application, NASA is developing a system capable of sintering the lunar regolith. Microwaves will be used to do the heating. The project, called Microwave Structure Construction Capability (MSCC), lead from Marshall Space Flight Center, involves multiple NASA centers, professors at multiple universities, and private companies. The current conceptual use of the technology is to produce a landing pad, for repeat visits to a site, and to construct other infrastructure to reduce mechanical elevations of "dust" to protect the astronauts and functionality of systems. Our current ambitions and working schedules aim to have a TRL 6 demonstration by 2022, test demonstrations on the Moon in 2026 and 2028, with deployment of a working unit in 2030.

While the concept of using microwaves to heat the lunar regolith can be traced in the literature back to 1969, and multiple people have heated lunar simulants in kitchen-type microwaves and small sample size experiments, it appears the current NASA effort is the first to seriously attempt to scale-up this concept into reality.

In so doing, a very large number of technical issues have been identified and must yet be solved. This paper will discuss some of the main challenges identified so far. We will not seek here to identify or to state possible solutions to the problems enumerated. It will be apparent from this paper, that reporting solutions to these issues will require a large amount of work and will need to be reported in a corresponding suite of publications.

How you think about a problem determines the answer you get: We suggest that possibly much of the previous work did not adequately think about the problems involved. Here we offer two points that are fundamental to how our approach to this project is framed.

Sintering vs. Melting. Melting lunar regolith or lunar regolith simulants is known to be rather easy in a microwave cavity. Therefore, producing a lunar glass on the Moon will be relatively easy. But using such melted material on the Moon requires solving fierce technical problems that, at this time, may not be solvable. For example, pickup, pre-processing, intakes, reaction vessel(s), outflow, forming, tempering to avoid cracking, handling, deposition on the lunar surface at temperatures of -170℃ are all tasks that have never been demonstrated on the Moon. Each represents an unavoidable technical hurdle, and for sintering to be useful, all must be solved. Concurrently, the solutions must work without human maintenance while processing thousands of kilograms of product. Sintering regolith in place avoids most of these problems completely. Of course, other problems arise.

For this paper, as a practical definition, sintering is said to be a process that liquifies less than 50% of the total mass; above that threshold, a melt is considered to exist. As a consequence of sintering, at least half of the original mass is likely to retain many of its original properties, including mechanical properties.

Microwave vs. laser or solar heating. Several methods have been proposed to heat the regolith in order to achieve various engineering goals. Three frequently proposed methods are to use microwaves, laser, or focused solar radiation. In the absence of more complex engineering, such as feeding thin layers of regolith past elements supplying heating energy, the latter two are rendered problematic by the low thermal conductivity of the regolith. Sintering by radiant energy (focused solar for example) applied directly to *in situ* regolith will not be viable on the Moon, due to the super-insulation property. One could consolidate the regolith with focused solar energy or a laser by fully melting a pool on the surface that in turn consumes the powder beneath it by a diffusion process. But such a melt pool doesn't present a solution with capability for volumetric sintering. Microwave radiation avoids this problem.

Challenges: For a concept that has been discussed repeatedly for more than 50 years, the magnitude of what is not known adequately to permit engineering of a device is astonishing. For convenience, we will break this discussion in three, largely artificial groups.

Science Questions. We do not have sufficient empirical data or models to predict the sensitivity of microwave heating contribution to such things as: particle size, particle shape, particle composition, particle texture, particle temperature.

We know there are limitations to the simulants in their fidelity to lunar regolith. For example, all simulants from terrestrial, geologic, feedstocks include minor or trace amounts of non-lunar species. For JSC-1A these include clays, sulfur compounds, carbonates, and salts. The nature of these non-lunar phases varies with the origin of the simulant. Simulants that are completely synthetic fail to include the low levels of H_2O, CO_2, and SO_X that are present in the real lunar material. At what level do these minor differences become significant? We know experimentally the non-lunar trace phases are significant in JSC-1A.

Experimental Design. The biggest handicap to the design of the necessary experiments is the fundamental lack of high-quality simulants. We have sufficient experimental data to strongly suggest that simulant with lower Figure of Merit scores (Schrader, 2009) are likely to introduce artifacts that may confuse our engineering design. The estimated minimum volume of simulant needed to complete TRL 6 testing is approximately 6 tons. If the targeted lunar landing is in a highlands site, that requires more high quality, lunar highland simulant than has ever been made, so far as we are aware.

Engineering. Some of the engineering questions we face are inherent in the fact no one has ever made such a system, so there is limited prior art. As a result, we have to answer such obvious questions as: applicator design, horn vs. antenna, how many applicators and at what power levels, if multiple, what will be their individual performance specifications, duty cycles, impedance matching, hardware type and frequency: magnetron, solid state, or gyrotron?

We have also recognized a class of problems that initially might not be obvious but can be profoundly important. What will happen if the system is deployed over an area that has heat sensitive, “volatile” species below the surface? The system will of necessity generate very large amounts of potentially wasted heat. Besides the emitted IR there will be backscattered radiation. On the Moon how can we monitor what is going on inside the regolith? Sintering is a sensitive process.

Conclusions: By integrating a large team with highly varied backgrounds, and using close collaboration, the MSCC project is identifying and solving a large number of scientific and engineering problems inherent in the old idea of microwaving the lunar regolith. We have changed the standard approach from melting to a very restricted sintering. We have identified the knowledge gaps that must be filled before engineering can be completed. We have identified the engineering questions that require refined scientific knowledge.

MICROWAVE SINTERING: INITIAL SCALE-UP FOR LUNAR LANDING AND LAUNCH PAD CONSTRUCTION.
M. R. Effinger[1], R. P. Wilkerson[1], H. S. Shulman[2], J. Sanchez[3], Z.S. Roberts[4], D. L. Rickman[3], [4]Q.H. Otte, [4]A.J. King, W. Kaukler[3], J. F. Gerling[5], J. N. Huleis[6], D. J. Hoppe[6], R. W. Bruce[7], and M. B. Barmatz[6], C. W. Bahr[3], [1]NASA Marshall Space Flight Center (MSFC), ST14, Huntsville, AL 35812, michael.r.effinger@nasa.gov, ryan.p.wilkerson@nasa.gov, [2]DrHollyShulman, LLC, Belmont, NY 14813 shulmanh@alfred.edu, [3]Jacobs Engineering, Inc. Huntsville, AL, doug.rickman@nasa.gov, javier.sanchez@nasa.gov, [4]Radiance Technologies, 310 Bob Heath, Huntsville, AL 35806, quinn.otte@radiancetech.com, aaron.king@radiancetech.com, Zachary.roberts@radiancetech.com, [5]Gerling Consulting, Inc., Modesto, CA 95350, john@jfgerling.com, [6]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA, John.N.Huleis@jpl.nasa.gov, Daniel.J.Hoppe@jpl.nasa.gov, martin.b.barmatz@jpl.nasa.gov, [7]RWBruce Associates, LLC, Joelton, TN 37080, ralph.w.bruce@Vanderbilt.Edu.

Introduction: NASA and its partners endeavor to initiate construction of a permanent lunar base. In order to achieve this, mitigation of dust from rocket plumes landing and taking off on the Moon will be necessary to prevent interference with solar panels, machinery, instrumentation, and crew operations. A landing and launch pad will be one of the first infrastructure constructions to be built in-situ.

The only construction method with volumetric heating to sufficient depth providing adequate strength while using the least consumables/upmass to manufacture infrastructure is the use of microwave energy to sinter (densify) the lunar regolith. Additionally, microwave sintering has minimal dust creation during processing and minimal regolith preparation. Magnetron microwave sources have delivery hardware that are robust, durable, low maintenance and can be a common tool among many other applications (e.g., oxygen and hydrogen generation [1, 2], beneficiation [3], fusing/joining parts, and repairing structures.

NASA MSFC has assembled a large team, Microwave Structure Construction Capability (MSCC), within the Moon to Mars Planetary Autonomous Construction Technology (MMPACT) project, from other NASA Centers, industry, and academia to identify and overcome the many challenges in order to deliver a capability to construct a landing pad in the mid-to late 2020s [4]. The first demonstration mission is anticipated to be on the end of an arm operated from the lunar lander vehicle (See Figure 1).

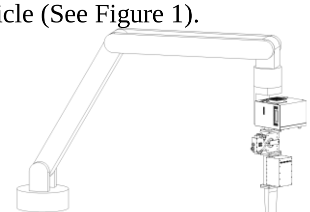


Figure 1. Magnetron demonstration design consideration that could be mounted to the landing vehicle.

The Olympus team within MMPACT is responsible for other construction aspects not related to the microwave sintering [5]. The specific lander has not been chosen yet for this mission. In order to develop requirements for the remote mobility arm with microwave sintering capability, initial testing, design, and analyses need to be conducted to downselect the microwave source & determine operational parameters.

Materials: Accurate highlands simulant have not, until recently, been produced in the USA since NU-LHT-2M was released more than ten years ago. Therefore, JSC1-A was used for initial testing and procedure development. The MSCC team now has limited access to the new NU-LHT-4M, so that will be used sparingly. To understand and anticipate behavior of various minerals in the lunar regolith in new locations, synthetic mineral equivalents will be developed and characterized. Any production of such would be the role of another project within NASA.

Testing: Testing will provide inputs to models and help define requirements and the concept of operations.

Simulant Tests The physics of microwave interaction with the simulant, which results in heating and sintering, is complex. Therefore, details of the simulant that heretofore have not been characterized have to be measured and evaluated. Thermal Gravimetric Analysis (TGA) in vacuum is one example of such a test for simulant JSC-1A (see Figure 3a).

a) b)

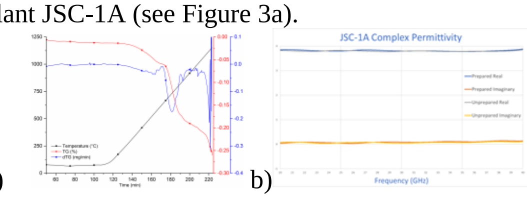


Figure 3. a) TGA b) Complex Permittivity

Samples of JSC-1A were analyzed using a focused-beam test stand and a two-port network analyzer in order to compute the complex permittivity of the material using the reflection and transmission S-parameters across a wide band from 20 to 40 GHz (see Figure 3b). Across the measured band, the real permittivity is approximately 3.8, and the imaginary permittivity is 0.05 to 0.1. These results indicate that the material has moderately low loss with no peak absorption frequency from across the measured band.

Sintering Tests The impact of such variables as particle size, particle shape, composition, glass fraction, and packing density all have to be understood and quantified to predict and control the behavior in the microwave during heating and sintering. The interaction of the simulant with the testing environment is important. For example, in certain frequency/temperature domains, the simulant can be transparent to the microwave energy and therefore interactions can occur with the boundaries of the test facility. This complicates understanding of experimental results. Strategies must be developed to eliminate or subtract this type of interference. These aspects are being examined in in a thermal vacuum chamber (see Figure 4).

a)  b) 

Figure 4. a) Microwave sintering in thermal vacuum chamber. b) First sintering example in air.

Design, Modeling, & Analyses: Power availability will drive many design decisions for early demonstration missions. Olympus is conducting analyses to determining the power availability for MSCC. While a power requirement is being established, that leaves room for several design options such as a waveguide or coaxial delivered microwave energy. Additionally, several applicators are being considered as well.

Applicator & Microwave coupling. Heating of simulant requires radiating device (the applicator) designed which can efficiently transfer the electromagnetic energy into the material. This requires a fundamental understanding of the electrical characteristics (permittivity/dielectric constant and dielectric loss tangent) of the simulant as well as how these parameters vary with temperature. Controlling the power deposition, scan rate (for making large horizontal structures) and depth of penetration (to insure sufficient mechanical strength) are several of the challenges that are to be solved.

Modeling of microwave applicators for regolith heating is also underway. Coupled Radio Frequency (RF) and thermal models that consider temperature-dependent RF and thermal properties are necessary to determine the figures of merit for the system, such as sintering depth and efficiency (CCs sintered per Joule). Two different modeling approaches are employed to allow for cross-checking of results.

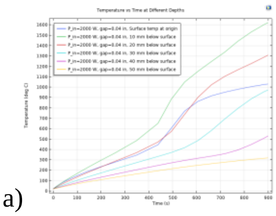
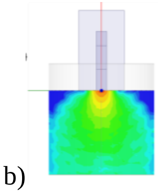
a)  b) 

Figure 4. a) COMSOL non-linearity of heating over time illustrates the change in dielectric properties with temperature. b) HFSS RF model in vacuum above the simulant and is enclosed in a radiation boundary condition, allowing any reflected energy to radiate into the space above the regolith. The frequency of operation is 2.45 GHz.

Microwave energy source. Current emphasis for developing the processing protocols relies upon a magnetron-based source. A magnetron is a vacuum tube device that was originally developed in its current form in the late 1930's finding wide use during World War II. This is a very well-known microwave source (i.e. home microwave oven) that has been shown to be very reliable with a high Technology Readiness Level. Other sources, e.g. Solid-State Power Amplifiers (SSPAs), are also being considered. While SSPAs have not had the experience level in high-powered (> 1kW) space-based applications, they offer useful advantages over magnetron-based microwave energy sources with regard to operating life, power supply requirements, and frequency agility. Methods being considered for microwave power transmission include rectangular waveguide and coaxial line, the configurations for which depend on the chosen microwave energy source and design constraints for construction machinery.

Summary: MSCC is a large team including government, industry, and academia that is scaling up microwave sintering approaches in order to construct horizontal infrastructure on the Moon. Future work will include developing microwave sintering-specific, site preparation hardware and operations concepts, microwave operations concepts, sintered simulant mechanical and thermal property testing, non-destructive evaluation, and process and product instrumentation development. Refinements on microwave design and modeling will also occur.

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Overview of NASA's Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT) Project,

R. G. Clinton, Jr.[1]
[1]NASA Marshall Space Flight Center, Science and Technology Office, ST01, MSFC AL 35812.
raymond.g.clinton@nasa.gov

NASA's Artemis Program is a two-phased plan to send American astronauts back to the Moon and to develop the capabilities for long term presence on the lunar surface. In Artemis Phase 1, NASA plans to land the first woman and next man on the Moon by 2024. In Phase 2, NASA and its international partners plan to create the infrastructure necessary to enable a sustained long-term presence on the lunar surface. NASA's Space Technology Mission Directorate (STMD) has formed Lunar Surface Innovation Initiative (LSII), which aims to spur the creation of novel technologies that will be needed for lunar surface exploration and to accelerate the technology readiness of key systems and components. The primary thrust areas of LSII include the following: sustainable power; dust mitigation; in-situ resource utilization (ISRU); surface excavation and construction; and extreme access/extreme environments.

NASA's Marshall Space Flight Center has formulated the Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT) project in partnership with other Government organizations, multiple academia, and industry organizations, and with the Jet Propulsion Laboratory and Kennedy Space Center. MMPACT was initiated to address the lunar surface construction thrust area of LSII. The goal of the MMPACT project is to develop, deliver, and demonstrate on-demand capabilities to protect astronauts and create infrastructure on the lunar surface via construction of landing pads, habitats, shelters, roadways, berms and blast shields using lunar regolith-based materials.

The ability to excavate, convey, and beneficiate large quantities of lunar regolith for construction materials is key to the successful development of infrastructure at scale. An early projection of lunar regolith materials needed for a 100 foot diameter landing pad was estimated at several hundred tons. Transportation of that quantity of materials, or even binders for the regolith, from Earth would be extremely costly and impractical as Artemis proceeds into Phase 2 with multiple infrastructure elements required on the surface such as the aforementioned landing pads (multiple), roadways, habitats, shelters, storage facilities, etc. While there are multiple constituent materials in lunar regolith that could serve as binder materials for raw regolith such as calcium, sulfur, aluminum, magnesium, and others. the ability to produce these materials in sufficient quantities from the raw regolith will require time. For these reasons, MMPACT is also evaluating directed energy methods, such as microwave sintering, laser sintering, and high temperature methods for melting and sintering regolith.

The MMPACT project is leveraging technology derived from NASA's 3D Printed Mars Habitat Centennial Challenge. Space Exploration Architecture, winners of two phases of the design element of the Habitat Challenge, are developing design concepts for lunar infrastructure and ICON, a finalist in the construction element of the Habitat Challenge, is leading the development of the construction hardware. The construction hardware development effort was initiated through a Small Business Innovative Research (SBIR) competitive selection in which NASA partnered with the Air Force. Multiple common key functional capabilities for military, commercial and space applications were identified, including dust mitigation, field reparability, remote operations, increased autonomy, etc., and serve as focal areas of the effort.

The MMPACT project is comprised of three interrelated elements, hardware and process development; construction feedstock materials development; and microwave structure construction capabilities. These elements are working together to address the multiple challenges of infrastructure construction on the surface of the moon including hardware operation and manufacturing under lunar environmental conditions, long-duration operation of mechanisms and parts, scale of construction activities, and material and construction requirements and standards.

This presentation will include an overview of the status of the development activities in each of the three elements, preliminary design concepts for future lunar infrastructure elements, and the vision for future technology demonstrations on the lunar surface. These demonstrations, targeting the mid-to-late 2020's, are expected to enable landing pad construction, habitat construction and commercial construction capabilities early in the next decade.

TRADE STUDY OF TECHNIQUES TO BUILD LUNAR LANDING PADS. Philip T. Metzger, Florida Space Institute, University of Central Florida, 12354 Research Parkway, Orlando, FL 32826, philip.metzger@ucf.edu.

Introduction: Landing pads will be necessary to mitigate the blast effects of landing and launching rockets on the airless Moon. As part of the Robotic Lunar Surface Operations 2 (RLSO2) study [1], the author performed a trade analysis of several candidate landing pad construction technologies. The study assessed the requirements for a pad that would prevent all ejecta from a 40 t (landing mass) vehicle. It evaluated the mass of hardware and consumables that must be delivered to the Moon, the energy required to construct the pad, and the time required to complete construction. The landing pad for this case study was 27 m diameter. The inner 12 m diameter disk must withstand high temperature stagnation of the plume and prevent gas diffusion, while the outer region must prevent erosion from shear stress of the gas. This study is updated and extended, here.

Candidate Technologies: The trade study focused primarily on (1) microwave sintering in-place across the surface, (2) sintering of pavers or bricks in an oven then robotically installing them, (3) application of polymer (palliative) into the soil, and (4) collection and sorting of rocks and gravel of different sizes to construct a size-layered “breakwater” [2]. The trade did not include solar sintering because prior efforts had not yet demonstrated ability to print thick layers and progress is needed to prevent delamination. It did not include luanr concrete due to the need for water, which is too valuable to waste, and progress is needed to demonstrate a concrete that recovers and recycles water in the lunar environment. Several other methods have been proposed but were not assessed since the technology readiness level is still low for each.

Methodology: The literature was reviewed for candidate technologies to determine reasonable estimates of hardware mass and consumables, energy requirements, and speed. Each method includes grading and compacting the soil as a sublayer to the landing pad. The time and energy of these processes were included in the sums. The data were written into a spreadsheet form so individual parameters can be modified and all calculations automatically updated. For example, changing the radius of the inner pad would automatically update the expenses for all candidate technologies. Physics-based equations were embedded in the calculations where appropriate. For example, it uses heat capacity of lunar soil to calculate the energy required from microwave sintering. An example of the spreadsheet is shown in Fig. 1.

	Rovering, Grading, and Compacting			
Basic data	Grading rate	10	s/m2	
	Compacting rate	20	s/m2	
	roving energy per m per kg	2.5	J/m/kg	Note 4
	Width of grader blade	1.5	m	
	Blade force	400	N	Note 5
	Energy to push blade	0.111111	kWh/m	
	Energy to grade	0.527778	kWh/m	
	Energy to compact	0.520833	kWh/m	ROM
Outer Area	Grading outer time	5.105088	hrs	
	Compacting outer time	5.105088	hrs	
	grading outer energy	0.638136	MWh	
	compacting outer energy	0.17726	MWh	
Inner Area	Grading inner time	1.256637	hrs	
	Compacting inner time	2.513274	hrs	
	grading inner energy	0.15708	MWh	
	compacting inner energy	0.043633	MWh	
Equipment	rover mass (empty)	300	kg	
	compactor	200	kg	
	grader blade	300	kg	

Figure 1. Example of the user interface in the trade study spreadsheet.

In the new work, the equations were inputted into Mathematica to enable repetitive testing with different parameter values. Detailed microwave susceptibility and heat capacity equations were programmed into the Mathematica version as shown in Fig. 2 to enable full simulations of sintering to obtain realistic energy and construction time values as a function of pad thickness.

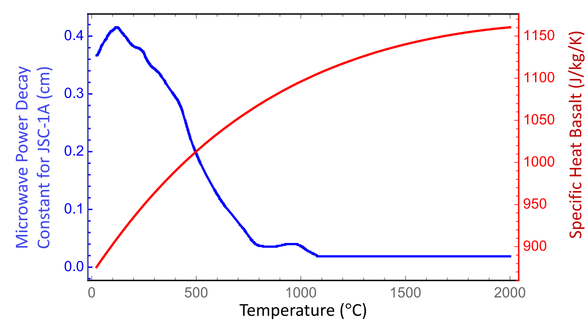

Figure 2. Blue: microwave absorption property of lunar soil simulant JSC-1A at 2.45 GHz following [3] but extrapolating for T>1100 °C. Red: specific heat of basalt following [4].

Results: The inner region of the pad can be sintered (Si) or pavers (Pa). The outer region can be sintered, pavers, gravel (Gr), or polymer (Po). In each pair the inner region is listed first, e.g., SiPo. Each method can be scaled-up with more equipment to work faster, requiring greater power to operate simultaneously although total energy to complete the job is the same. Fig. 3 shows the relationship of total mass (equipment plus consumables in the case of Po) versus power. Fig. 4 shows construction time vs. total mass.

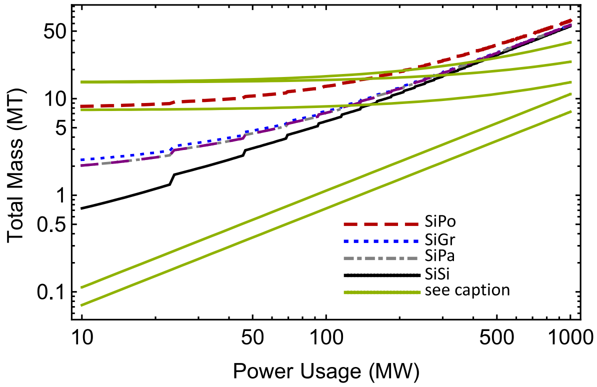

Figure 3. Scale-up of mass and power for nine construction methods. Green, top to bottom: PoPo, PoGr, PaPo, PaGr, PaPa. Inner pad Po shown for reference though not included in the entire analysis due to concerns over polymer breakdown at high temperature.

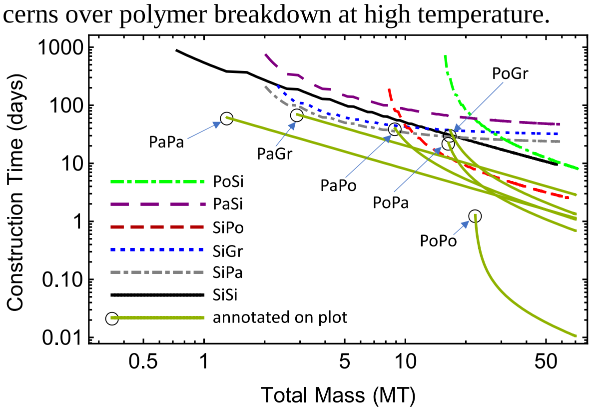

Figure 4. Contruction time vs. total mass for 12 construction methods. The circles represent the starting cases for six, with green curves showing their scale-up.

A cost metric was developed including estimates ost of hardware development per [5], transportation cost to the lunar surface, energy cost based upon the historic cost of space solar power systems including their transportation to the Moon, operations cost during construction, and a delay cost that accounts for some construction methods taking longer than others resulting in varying delay of the benefits of lunar surface activity. These were calculated using a discount rate of 3.5% as typical of the federal cost of money. The energy cost is the fraction of the yearly energy value that the construction consumes. The delay cost is the total program value as determined by Congressional funding in equal appropriations over 20 years converted to present value then delayed at the discount rate. Without optimizing individual construction methods, the costs are shown in Fig. 5.

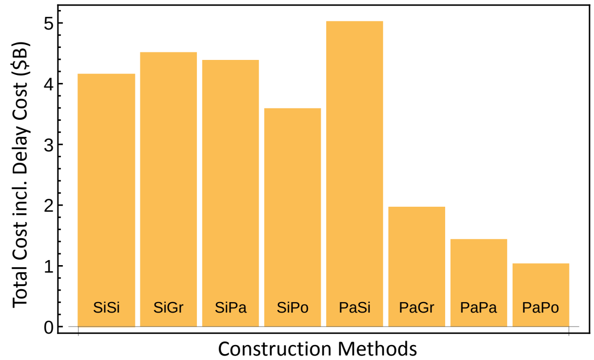

Figure 5. Total cost of reference cases.

Next, each technology in each pairing was individually scaled up or down to minimize its cost metric. This produced completely different results (e.g., Fig. 6). This demonstrates that a trade study is not valid unless scale-optimization is included. For example, SiPo originally seemed non-competitive (Fig. 5), but after optimization it is the most competitive choice. The economic assumptions were varied over a wide range: lunar transportation costs between $1Mv/kg and $300/kg, and program delay costs between zero and $50B. The optimized results were not sensitive to the variation in values. Additional trades were made incorporating expected improvements in sintering by modification of the soil (not shown here), which makes SiPo by far the leading candidate, in addition to being the simplest and most robust.

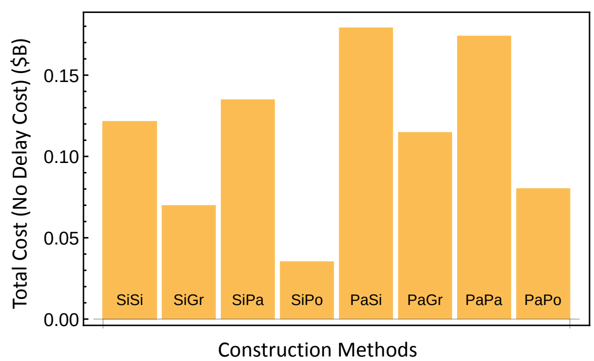

Figure 6. After optimization, with cheap transportation and no delay cost

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LARGE VEHICLE LUNAR LANDING SURFACE INTERACTION AND IN-SITU RESOURCE BASED RISK MITIGATION. R. P. Mueller[1], N. J. Gelino[1], K. L. Dixon[1], B. T. Vu[1], and L. Sibille[2], [1]National Aeronautics & Space Administration (NASA), Kennedy Space Center, Swamp Works, M/S: UB-E-2, KSC, Florida 32899, [2] Swamp Works, Southeastern Universities Research Association (SURA), LASSO-013, Kennedy Space Center, FL 32899, USA

Introduction: A key capability required for the exploration of planetary bodies is the ability to land on the surface. Previous work performed by NASA and other institutions has primarily focused on landing small spacecraft on planetary surfaces and the associated small-to-medium thrusters required for the soft landing. In the case of human exploration—particularly the establishment of long duration exploration and habitation outposts—the ability to land large landers, such as the SpaceX Starship, is necessary.

These larger landing systems require the use of more powerful engines, with higher temperature engine exhaust and higher landing loads. Understanding the excavation of material by the engines, as well as the potential for the landing legs to sink into the subsurface, is key in ensuring reliable and safe landings. A further improvement in landing reliability can be achieved by constructing landing / launch pads, especially with in-situ resources.

Computer Modeling & Test Campaign:

Using a large chemical rocket engine for landing on the Moon and Mars will result in the plume rapidly expanding (due to an under-expanded nozzle), in effect resulting in a large fan of exhaust gas rather than a collimated stream. This condition is quite different from what has been previously studied (Figure).

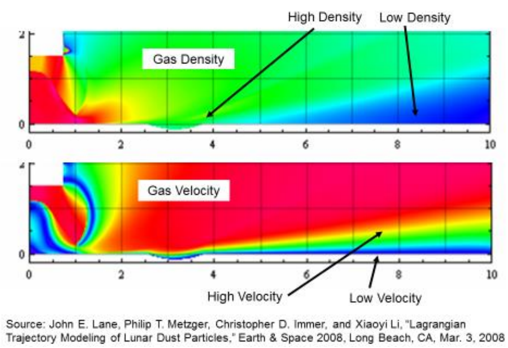

Figure 1: Lunar regolith plume surface interaction ejecta modeling [1]

Looking at plume surface interaction (PSI) more holistically, the details of the landing profile may also affect the plume interaction. To optimize landing-propellant usage, a higher thrust with a shorter duration landing profile is preferred. Understanding the effect of this type of landing compared to the lower rate of descent (and thus longer pressure and heat load profiles exerted on the surface) is of interest.

These differences in the rapidly expanding plume from the under-expanded nozzle, the very high plume temperature, the unique landing profile, and the high thrust will result in surface effects, including plume induced excavation, that are distinct from what has been studied so far. Some material excavation by the plume is inevitable, leaving at least a portion of the surface scoured and uneven under the lander and ejecting regolith particles and rocks at very high velocities.

One possible solution would be to robotically build landing / launch pads (ideally autonomously) at the destination using in-situ materials. In this case, the first one or few landers will need to land on unimproved surfaces at higher risk; however, they would bring the required equipment to build the landing pads with mostly local resources, thus increasing the reliability of safe landing for subsequent larger landers. A number of methods to build in-situ landing and launch pads have already been developed. These methods have various levels of required binder additives to the local regolith material, methodologies and resulting landing pad strengths. A simulated subscale rocket engine plume, analogous to that of landing on the Moon was used to assess the effectiveness of an in-situ built landing pad, The GO2/CH4 rocket engine fired on 1m x 1m coupons of representative pad materials. The results will allow continued development towards materials that satisfy the landing pad properties required for the effective risk reduction and increased reliability for landing people and equipment on planetary surfaces.

This work contained two parts: (1) computer modeling of a large rocket engine plume interacting with regolith on the Moon, using the Granular Gas Flow Solver (GGFS) provided by CFD Research Corporation as well as other computational fluid dynamics codes (CFD) such as Loci/CHEM. (2) Developing landing/launch pad materials that could be used for in-situ construction on the lunar surface in the future, to mitigate the calculated effects of a large vehicle rocket engine landing and launching on the Moon.

The resulting values of plume impingement surface temperature, stagnation pressure, gas velocity, shear stress and heat flux were then matched as closely as possible in the Earth's atmosphere in a sub-scale rocket engine GO2/CH4 test which was provided by Masten Space Systems in Mojave, California. The rocket engine was mounted on a test stand with vertical translation capabilities so that the landing operations of a lander could be simulated (Figure 2).

Figure 2: Masten Space Systems Rocket engine vertical translation test stand

The pad materials test coupons were placed in a regolith bin containing simulated basalt lunar regolith granular material and subjected to a test firing as shown in Figure 3.

Figure 3. Regolith bin with pad material coupon under the rocket engine test stand

After a large selection of concepts was examined and ranked [3], five types of materials coupons were tested:

- Sintered Hawaiian basalt pavers [2]
- Ablative polymer regolith mix pavers
- Anorthosite rocks in Gabion cages
- High temperature textile regolith bags
- High temperature textile blankets

The results of this testing will be presented at the 2021 Planetary & Terrestrial Mining Sciences Symposium (PTMSS) / Space Resources Roundtable (SRR) with related findings and discussions. (Figure 4).

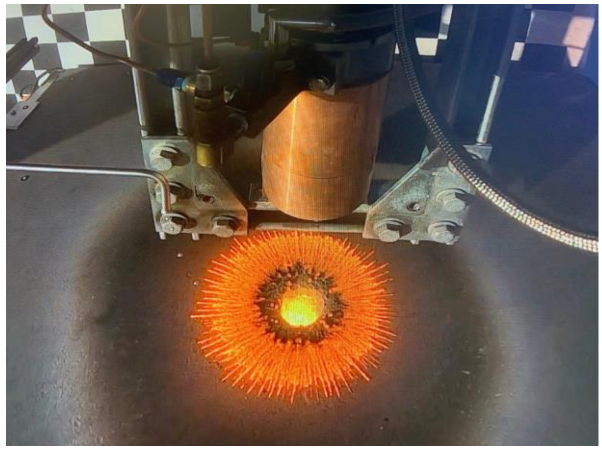

Figure 4. Ablative Polymer Regolith paver shortly after rocket engine testing with a collimated plume which is more severe than a lunar vacuum scenario

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CONCEPT DEMONSTRATION OF A SURFACE SAMPLING TOOL FOR LUNAR SAMPLE RETURN MISSIONS. T. Lamarche[1], N. Jackson[1], P. Allard[1], D. Gingras[1], M. Picard[1], [1]Canadian Space Agency, 6767 route de l'aéroport, Saint-Hubert, Québec, J3Y 8Y9, Canada, E-mails: firstname.lastname@canada.ca

Introduction: The Canadian Space Agency (CSA) Lunar Exploration Analogue Deployment (LEAD) and the European Space Agency (ESA) Human Operations Precursor Experiments (HOPE) projects collaborated to conduct two joint mission simulations in 2017 and 2019, emulating various segments of the Human Enhanced Robotic Architecture and Capability for Lunar Exploration and Science (HERACLES). The 2019 LEAD/HOPE focused on having operators carry out a HERACLES-inspired lunar sample return mission [1] using a CSA rover [2]. Among the various tests conducted, a rover-based system to robotically acquire, handle, and deliver rocks and soil samples to a lander/ascent vehicle was demonstrated [3]. A key element of this concept is a miniature excavator-type sampling tool described herein.

Background: The target scenario includes a lunar rover controlled from Earth to collect surface samples, operating under a 3 to 10 sec. (round-trip) communication delay with limited bandwidth, constraining the amount of situational awareness data that can be transmitted and precluding real-time operator-in-the-loop schemes. As a preliminary phase of geological exploration, this scenario called for three types of surface samples to be collected. Consultations with planetary geologists led to establish the minimal sample size requirements:

a. Loose regolith volume: > 25 cm³
b. Gravel size rocks: > 1 cm
c. Fist size rocks: > 5 cm

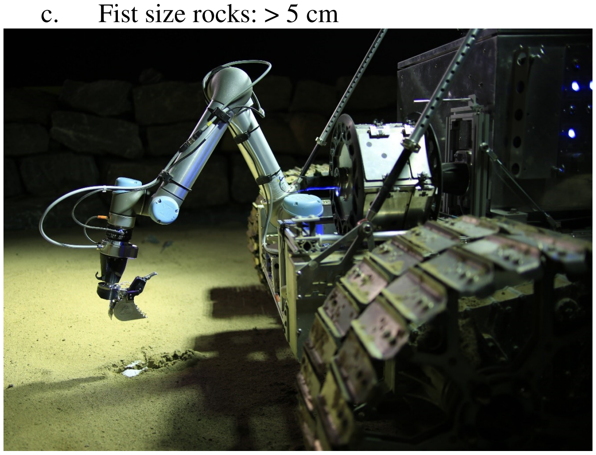


Figure 1: Sample Handling Subsystem on the rover

Sample Handling Subsystem (SHS): The SHS includes a robotic manipulator equipped with a custom scoop/gripper tool, as well as a dedicated sample canister. A set of on-board automated scripts, launched and monitored remotely by the operators, is used to acquire, store and ultimately deliver the samples to the lander/ascent vehicle. For more realism, the arm controller power draw is limited to 80 W and movements are performed at low speeds (typ. < 5 cm/s).

Scoop-Rake-Gripper (SRG) Tool: The SRG (Figure 2) is the end effector used to acquire rocks and soil samples. Its scoop can hold up to ~100 cm³ of loose soil and gravel-size rocks up to ~2 cm. An actuated thumb acts as a gripper to grasp rocks in the ~4 to 10 cm range. The narrow scoop has very sharp edges and teeth to maximize the ground pressure. This effectively facilitates excavation.

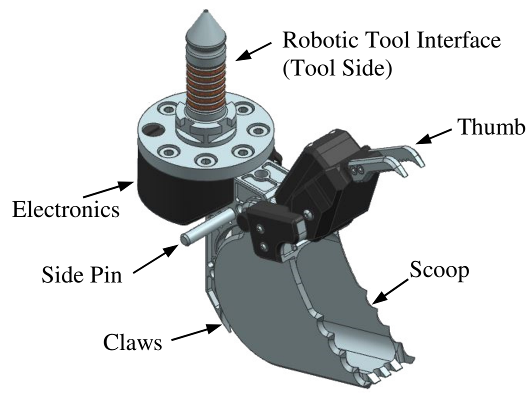


Figure 2: Scoop-Rake-Gripper (SRG) tool design

The scoop is fully passive, relying solely on the robotic arm's actuators to operate. Multiple features help prevent samples from remaining stuck inside the bucket: 1) The bucket is mounted on a spring-loaded pivot. The robotic arm can pivot the scoop then snap the bucket back to its nominal position by manoeuvring against a fixed surface. 2) The back of the bucket is made of flexible spring steel which deforms in the rest position to help expel the material. 3) The bucket geometry minimizes soil compaction when scooping. 4) An aluminum version of the bucket performed well, but stainless steel was used for the final prototype to reduce bucket to soil friction. These prototypes respectively weigh 332 g and 600 g, not including the Robotic Tool Interface (256 g).

The tip of the scoop can be used to rake the ground. The scoop's spring-loaded pivot facilitates the automated raking of uneven ground without adding control constraints on the robotic arm.

Sharp claws at the back of the scoop assembly are designed to break and rip harder consolidated soils, facilitating digging. This approach was inspired by excavator bucket designs used to dig permafrost.

A side pin serves to actuate other surrounding subsystems with the robotic arm, such as indexing the sample canister and closing its doors.

A small side brush proved useful to prevent issues with the sample canister door closure, allowing soil spills to be brushed away from the narrow compartments openings.

The thumb actuator is driven by a simple on-off (open-close) control scheme which only requires power during transitions between open and closed states. A spring-loaded contact switch embedded in the thumb is used to detect when the grasp is effective. This also provides automatic re-grasp behaviour if the rock moves and starts slipping away during manipulation. A lighter, simplified version could omit the thumb to make easier to build and qualify for space, but would remove the capability to pick up larger rocks.

Results: The LEAD 2019 mission simulation and characterization demonstrated that with minimal training, operators could remotely collect and store various rocks and soil samples, and transfer the sample canister to a lander using the SHS. Over the 2019 four-day campaign [2], the teams successfully collected two rocks and one soil sample through 1.59 km of traverses. It took on average 100 minutes from the initial rover alignment phase to the end of the sampling operation with the arm stowed. Subsequent tests run by operators more familiar with the SHS typically took 15 to 30 minutes to scoop soil and 20 to 45 minutes to grasp a rock, from rover alignment to end of operation (arm stowed) under a 10 sec. round-trip communication delay. Because every sample and its surrounding site is unique, deriving quantitative performance statistics remains challenging. A high rate of success has, however, been demonstrated. Failure cases typically succeed by tweaking the tool positioning and trying again, when time permits. The biggest challenge to address remains the assessment of rocks sizes from the camera views. While camera overlays enable the operators to get a good size estimate once a rock has been grasped by the SRG, assessing their sizes before manipulation proved to be difficult.

SRG Characterization: Following the LEAD simulation, additional functional tests of the SRG were performed in a variety of media. Forces required to excavate were characterized along with the depth achieved and weight of material collected. Rock handling, including collecting a specific sample of interest from a rock bed, was also demonstrated. The SRG was capable of retrieving a 120 g surface sample from frozen and compacted lunar simulant (CHENOBI) with 1.7% moisture content and density of 1.4 g/cm³ (Figure 3). The excavated depth was 25 mm, while vertical and horizontal forces on the order of 30–50 N and 80 N respectively were required. At 6.8% moisture, excavating any significant depth in frozen and compacted CHENOBI was not possible at up to 100 N and 120 N vertical and horizontal applied force. However, a series of rip commands using the claws successfully loosened and allowed to retrieve a small but measurable surface sample of almost 2 g. This compares with a 150 g sample of dry, loose sand at 1.6 g/cm³, retrievable with < 40 N applied load in each the horizontal and vertical direction.

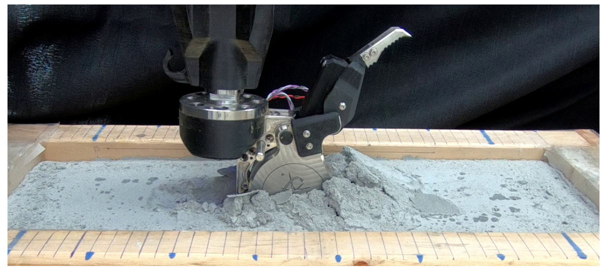


Figure 3: Scooping through frozen lunar simulant

Some of the lessons learned: Cohesive materials can overfill the scoop, necessitating a means of scraping away overfill before storing. This was done using the bottom front bar of the rover chassis.

Picking rock from a pile is feasible. It was most flexible and successful when implemented with a series of operator-commanded repositioning, push, and pull commands, instead of a more automated process. It is, however, operator intensive and more time consuming.

A four Degrees of Freedom (DoF) arm is sufficient for sampling, while two other DoFs were needed to interact with the other elements of the system.

Having an impact mode on the scoop would help better excavate consolidated soils, but also increase complexity of the device.

Conclusion: The Scoop-Rake-Gripper tool was successfully demonstrated in 2019 by CSA as part of the Sample Handling Subsystem. The results showed a reliable approach to acquire, store and transfer rock and soil surface samples, under a simulated lunar exploration scenario, by using straightforward tools and automation. Video footage of the resulting approach is available online [4]. While the prototypes built are at a proof-of-concept stage, the architecture, designs and concepts put forward all have a relatively clear path to flight.

References:

[1] Hiesinger H. et al. (2019) *Proc. of 50th LPSC, LPI*, 1327. [2] Gingras D. et al. (2020) *Proc. of iSAIRAS*, 5015. [3] Lamarche T. et al. (2020) *Proc. of iSAIRAS*, 5046. [4] https://youtu.be/TmxafOXh7Xs

Synthetic H_2O weathering and wet-processing of unrefined regolith towards high strength 'sandcastles'.
D. Karl[1] and A. Gurlo[1], [1] Chair of Advanced Ceramic Materials, Technische Universitaet Berlin, Sekr. BA3, Hardenbergstr. 40, 10623 Berlin, Germany. Correspondence: david.karl@ceramics.tu-berlin.de.

Introduction: Various past ISRU works focused on concrete-like materials or the sintering of extraterrestrial regolith into (often dry-pressed) ceramic bricks. However, dry-processing of space weathered regolith materials (with their sharp morphologies and unique surface properties) can be expected to faces various challenges. In this respect, wet-processing, which is the most used approach for the shaping of oxidic materials on Earth, has significant advantages (e.g., higher particle packing, dust reduction) and what is essential, after 'fusion drying' wet-processing leads to hard powder agglomerate structures due to the interaction of minerals with water.

Wet-processing of Lunar regolith simulants: Why are sandcastles hard after they dry? The water in wet sandcastles has dissolved parts of the minerals [1]. During drying, precipitation leads to solid bridges in the shape of interparticle necks (similar to sintering necks) with agglomerate cohesion strength dependent on the nature and number of particle to particle interfaces. On Earth, fusion drying of phyllosilicates (nature's nanomaterials) has been an essential construction technology for all major civilizations (e.g., the 30 m high ancient skyscrapers of Shibam in Jemen build with unfired blocks of clay earth). There is aqueous mineral alteration on the Moon [2], which could hint at phyllosilicates' presence [3]. If water ice and phyllosilicates were found in the permanently shadowed regions (PSRs) [4], mined regolith might be turned into solid bricks by simply heating and drying. However, if clay is unavailable, even unaltered regolith can be turned into hard granular compacts by mixing with liquid water, aging and drying. From the dispersion of Apollo samples [5], it is known that regolith is highly reactive to H_2O [6].

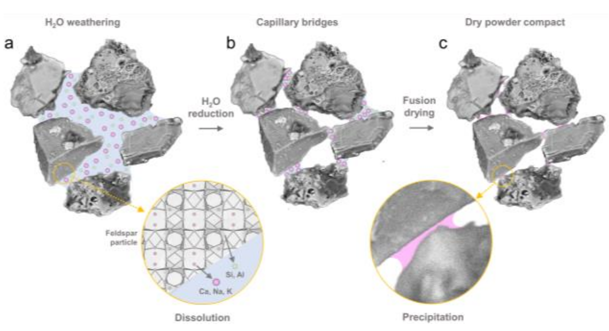


Fig. 1: Illustration of lunar regolith fusion drying: (a) During weathering, mineral ions are dissolved in the water. (b) After water reduction, capillary bridges between particles form (this mechanism gives wet sandcastles their strength). (c) Precip. of dissolved ions leads to solid interparticle necks. Cut out SEM images of Apollo 17 particles courtesy of NASA [7].

Weathering lunar regolith through dispersion in water will lead to the release of ions into the liquid – if such dispersions are dried, the ions will be precipitated at interparticle contact points resulting in hard powder compacts/agglomerates. This mechanism could either be used to build infrastructure or complement other ISRU efforts on the Moon. Furthermore, the dissolution/precipitation of individual Lunar minerals and glasses might be employed to produce synthetic phyllosilicates. In recent work [8], we have used the wet-processing of simple Lunar regolith simulants from two feldspar powders for dry powder compacts (similar to dry sandcastles). In a first step, feldspar powders were dispersed in deionized water and a pH buffer to study mineral dissolution. Dispersions were aging to increase ion concentrations, and subsequently, water content was reduced. The resulting pastes were molded into cylindrical shapes and dried. Dried powder compacts yielded compressive strength of ~ 0.23 MPa from deionized water and 0.52 – 0.7 MPa for powders dispersed in buffer solution. Longer and more specialized leaching experiments with high fidelity simulants can be expected to result in powder compacts with higher compressive strength, especially relevant for real Lunar regolith, which is highly reactive to H_2O.

Wet-processing of Martian clay regolith simulants: Fusion drying of clays has been (and still is) an essential construction technology for all major civilizations on Earth. In recent work [9], we have introduced wet-processing of phyllosilicates for ISRU, using Mars global simulants (MGS-1C). We could develop a universal clay-based material system for unfired clay structures (adobe) on Mars that can be formed using all common shaping processes. Fusion dried adobe from clay slurries/pastes had a compressive strength of 5 – 30 MPa, which is similar to common terrestrial concretes. What is more, sintering such green bodies in terrestrial/simulated Martian atmosphere lead to ceramics with flexural strengths of 57.5/53.3 MPa [10].

References: [1] A. Maskara, D. M. Smith, J Am Ceram Soc 1997, 80, 1715. [2] A. R. Hendrix *et. la.*, Geophys. Res. 2012, 117. [3] F. Vilas, *et al.*, Earth, planets and space 2008, 60, 67. [4] K. M. Cannon, D. T. Britt, Icarus 2020, 347, 113778. [5] B. L. Cooper *et al.*, Fluids and their Effect on Measurements on Lunar Soil Particle size Distribution 2011, https://ntrs.nasa.gov/search.jsp?R=20110008012. [6] D. S. McKay *et al.*, Acta Astronautica 2015, 107, 163. [7] R. Christoffersen *et al.*, 2008, https://ntrs.nasa.gov/search.jsp?R=20090015239. [8] D. Karl, A. Gurlo, in Earth and Space 2020: Engineering for Extreme Environments, ASCE. Reston, VA 2021. [9] D. Karl *et al.*, Acta Astronautica 2020, 174, 241-253. [10] D. Karl, F. Kamutzki, P. Lima, A. Gili, T. Duminy, A. Zocca, J. Günster, A. Gurlo, Open Ceramics 2020, 2, 100008.

Science & Technology Office

Basis of Creating a Microwave-Based Construction System for the Moon

Doug Rickman (presenting)
Jacobs Space Exploration Group, MSFC
June 10, 2021

Doug Rickman	Jacobs Space Exploration Group/NASA Marshall Space Flight Center
Martin B. Barmatz	Jet Propulsion Laboratory, California Institute of Technology
Ralph W. Bruce	RWBruce Associates, LLC
Michael R. Effinger	NASA Marshall Space Flight Center
William F. Kaukler	University of Alabama in Huntsville
Holly S. Shulman	DrHollyShulman, LLC

❑ Introduction

- The concept of using microwaves to heat the lunar regolith can be traced in the literature back to 1969.
- Multiple people have heated lunar simulants in kitchen-type microwaves and small sample size experiments, **but . . .**
- The NASA/MSFC effort is apparently the first to seriously attempt to scale-up this concept into reality.

How you think about a problem determines – the answers you can get!

Therefore, Consider These Two Basic Processes . . .

❑ Sintering vs. melting

❑ Microwave vs. laser or solar heating

❑ Sintering vs. melting

As a practical definition, sintering is here defined as a process that liquifies < 50% of the mass. Melting liquifies >50% of the mass.

- Melting lunar regolith or simulants is known to be rather easy in a microwave cavity. Therefore, producing a lunar glass on the Moon will be relatively easy. **But** using melted rock on the Moon requires solving fierce technical problems.
- You can not just pour molten rock on the lunar surface and thereby make anything but shattered glass . . .
- Therefore, you must do various pre- and post- operations. Examples could include:
  - Pickup and other handling
  - Pre-processing (sizing, sorting, etc.)
  - Intakes/outflows
  - Reaction vessel(s)
  - Forming

Such tasks have never been demonstrated on the Moon.

- The main advantage of *in situ* microwave sintering is no additional processes are absolutely required. You may also obtain the virtues of a composite material.
- The fundamental problem with sintering is the precision required to make it work.

❑ Microwave vs. laser or focused solar radiation

- **The thermal conductivity of the lunar regolith *in situ* is approximately in the range of 0.0005 to 0.03 W/(m K). For comparison, the value for Styrofoam is 0.033.**

- In the absence of more complex engineering, such as feeding thin layers of regolith past elements that supply energy, laser or focused solar radiation are rendered problematic by the low thermal conductivity of the regolith.

- In contrast microwaves offer, at least theoretically, an enormous advantage. The regolith is translucent, not transparent, nor opaque to microwaves. The portion of energy that does not get transmitted, or reflected, does work to elevate the temperature of a thickness.

- Significantly, the disadvantage that the regolith is a good insulator for thermal transmission becomes a potential advantage with microwaves. The hot material will inherently be insulated for radiating energy to space, creating slower cooling.

❑ Challenges

- Although talked about and is the subject of simple experiments, microwave sintering of the regolith has many very serious unknowns: scientific, experimental design, and engineering.

❑ Science Challenges

We do not have sufficient empirical data or sufficient models to predict the sensitivity of microwave heating to such things as:

- Particle size
- Will rocks interfere?
- Particle shape
- Particle composition (especially amorphous silicate glass vs. crystalline minerals)
- Particle texture
- Particle temperature
- Particle packing density in-situ and after consolidation
- Frequency response
- Effect of applied power levels and duty cycles
- How well do simulants replicate the regolith?
- How spatially variable will the regolith be?
- How significant will that variation be?
- Joining of layers or passes, what is the surface bond joint composition and properties?
- Resultant glass-ceramic properties and their variability

This is a partial list of scientific questions we are wrestling with.

❑ Experimental Design Challenges

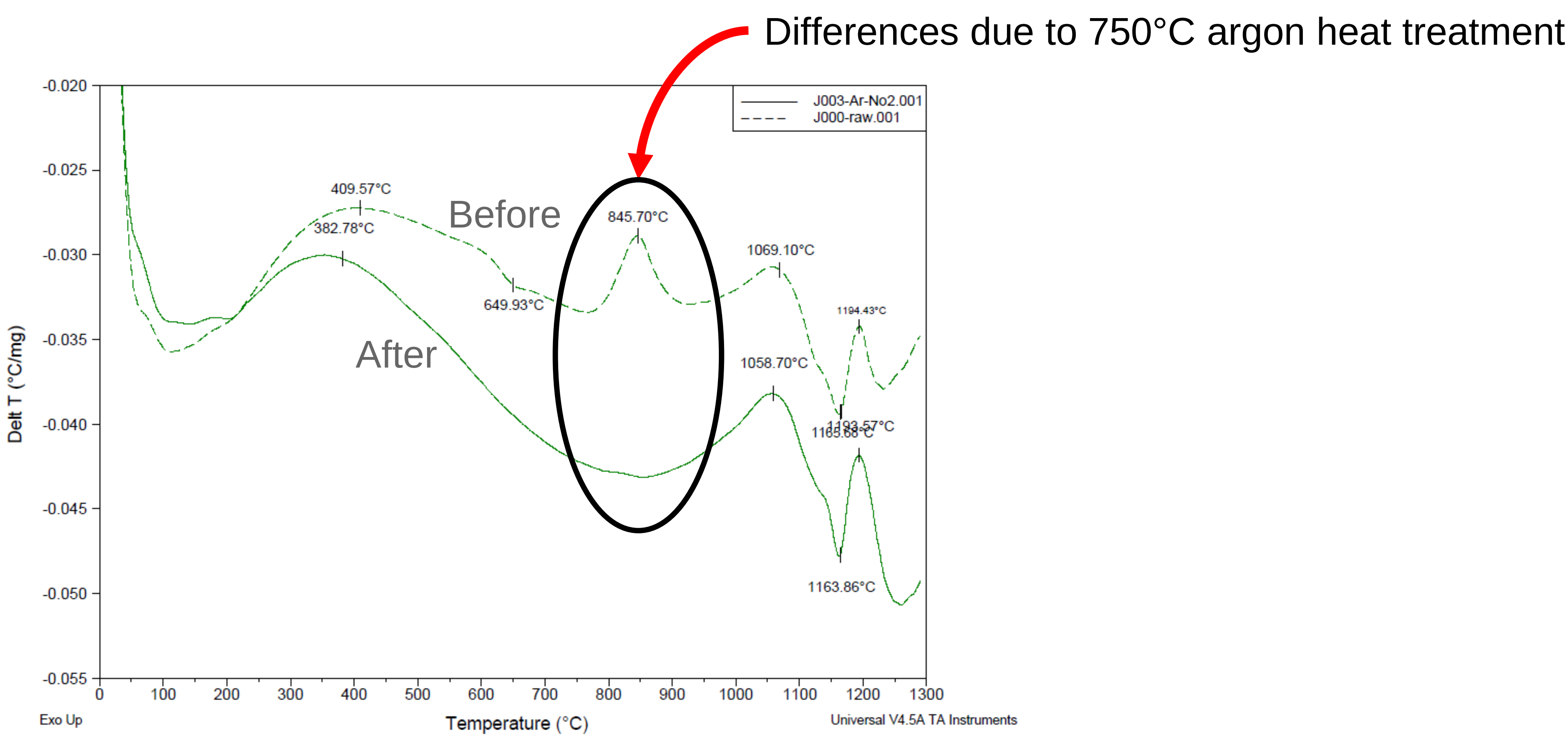
- The simulants have various non-lunar phases in them. These apparently can interfere with the testing. The nature of these phases varies with the simulant.
  - Surface bound H_2O
  - Carbonates
  - Clays
  - "Rust"
  - Metamorphic minerals

- It is apparent that a very large number of experiments are needed.
- It is tempting to think all experiments will use larger masses, this is neither desirable nor physically possible.
- The larger scale work has to be done in vacuum, with oxygen levels strictly controlled. Our temperature ranges are <150°C to >1200°C.
- Our biggest handicap is the fundamental lack of high-quality, lunar highland-type simulants. The estimated minimum volume of simulant needed to complete TRL 6 testing is approximately 6 tons.

❑ Engineering Challenges

- Consider the target of designing to create a landing pad.
  - Size
  - Strength (various measures)
  - Resistance to lifting
  - Abrasivity of the finished surface
- There are multiple “chicken and egg” problems to the engineering, such as required strength and power availability.
- No one has ever engineered a system like we are making. So, there are many very fundamental questions that must be answered for the first time.
  - How do we design for unexpected volatiles?
  - How do we handle the large amounts of waste heat?
  - How do we handle the intense back scattered thermal radiation?
  - How do we monitor and then how do we control the processing?

Thermal Gravimetric Data for JSC-1A Before and After Bake Out in Argon at 750°C



Data by Dr. Holly Shulman

- ❑ Not all experiments work

- ❑ But you can still learn from them!

- Do not touch that dial. Stay tuned for the following paper.

- Discussion and Questions?

- **Acknowledgement:**
  Some of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).

NASA

MICROWAVE SINTERING: INITIAL SCALE-UP FOR LUNAR LANDING AND LAUNCH PAD CONSTRUCTION

The 11th joint Planetary and Terrestrial Mining Sciences Symposium

and Space Resources Roundtable

June 8-11, 2021

Michael R. Effinger[1], Ryan P. Wilkerson[1], Gerald E. Voecks[7], Holly S. Shulman[2], Javier Sanchez[3], Zack S. Roberts[4], Doug L. Rickman[3], Quinn H. Otte[4], Aaron J. King[4], William Kaukler[3], John F. Gerling[5], Ron Hutcheon[6], John N. Huleis[7], Dan J. Hoppe[7], Ralph W. Bruce[8], Mike Baysinger[1], Martin B. Barmatz[7], and Curtis W. Bahr[3]

[1]NASA Marshall Space Flight Center (MSFC), [2]DrHollyShulman, [3]Jacobs Engineering, Inc., [4]Radiance Technologies, [5]Gerling Consulting, Inc., [6]Microwave Properties North, [7]Jet Propulsion Laboratory, California Institute of Technology, [8]RWBruce Associates, LLC.

Agenda

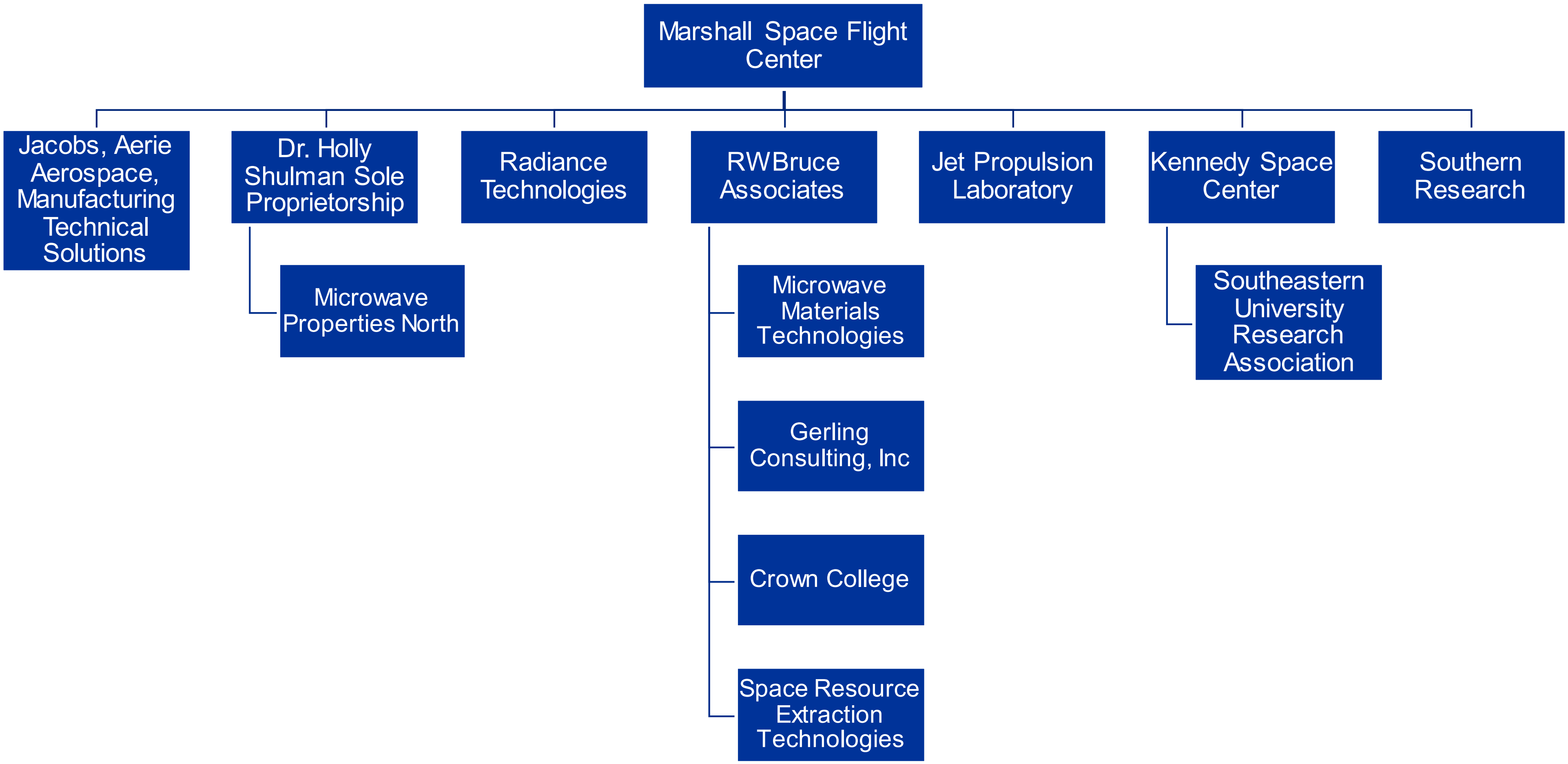
- **Overview**
  - Goals
  - Objectives
  - Partners
- **Materials**
  - Synthetic equivalents
  - Bakeout
- **Testing**
  - TGA mass spectrometry
  - Dielectric
  - Frequency
  - Sintering
- **Modeling & Analyses**
  - Microwave coupling
- **Design**
  - Magnetron
  - Solid state
- **Summary**

Microwave Structure Construction Capability (MSCC) Overview

- **Goal**
  - Mature the technology and capability to emplace in-situ-based construction process on the Moon to form horizontal infrastructure elements (e.g., landing pads, roads, etc.)

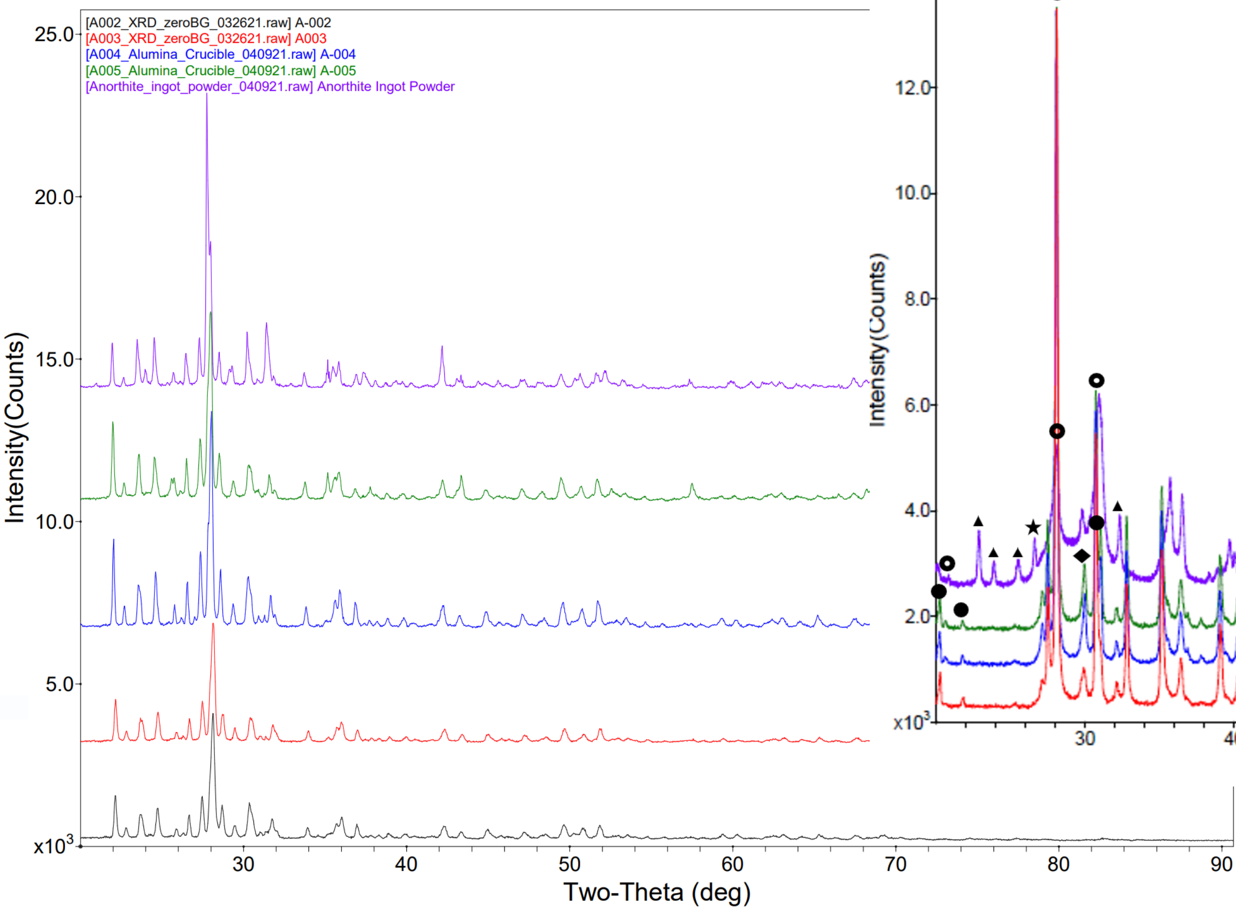
- **Objectives**
  - Develop and demonstrate microwave sintering protocols/processes using lunar simulants in thermal vacuum
  - Develop microwave horn/applicator designs
  - Fabricate plates for property testing

MSCC Partners

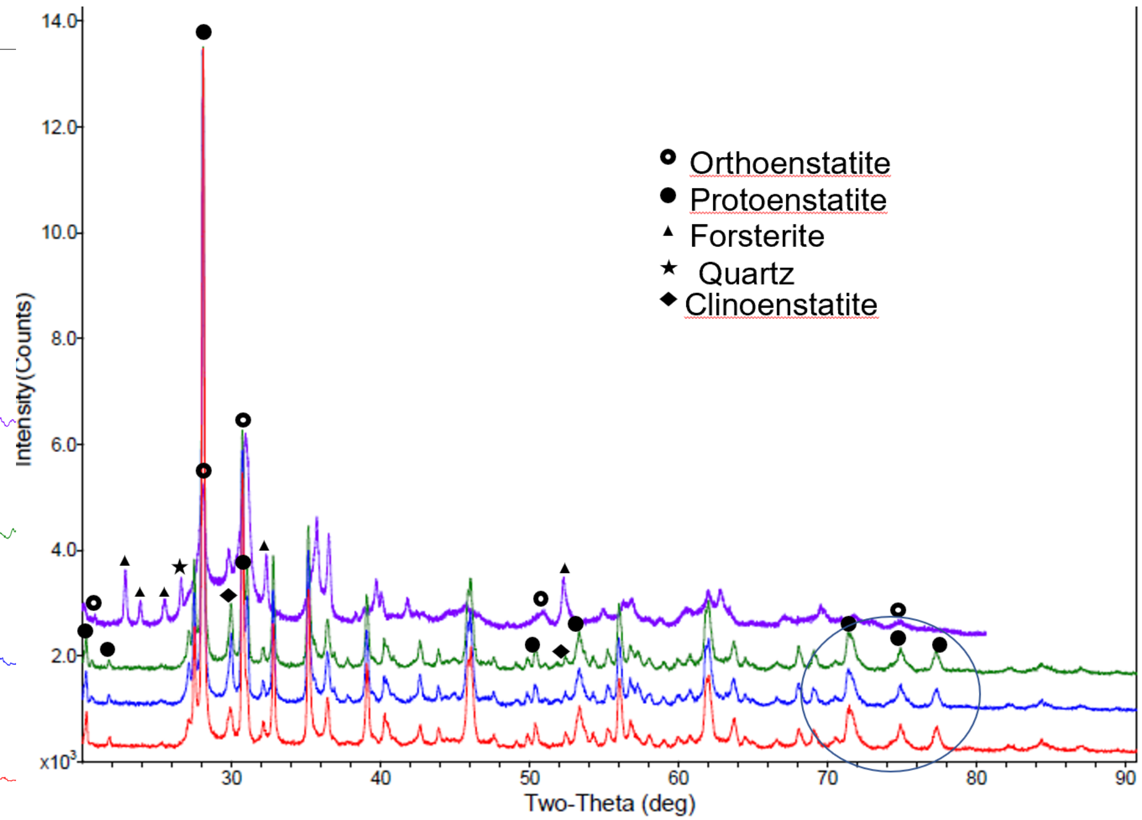


Synthetic Mineral Equivalents

- **Scalable methods identified**
  - Anorthite ($CaAl_2Si_2O_8$) Common plagioclase mineral on the moon, rare on Earth
  - Diopside ($MgCaSi_2O_6$) Common clinopyroxene mineral, however typically found in solid solutions on Earth
  - Enstatite ($MgSiO_3$) Common orthopyroxene mineral, however isolated pure crystals are rare on Earth



XRD **Anorthite** from a variety of scalable process methods

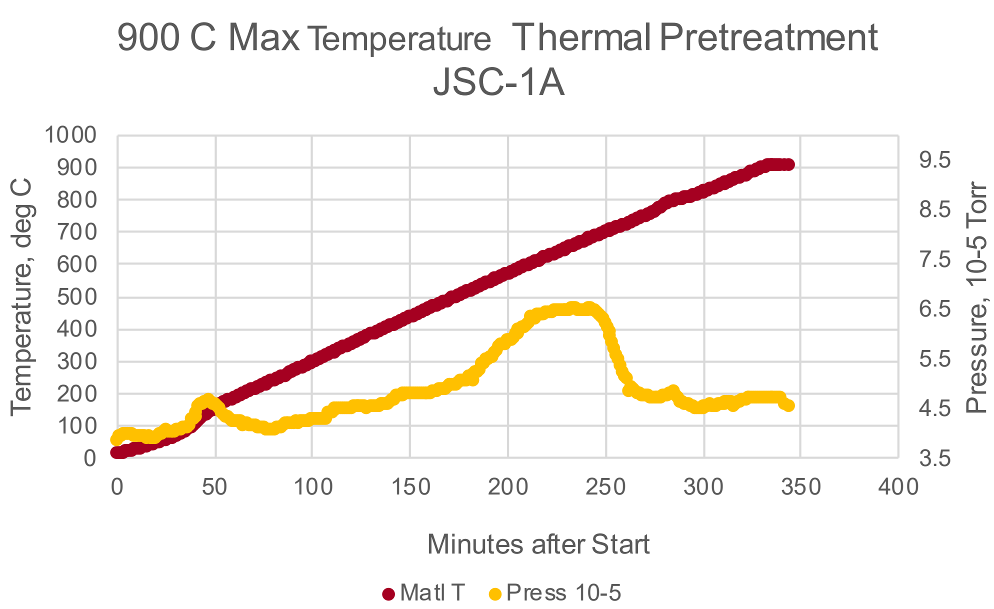


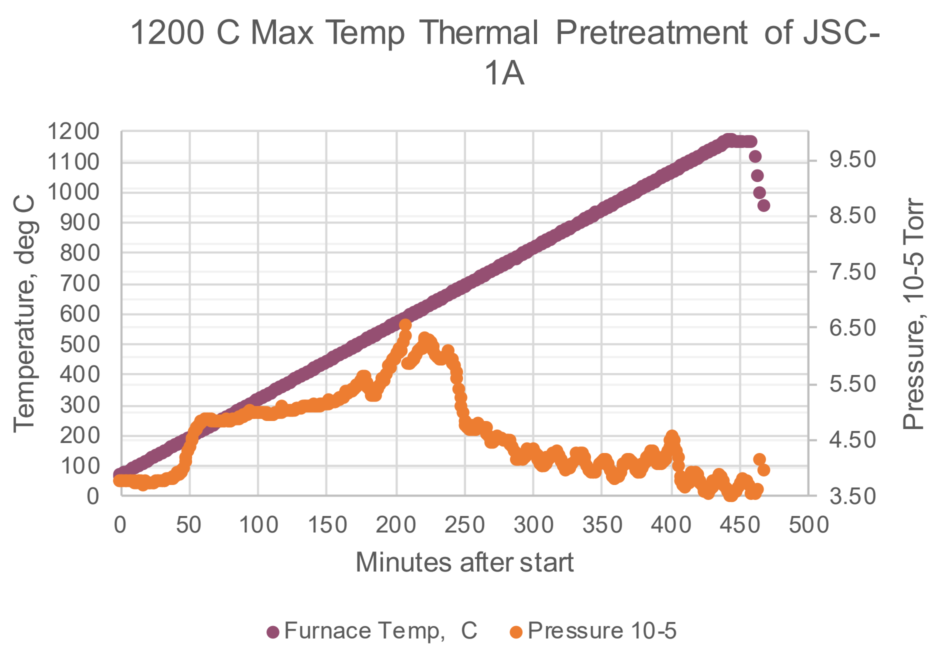
XRD **Enstatite** showing disappearance of protoenstatite in favor of orthoenstatite (desired phase)

Fabrication & testing done at Alfred University

Bakeout

- **Objective: Determine optimal bakeout temperature and time to remove non-lunar material**
- Inert and vacuum heat treating with radiant furnace to various temperatures
- Testing to examine what comes off and what is left behind
  - Microscopy, particle size analysis, Thermal Gravimetric Analyses (TGA)-Fourier Transform Infrared, TGA with Mass Spec, Vacuum TGA, Liquid Nitrogen trap, etc.

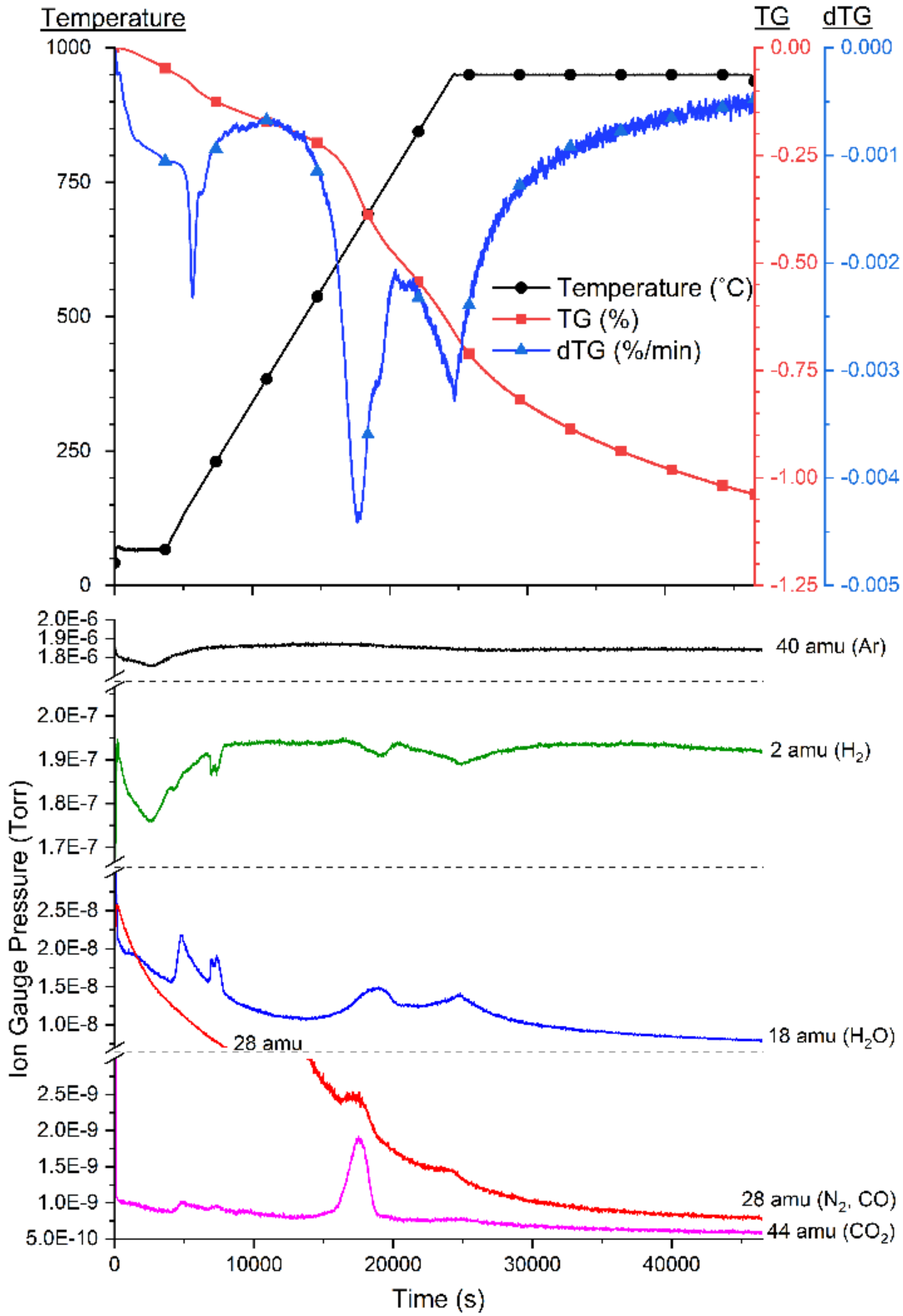




Comparison of temperature/pressure changes during JSC-1A pretreatment tests (JPL)

This research depicted in graphs was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).

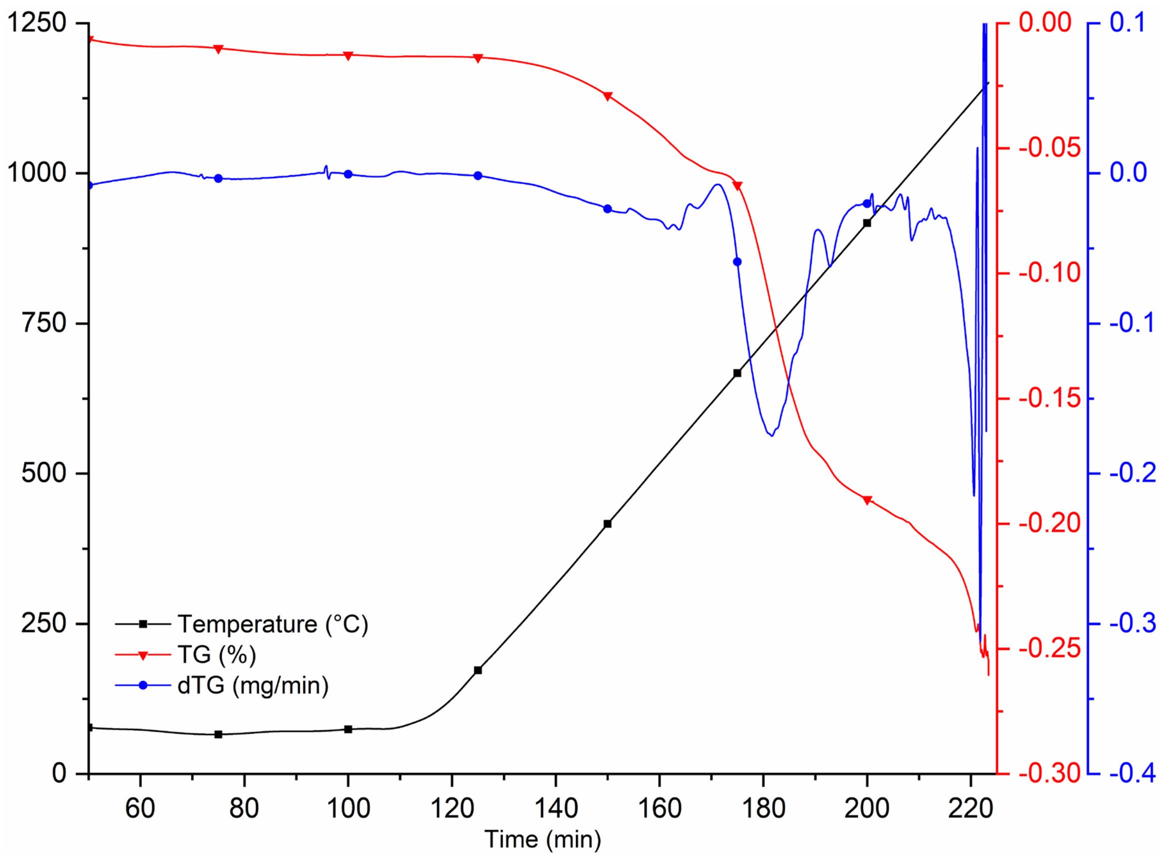
TGA + Mass Spectroscopy



- JSC 1A in Ar/5H_2 gas flow
- MS captures outgassing events:
  - ~100˚C: H_2O
  - ~700˚C: CO_2
  - 950˚C and higher: H_2O – oxide reduction

Testing done at MSFC

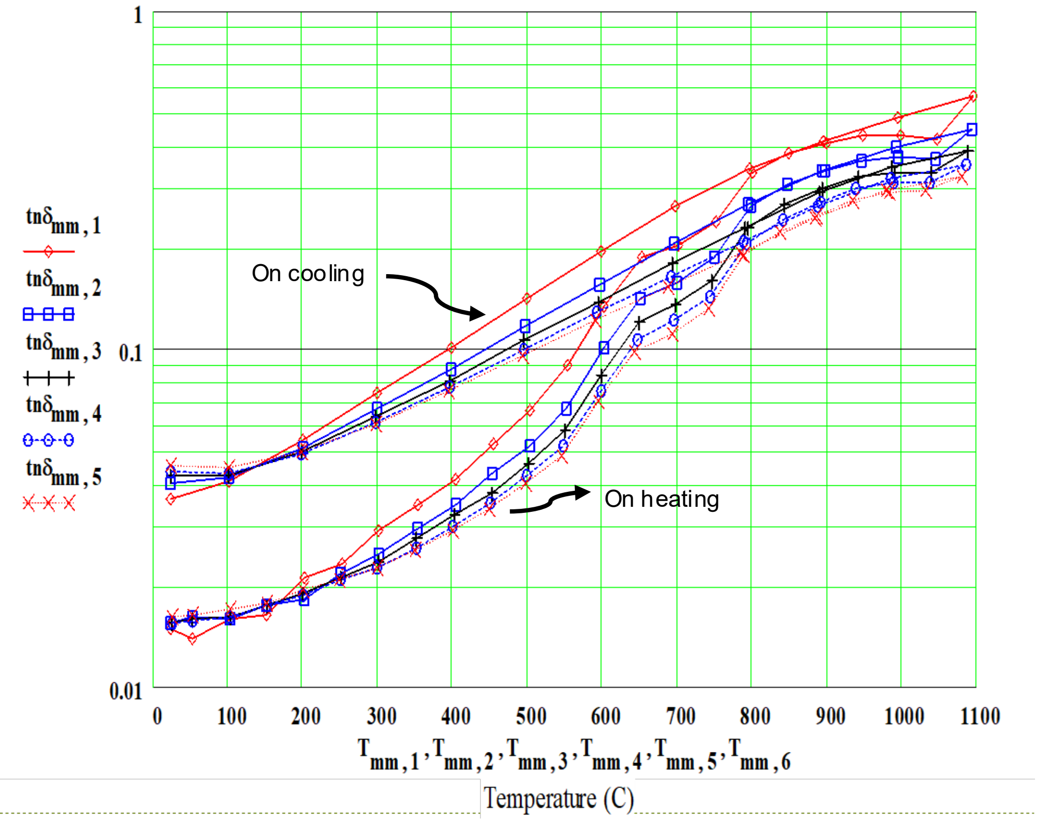
Vacuum TGA Testing

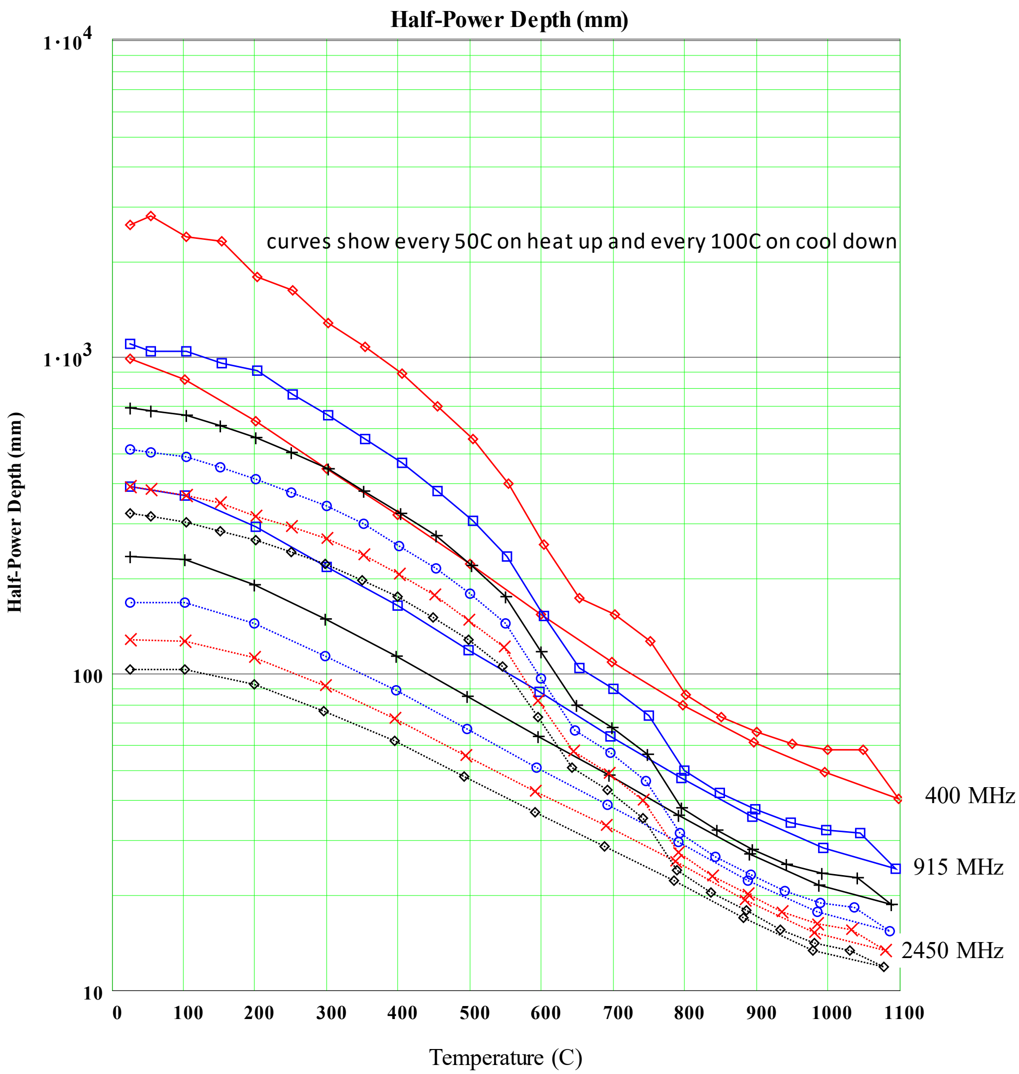


JSC-1A TGA in Vacuum with 200C Bakeout (MSFC)

- Thermal conductivity, frequency, permittivity, dielectric, TGA inert and vacuum, microscopy, etc. also being conducted

Dielectric Properties: JSC-1A (Heating and Cooling)





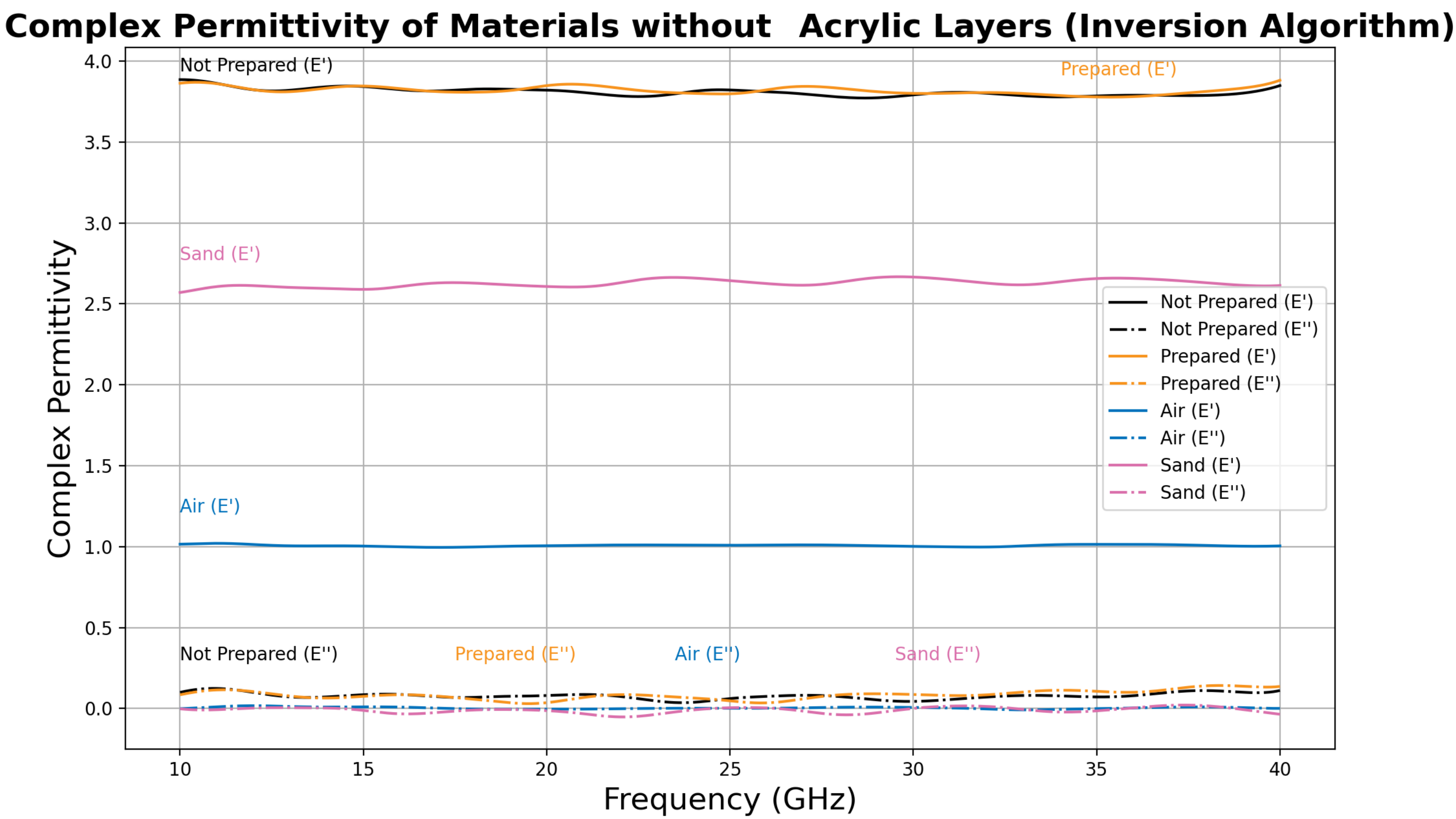
Dielectric Loss Tangent as a Function of Temperature and Frequency

Penetration Depth as a Function of Temperature and Frequency

Heat treat was 500C Argon

Testing done at Microwave Properties North

JSC-1A Frequency Testing at Ambient Conditions

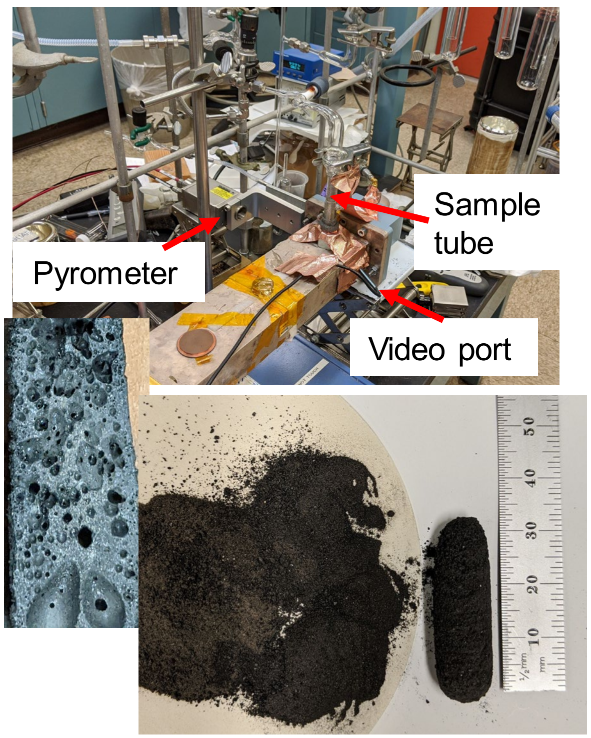


The prepared and unprepared samples are JSC-1A. The Prepared samples have been baked out at 200°C for 8 hours and stored in vacuum jars for transport to the testing site. The Unprepared samples were used as received.

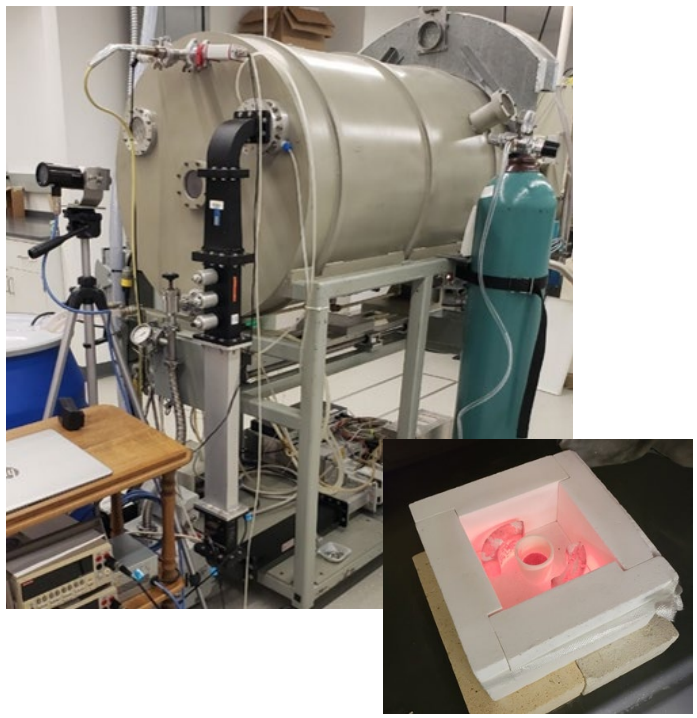
Testing done through Radiance Technologies

Microwave Sintering

- Objectives
  - Gain understanding of the heating profile, uniformity, and depth of penetration of the microwaves into the regolith
  - Determine and develop optimized energy efficient process
    - Volume sintered per hour from -200C to sintering temperature, accounting for porosity
    - Mitigating thermal runaway



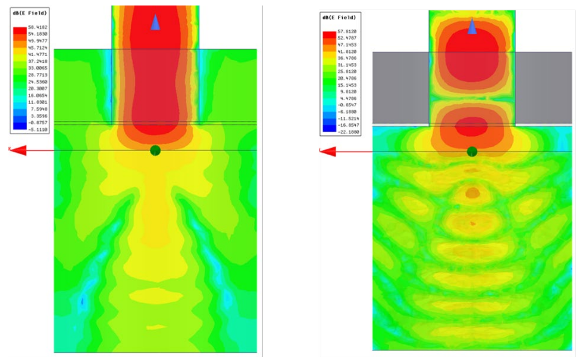
Small-scale Thermal Vacuum (TVAC) chamber with 200W microwave system. Sintered sample was done in vacuum. (JPL)



2’ diameter inert atmosphere chamber with 3kW microwave system (Alfred University)

4’ diameter TVAC chamber with 2kW microwave system and various horn configurations. Sintered sample was done in air. (MSFC)

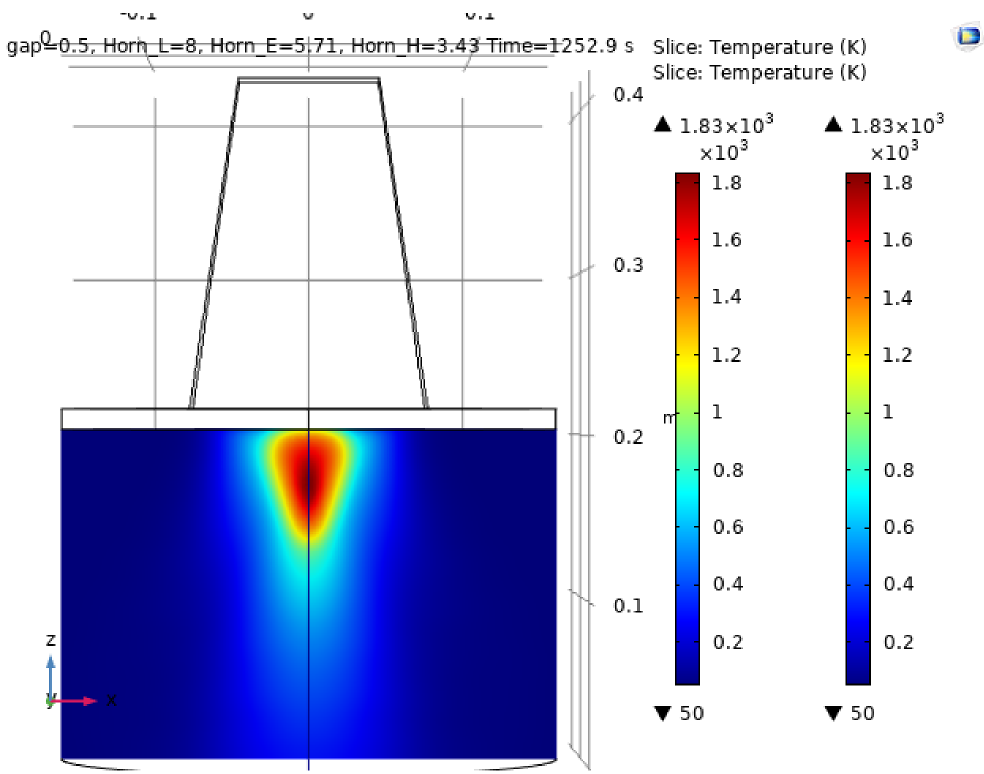
Microwave Coupling with JSC-1A

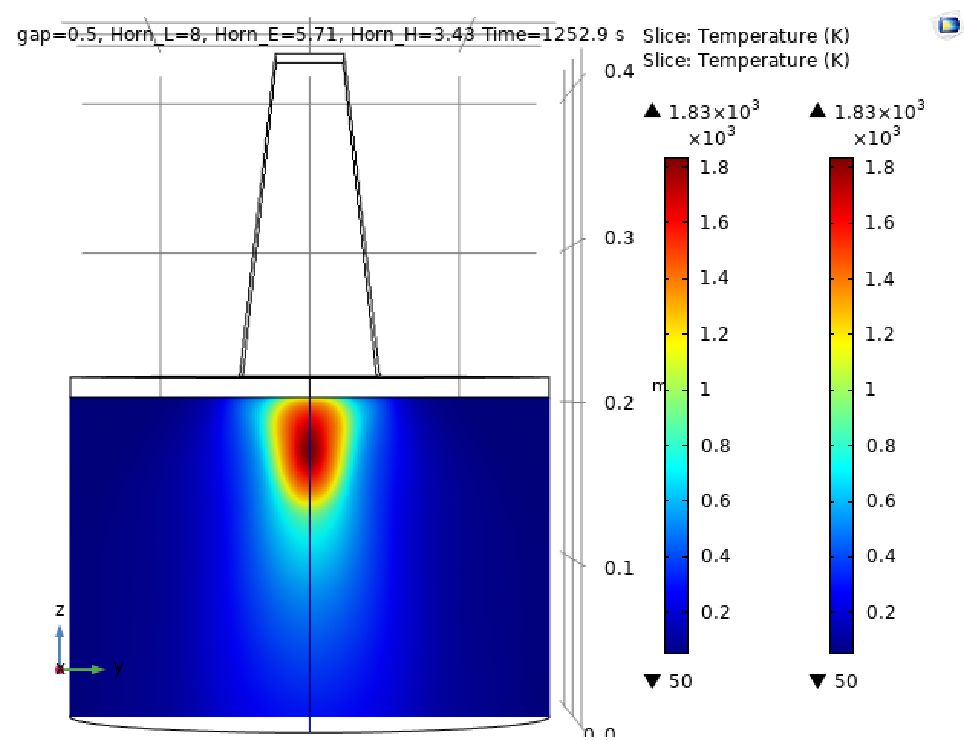


E Field: No Ground Plane

E Field: With Ground Plane

Open-Ended Waveguide Launcher With and Without Ground Plane via HFSS (JPL)

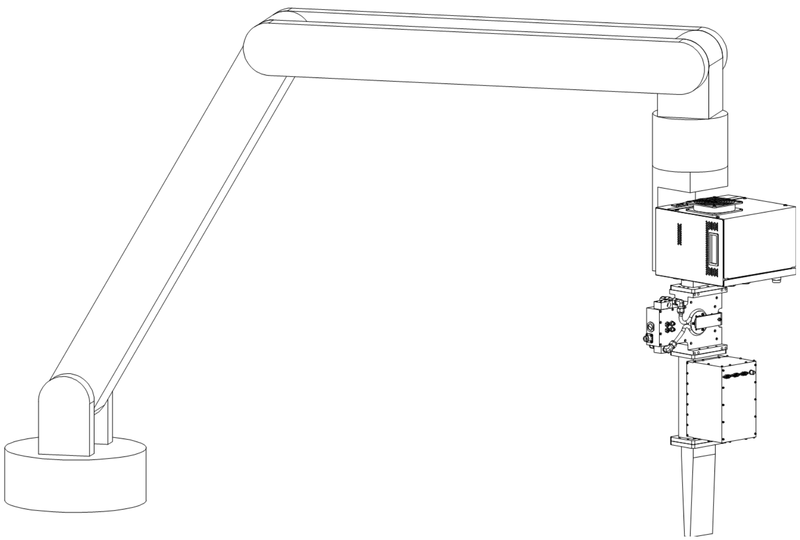


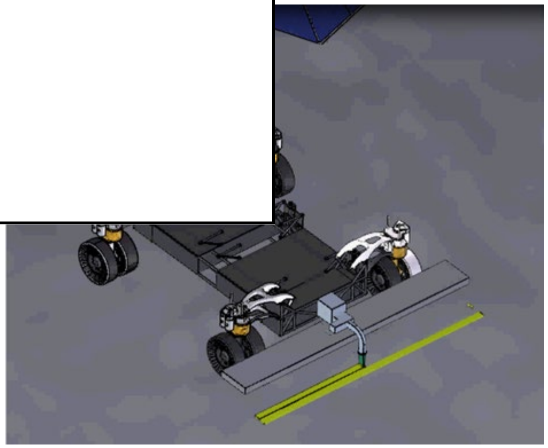


COMSOL analysis of microwave heating with a horn and 0.5” gap between horn and simulant bed (MSFC).

Design

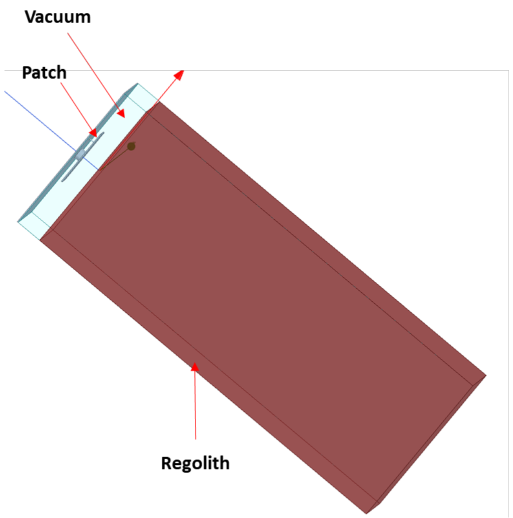
- Microwave source (magnetron, solid state)
- Thermal management system
- High temperature applicator that can work continuously in a lunar environment while exposed to an 1100C radiant surface and volatiles

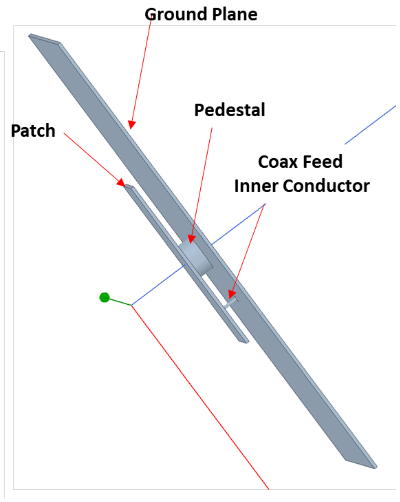




Various options being considered
(Gerling Consulting left image and MSFC right image/video).

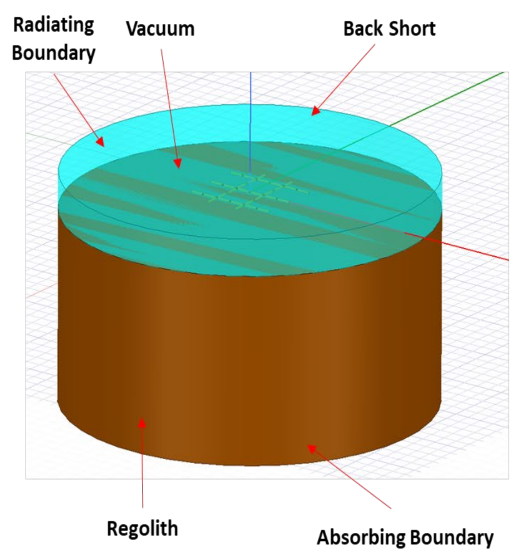
Solid State Design

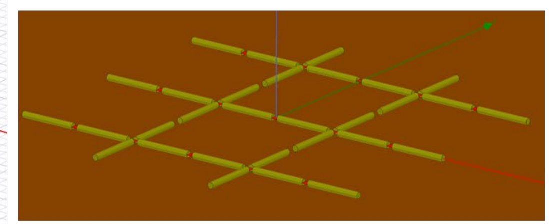




All-Metal Patch Array Element

Close-Packed Dipole Array for Regolith Sintering





Array Close-Up

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).

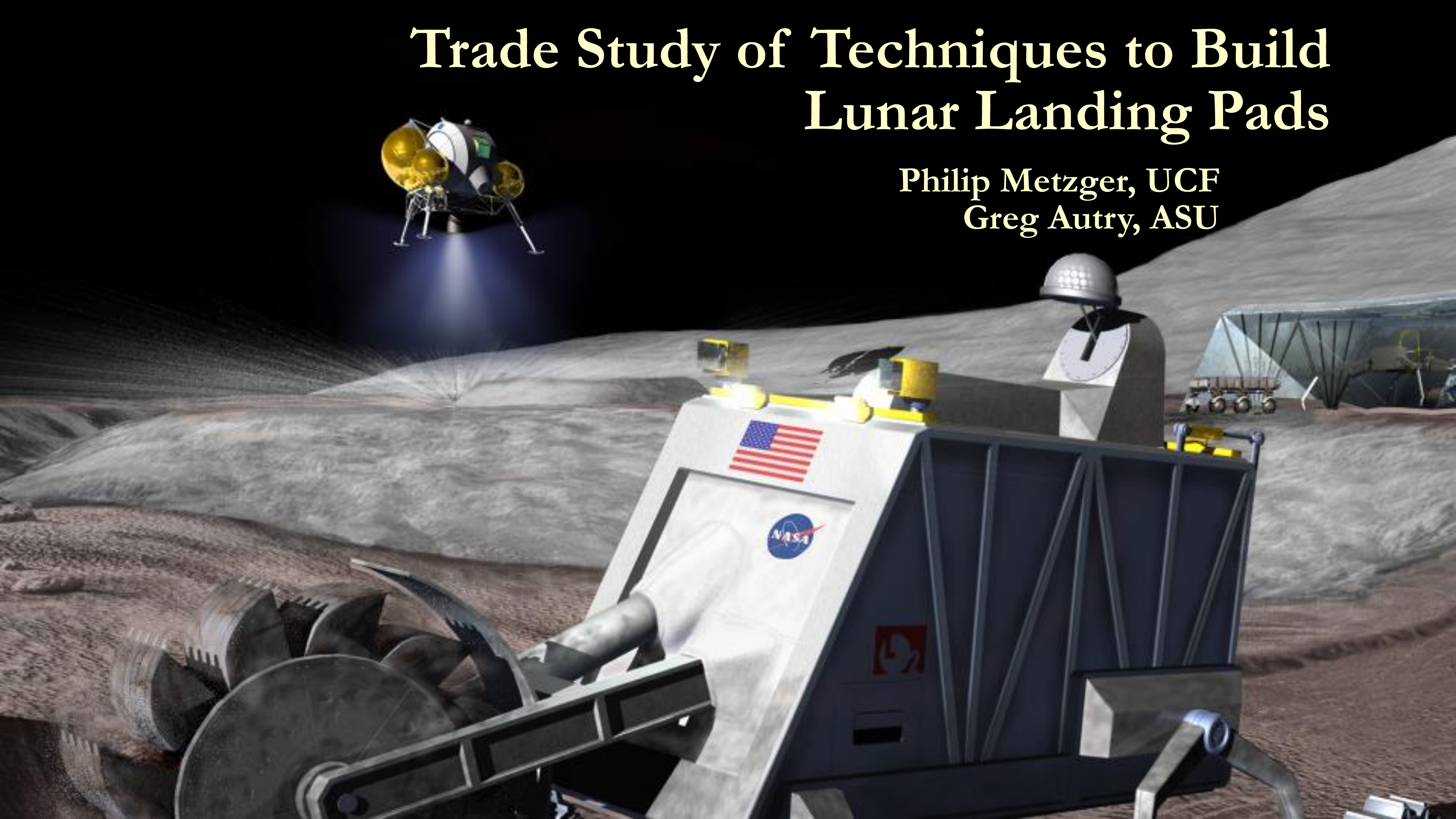
Summary

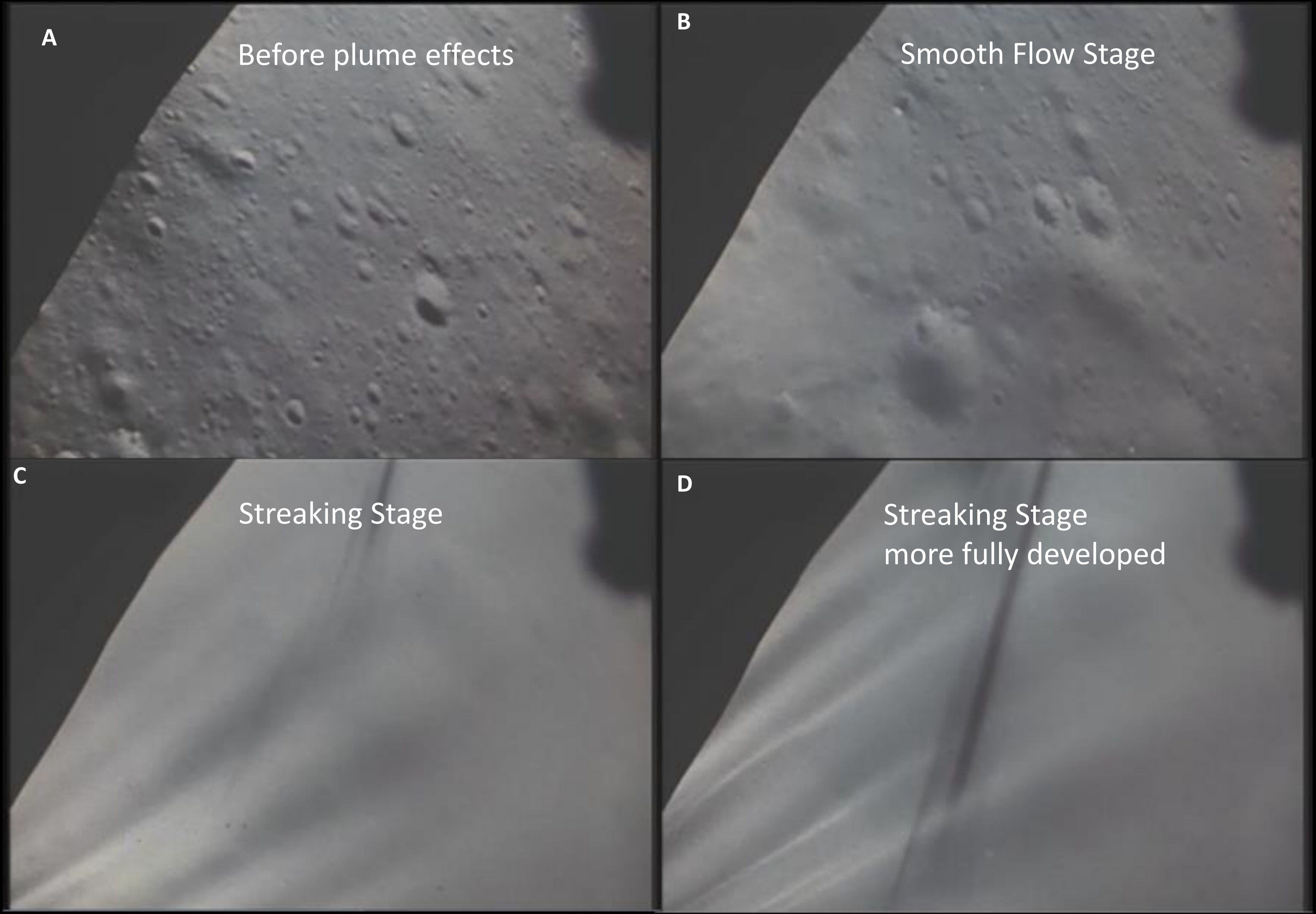
- Fabricating synthetic minerals to characterize constituent materials
- Defining bakeout cycle for simulants
- Characterizing simulant to support processing protocols development
- Conducting microwave sintering experiments at multiple locations with different capabilities to develop sintering protocols and provide inputs to con-ops
- Conducting microwave coupling analyses at multiple locations and using different software
- Pursuing various design configurations and microwave sources

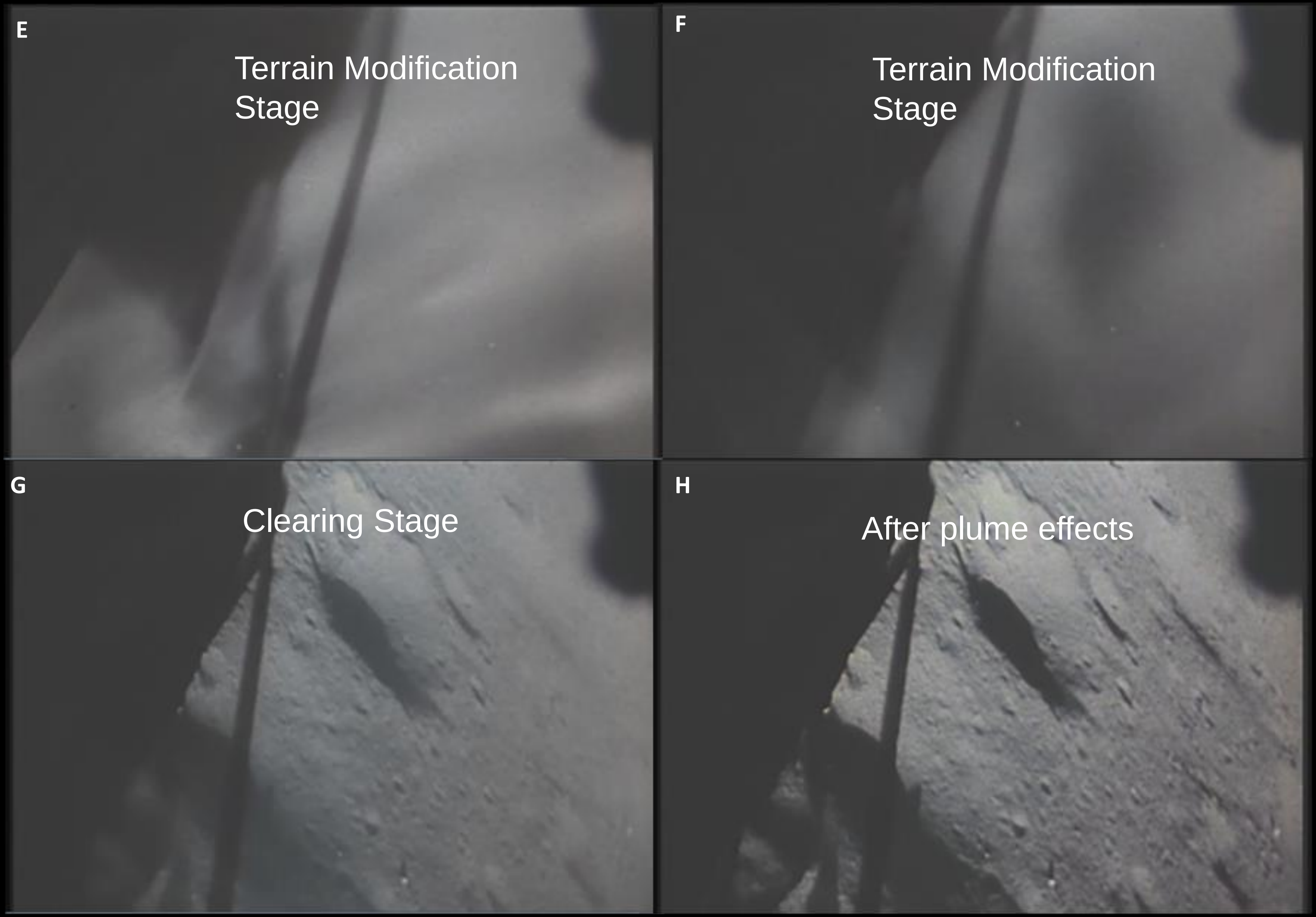
www.nasa.gov

Trade Study of Techniques to Build Lunar Landing Pads

Philip Metzger, UCF
Greg Autry, ASU

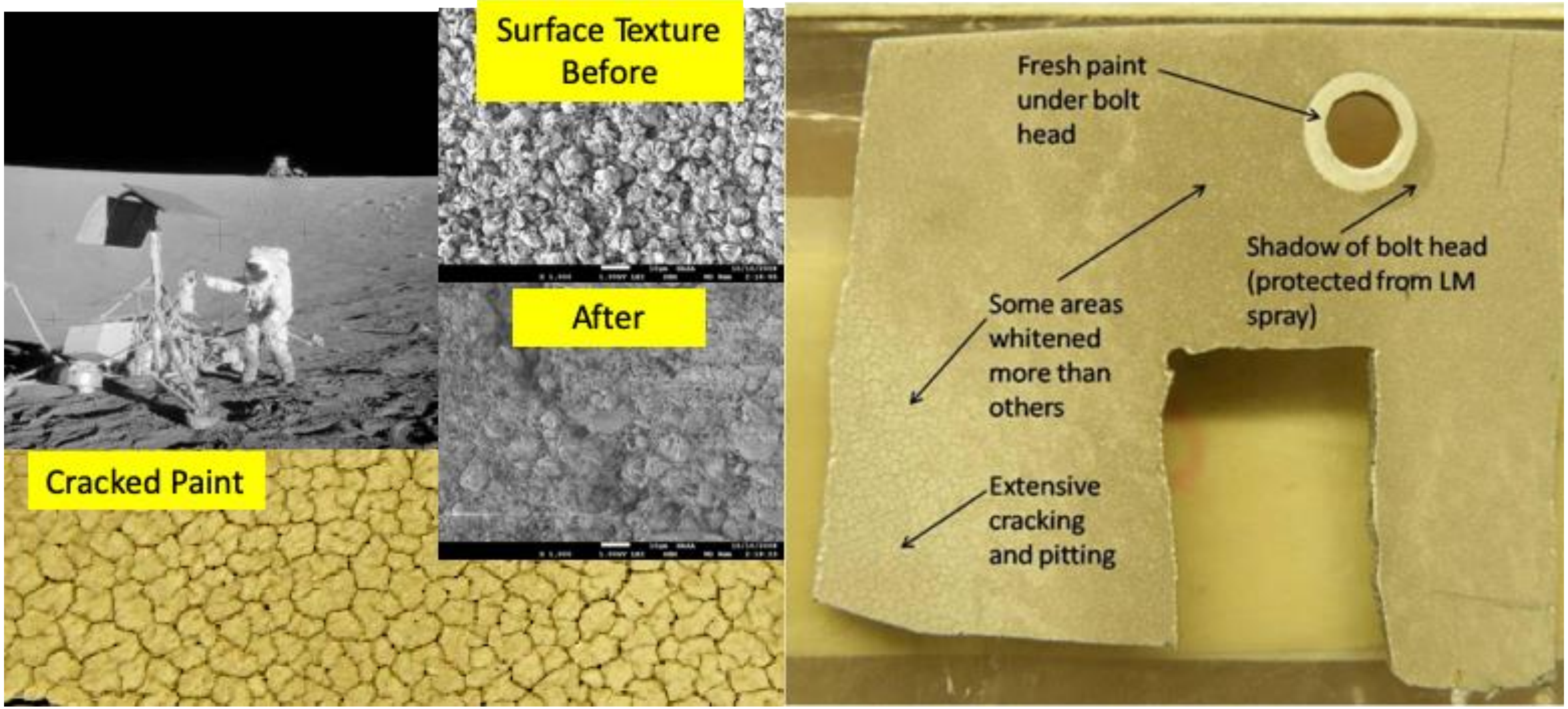


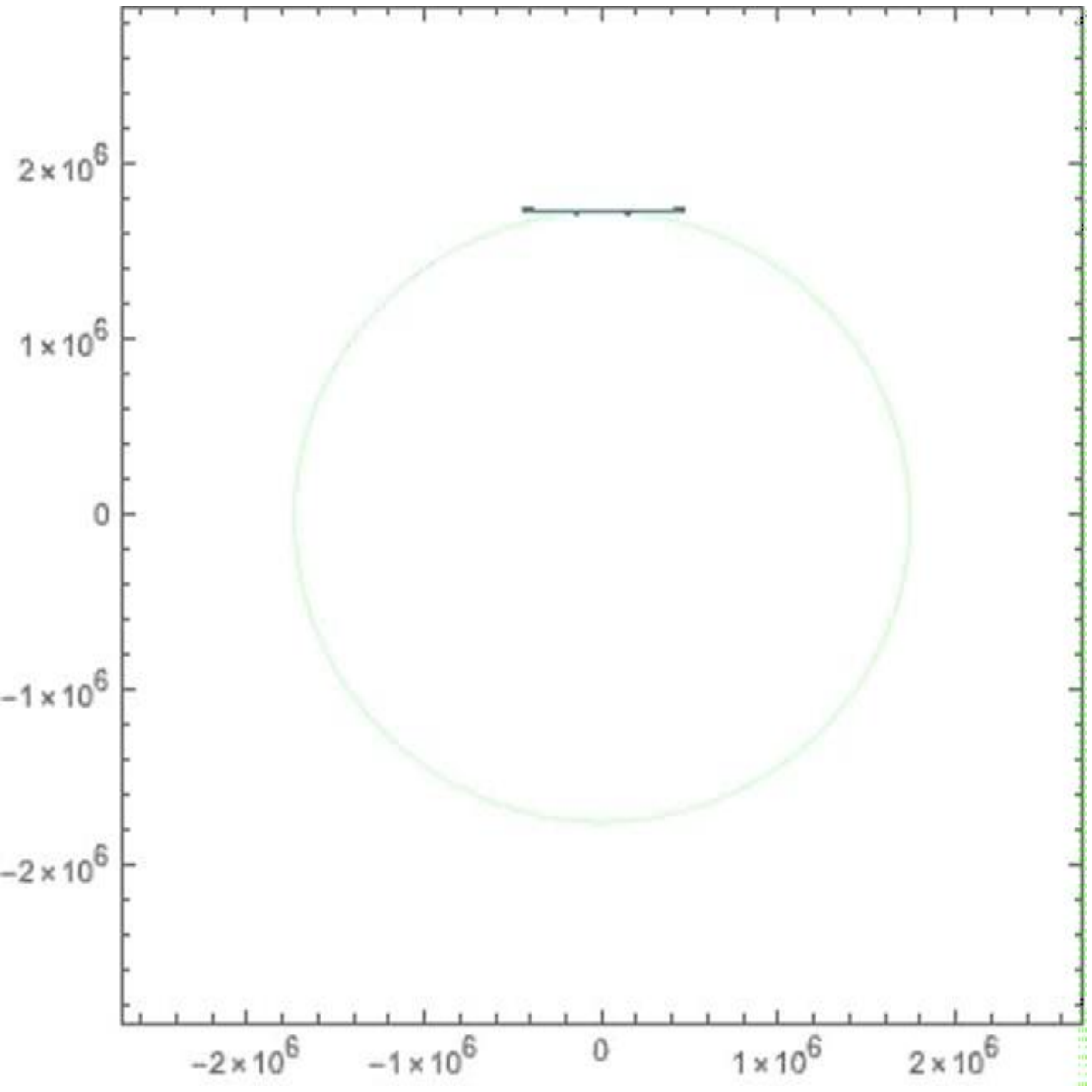

A
Before plume effects
B
Smooth Flow Stage
C
Streaking Stage
D
Streaking Stage
more fully developed


E
Terrain Modification Stage
F
Terrain Modification Stage
G
Clearing Stage
H
After plume effects

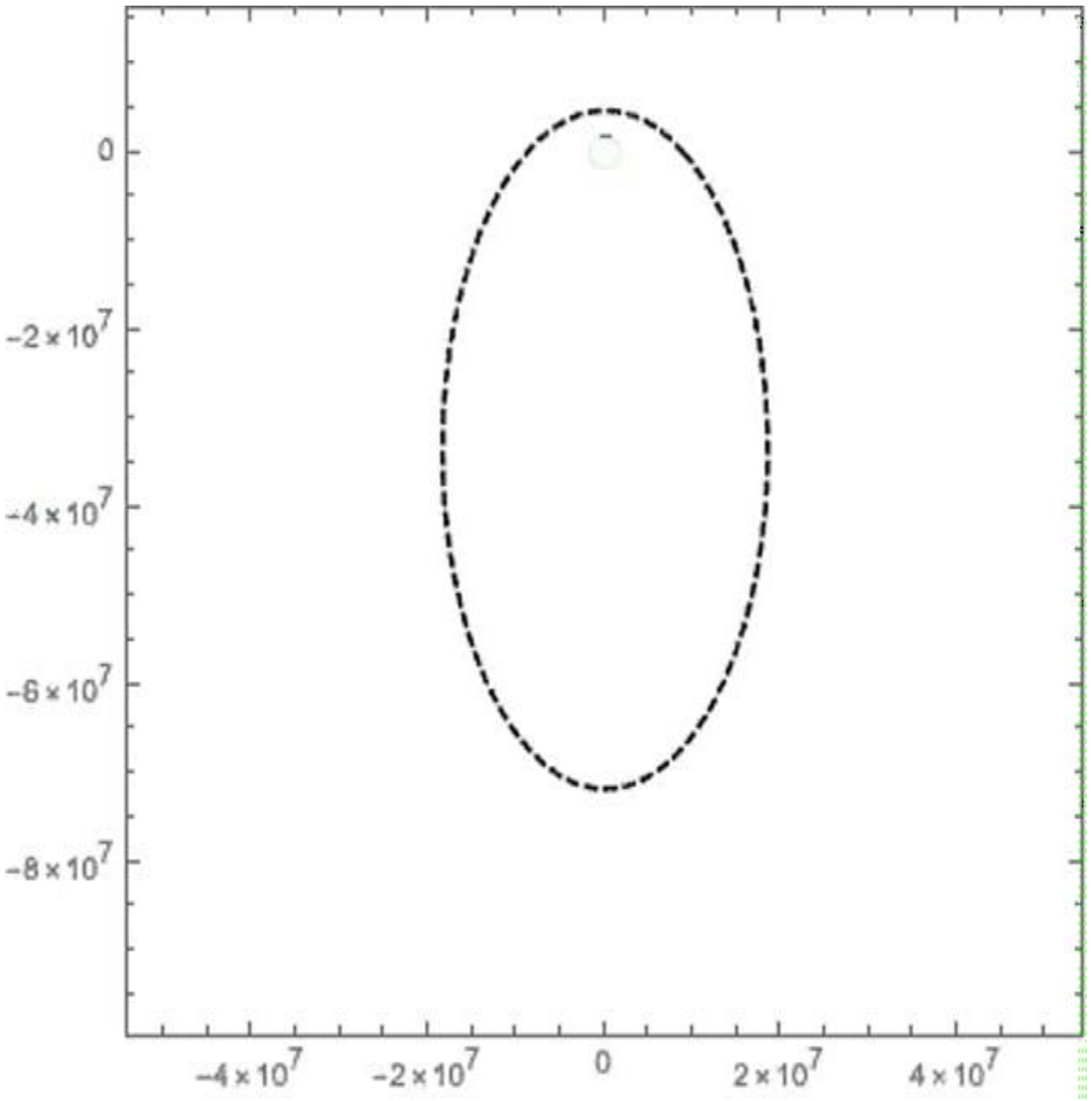
Resulting Damage

- Thermal control, radiators, optics, impact breakage, etc.
- Surveyor 3 provides a case study.
  - Analysis shows most ejecta flow harmlessly overhead
  - In the direct spray would have been 1000x worse





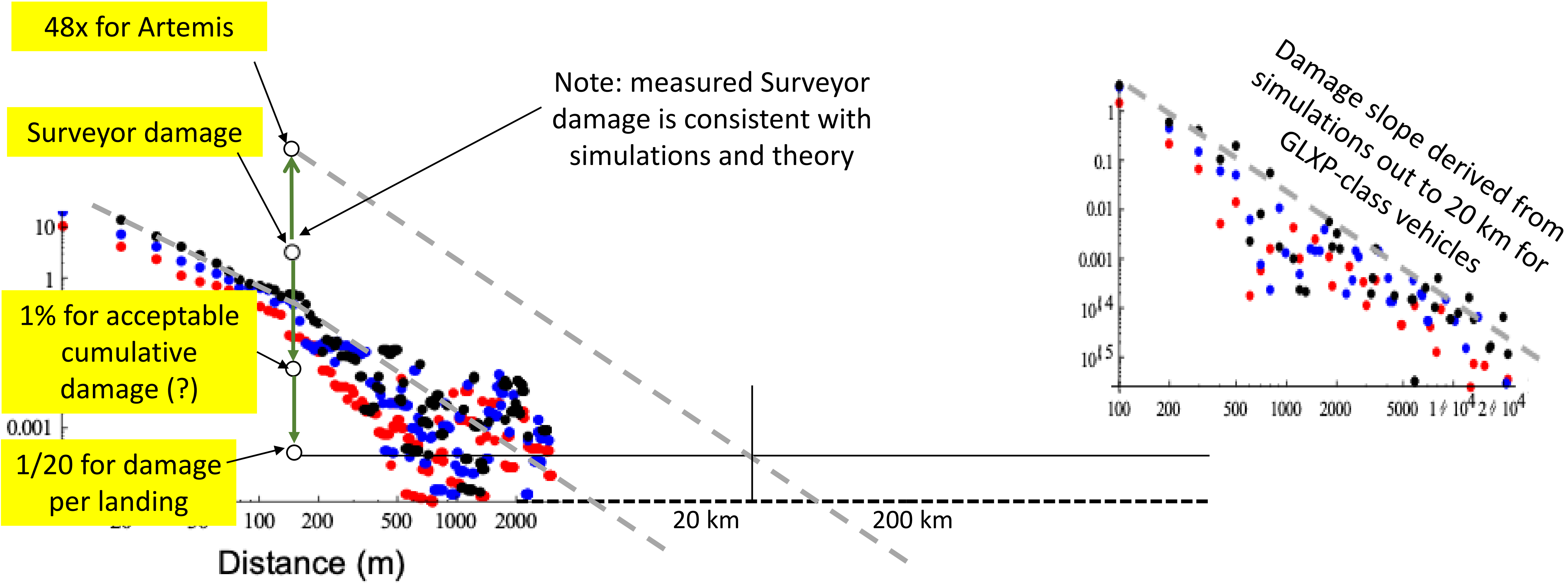
2×10^6
1×10^6
0
-1×10^6
-2×10^6
-2×10^6
-1×10^6
0
1×10^6
2×10^6



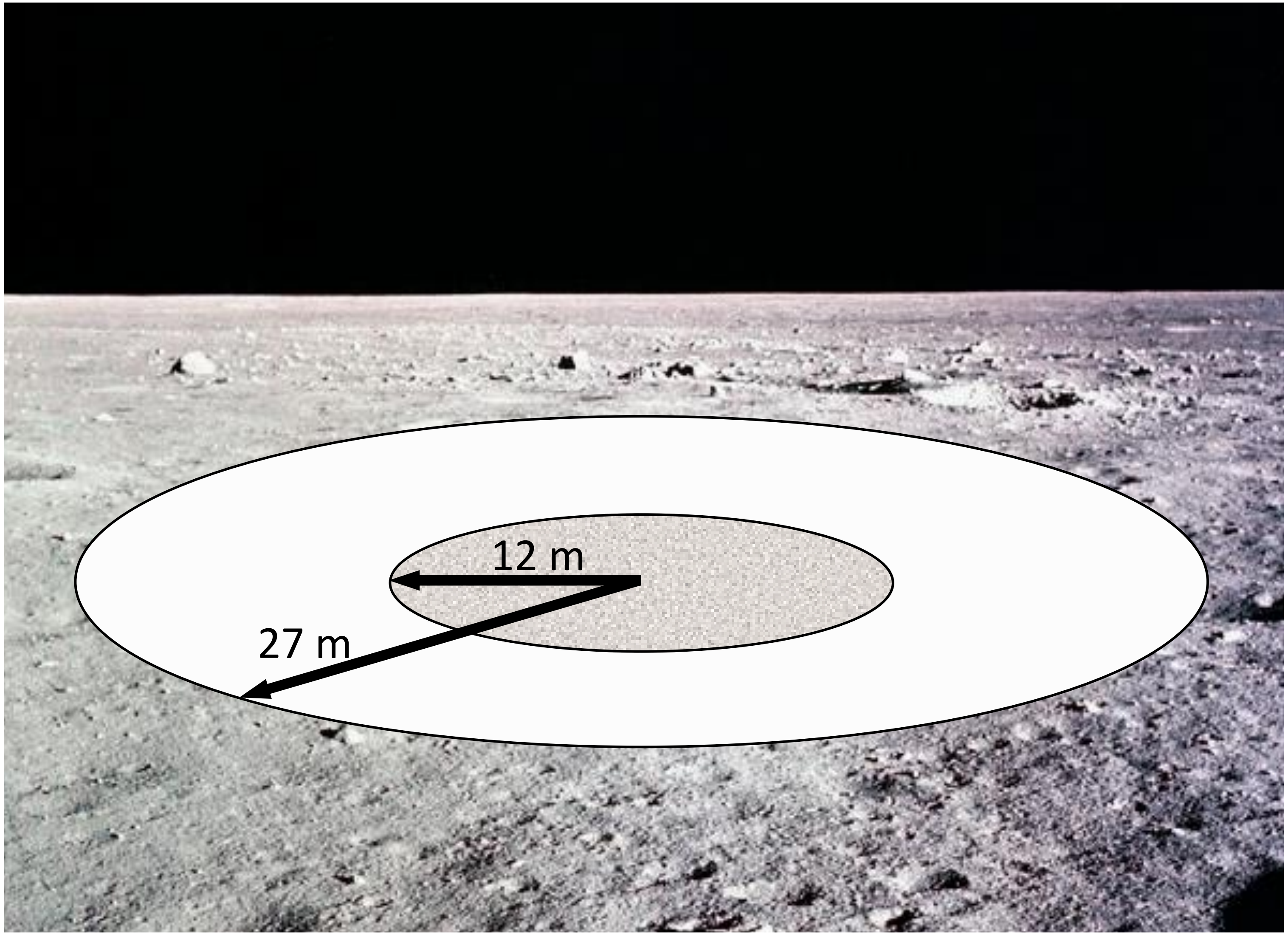
0
-2×10^7
-4×10^7
-6×10^7
-8×10^7
-4×10^7
-2×10^7
0
2×10^7
4×10^7

Scaling for Artemis-Class Vehicles

- The best available science says damage to an outpost will be unacceptable even to 26 km
- This neglects higher speed of ejecta from larger vehicles



RLSO Landing Pad Dimensions



Assumes 40 t vehicle, four engines off-center, 5 m landing accuracy

Site Preparation

- Grading
- Boulder removal
- Compaction

- Significant progress has already been made
- Requires adequate AI for telecom time delay

Rovering, Grading, and Compacting

Basic data	Grading rate	10	s/m2	
	Compacting rate	20	s/m2	
	roving energy per m per kg	2.5	J/m/kg	Note 4
	Width of grader blade	1.5	m	
	Blade force	400	N	Note 5
	Energy to push blade	0.11111111	kWh/m	
	Energy to grade	0.52777778	kWh/m	
	Energy to compact	0.52083333	kWh/m	A guess!
Outer Area	Grading outer time	5.10508806	hrs	
	Compacting outer time	5.10508806	hrs	
	grading outer energy	0.63813601	MWh	
	compacting outer energy	0.17726	MWh	
Inner Area	Grading inner time	1.25663706	hrs	
	Compacting inner time	2.51327412	hrs	
	grading inner energy	0.15707963	MWh	
	compacting inner energy	0.04363323	MWh	
Equipment	rover mass (empty)	300	kg	
	compactor	200	kg	
	grader blade	300	kg	

Microwave Sintering

- Deep penetration, produces mechanically strong surface
- Survived on Masten landing pad with no degradation
- Runaway heating; lumpy surface texture can result
- Expts in 2012 – 2014 showed multi-wavelength heating is more efficient & effective (Microwave through IR)
- NASA reports npFe hardly improves microwave susceptibility
  - Use heat capacity for basalt

Microwave Sintering

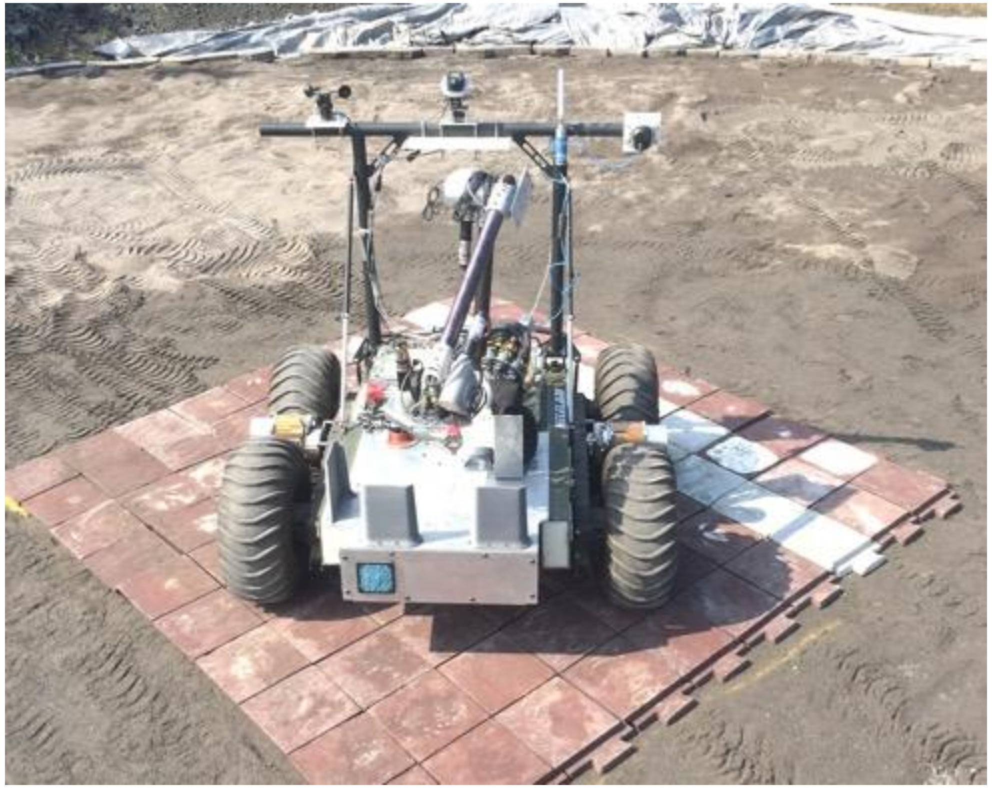
Basic data	density of compacted regolith	3000	kg/m3
	power from experiment	2000	w
	time in experiments	5400	s
	mass sintered in experiment	1.35	kg
	Available power to sinter	50	kW
	Microwave efficiency	0.5	
Outer Area	thickness	2.5	cm
	outer mass	137.8373777	MT
	unscaled time	153152.6419	h
		6381.360078	d
		17.48317829	y
	microwaving energy	2.2054E+12	J
		612.6105675	MWh
	Sinter time	86.89285306	d
	Grading & Compacting time	10.21017612	h
	Total time	87.31827706	days
	Grading & Compacting energy	0.81539601	MWh
	Total energy	613.4259635	MWh

Inner Area	thickness	7.62	cm
	mass	103.4162036	MT
	unscaled time	114906.8929	h
		4787.787204	d
		13.11722522	y
	microwave energy	1.65466E+12	J
		459.6275716	MWh
	Sinter time	65.19370243	days
	Grading & Compacting time	3.769911184	hours
	Total days	65.35078206	days
	Grading & Compacting energy	0.81539601	MWh

	Total energy	460.4429676	MWh
Equipment	Sinter device	1911.640212	kg
	Rover payload limit	1000	kg
	Number of rovers	2	
	Total rovers mass	600	
	grading & compacting mass	500	
	Total mass	3.011640212	MT

Pavers

- Tests found that gas penetrates joints and flips the pavers
- Interlocking pavers at PISCES test with Honeybee Robotic Arm prevent isolated flipping, but gas can still inflate the entire pad leading to mechanical failure
- Grouting could seal the joints to prevent gas intrusion
- Venting channels under the pad could relieve the buildup of pressure



Baked Interlocking Pavers

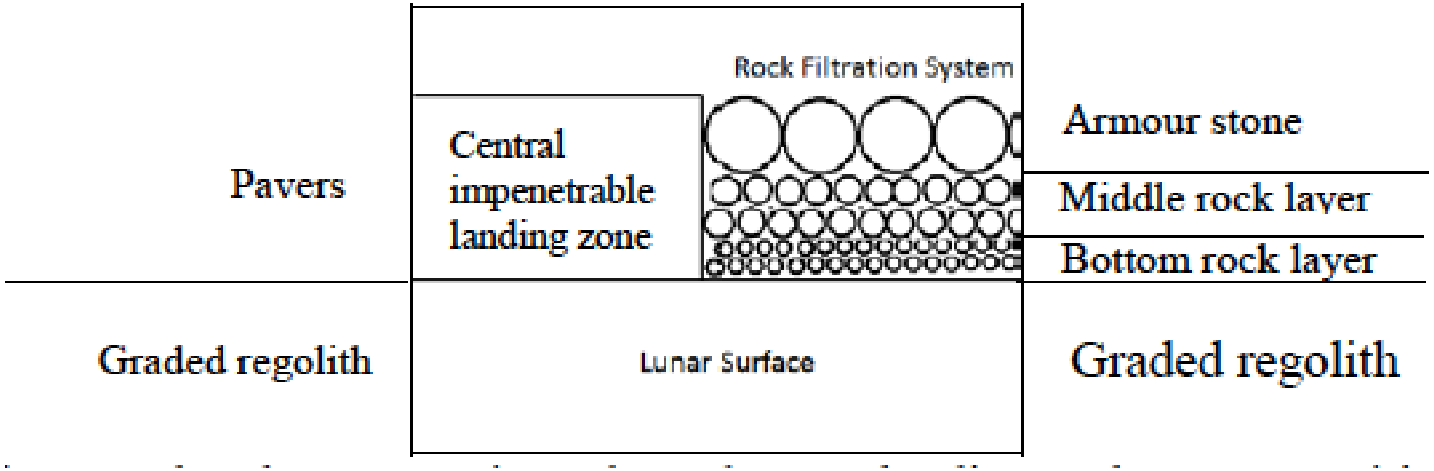
Basic data	Paver width	18	inches
	area/paver	0.20903184	m^2
	Install rate	60	s/paver
	Distance from oven to pad	1	km
	Mass hauled from oven to pad per trip	1000	kg
	Density of soil	2200	kg/m3
	Sinter temp	2250	C
	Starting temp	100	C
	"Avg" thermal conductivity	346.990248	mW/m/K
	"Avg" heat capacity	886.666667	J/kg/K
	exponential time constants	6	
	cooling time relative to bake time	0.5	
	oven reheat time per batch	1	hr
	pavers per batch	30	
	Energy per kg of brick	2	kWh/kg
Outer Area	number pavers	8793	
	number of oven batches	294	
	paver thickness for outer	2.5	cm
	paver mass	11.4967512	kg
	bake time/batch	0.73198903	hrs
	Cooling time per batch	0.36599452	hrs
	total manuf time per batch	2.09798355	
	total manuf time	25.7002984	days
	Install time	6.10625	days
	grading & compacting time	0.42542401	days
	Total manuf & constr time	25.7211318	days
	Energy per oven cycle	689.805072	kWh
	baking energy	202.802691	MWh
	pavers hauled from oven per trip	86	
	number of hauling trips	103	
	distance driven to constr	210.019754	km
	roving energy	131.262346	kWh
	excavation & sieving energy	100	kWh
	total energy	203.034954	MWh
Inner Area	number of pavers	2165	
	number of oven batches	73	
	thickness of paver for inner	7.62	cm
	paver mass	35.0420977	kg
	bake time/batch	6.80040062	hours
	Cooling time per batch	3.40020031	
	total manuf time per batch	11.2006009	hrs
	total manuf time	34.0684945	days
	Install time	1.50347222	days
	grading & compacting time	0.42542401	days
	Total manuf & constr time	34.0893278	days
	Energy per oven cycle	2102.52586	kWh
	baking energy	50.3557703	MWh
	pavers hauled from oven per trip	28	
	number of hauling trips	78	
	distance driven to constr	160.019754	km
	roving energy	100.012346	kWh
	excavation energy	75.0474241	kWh
	total energy	50.53183	MWh
Equipment	oven mass	500	kg
	robotic installation arm	100	kg
	rover	300	kg
	robotics manipulation energy	1	kWh
	Excavator	300	kg

Credit: MaltaGC/Wikimedia, CC BY-SA 3.0

Credit: Ziegelindustrie International

Gravel & Rocks

- Tests show gas stagnation on the rough surface drives gas through the rocks and brings up soil, undercutting the surface
- van Susante innovated a rock filtration system to fix this
- Requires rock rake, size sorter, and emplacement robotics



Gravel Filter

Basic data	percent of regolith usable rock	2	%
	depth of rake	10.16	cm
	speed of rake	25	s/m
	width of rake	1	m
	speed laying rock per layer	300	s/m2
	Number of rock size layers	4	
	energy of vibratory rake	0.22222222	kWh/m
	energy of rock sorter	0.005	kWh/kg
	power of rock laying device	100	W
	distance betw rake area & pad	0.25	km
	rock load per trip	1000	kg
	driving speed	1	m/s
Outer Area	%wt additive	7	%
	thickness	22.86	cm
	mass of rock layers	924.28232	MT
	mass of raked regolith	13204.03	MT
	area of raked regolith	59073.16	m2
	distance of racking paths	59.0731619	km
	time raking	17.0929288	d
	No grading and compacting		
	time laying rock	6.38136008	d
	number rock loads hauled	925	
	driving distance hauling rock	231.25	km
	driving time hauling rock	2.67650463	d
	total construction time	**26.1507935**	**d**
	energy raking	13.1273693	MWh
	energy sorting	4.6214116	MWh
	energy laying rock	0.01531526	MWh
	total energy	**17.7640962**	**MWh**
Inner Area	Not Applicable		
Equipment	Rake and Sorter Rover	1000	kg
	Rock laying device	300	kg

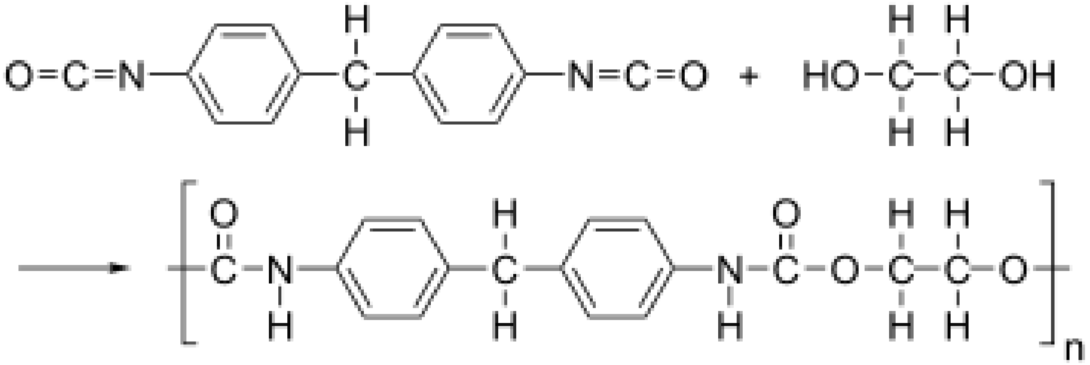
Credit: HDTrommels.com

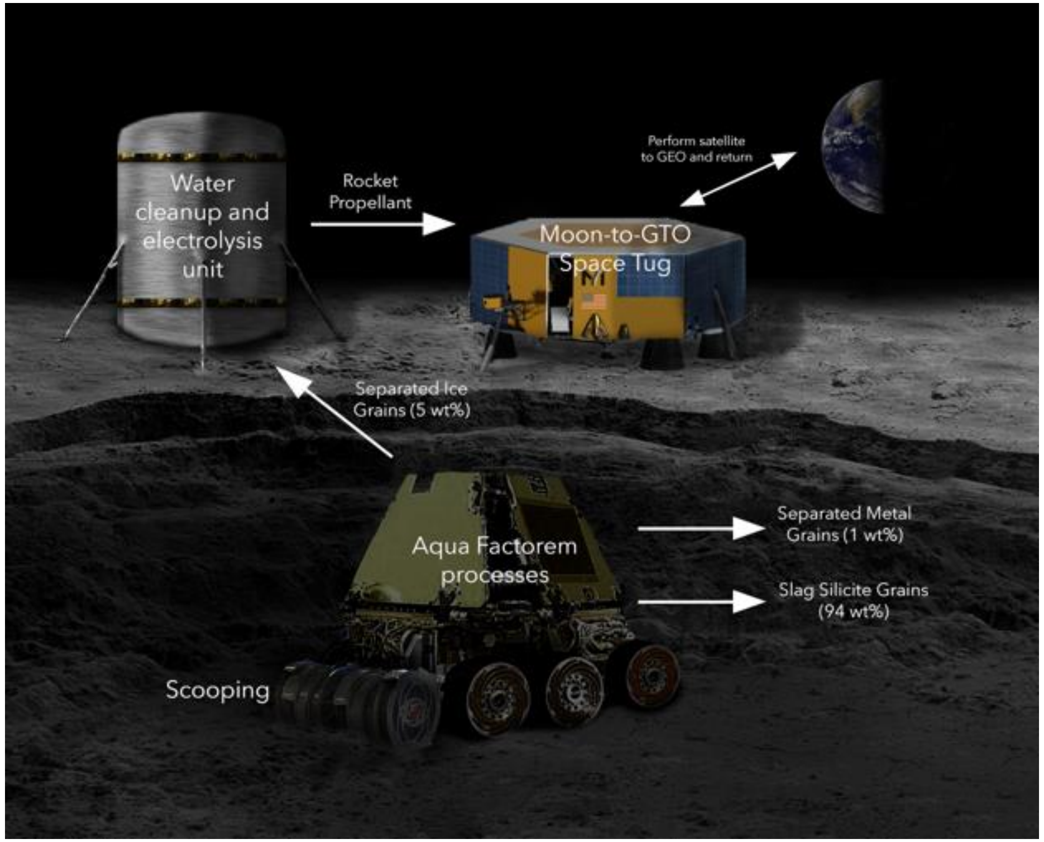
Polymer Application

- Used terrestrially on makeshift airfields in deserts
- SBIR developed by Adherent Tech
- 5%wt may be adequate for low temperature
- 15%wt may be needed for high temp
  - High temp case tested for Mars entry heat shields
  - Ablates under high temperature, may need replacement

Polymer Infusion

Basic data	density of compacted regolith	2200	kg/m3
	application speed	0.1	m^2/s
	Spray width	1	m
	Distance from pad to polymer storage	1	km
	polymer density	1000	kg/m3
Outer Area	%wt additive	7	%
	thickness	2.5	cm
	outer mass of involved soil	101.080744	MT
	brought mass	9.65	MT
	Grading & Compacting time	10.21	hours
	infusion time	10.2101761	hours
	Trips to refill tank	10	
	Total time	1.08232949	days
	Driving distance while sprayiing	1837.8317	m
	Total energy	0.01364864	MWh
Inner Area	percent	30	%
	thickness	5.08	cm
	mass	68.94	MT
	brought mass	20.68	MT
	Grading & Compacting time	3.77	hours
	infusion time	2.51327412	hours
	Trips to refill tank	21	
	Total time	0.7479105	days
	Driving distance while sprayiing	452.389342	m
	Total energy	0.02653274	MWh
Equipment	Rover mass	300	kg
	Sprayer attachment & tank	100	kg
	Tank volume	1	m3
	Mass polymer in full tank	1000	kg
	Driving speed	1	m/s



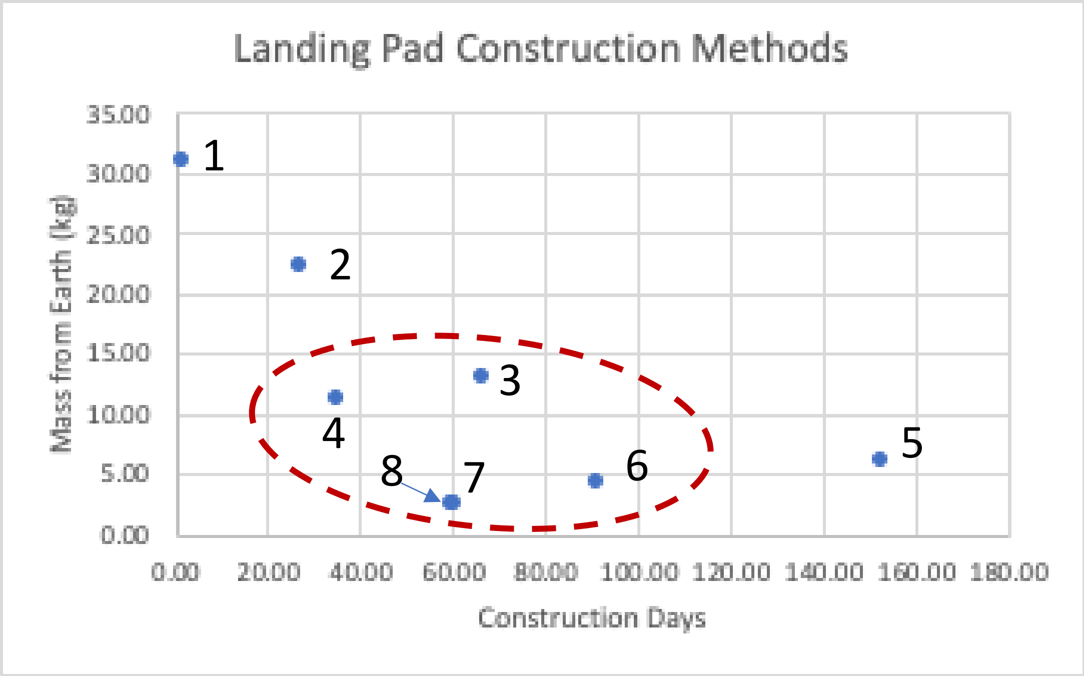


Trades, Combined Inner & Outer

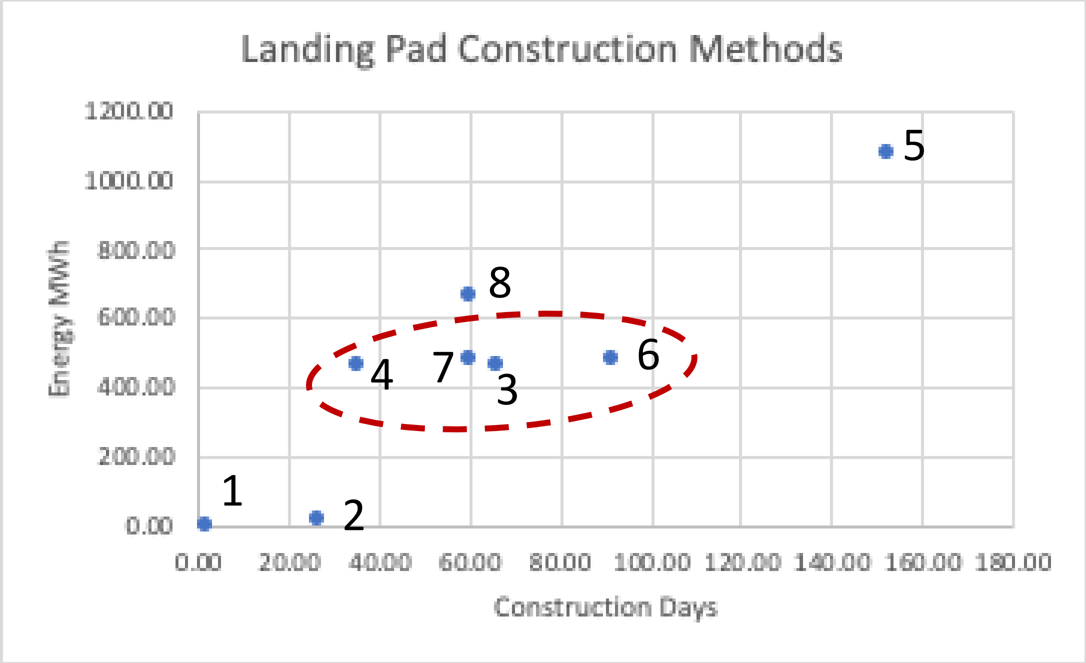
Methods		Time	Energy	Mass
Inner	Outer	days	MWh	MT
Sinter	Sinter	152.67	1073.87	6.02
Sinter	Polymer	66.43	460.46	13.06
Polymer	Polymer	1.83	0.04	31.13
Pavers	Polymer	35.17	460.46	11.25
Pavers	Pavers	59.81	663.48	2.40
Sinter	Gravel	91.50	478.21	4.31
Polymer	Gravel	26.90	17.79	22.38
Pavers	Gravel	60.24	478.21	2.50

Additional Considerations

- Mass of Power Systems
  - Microwave Sintering doubles the power demand compared to the other methods
- Chicken-and-Egg problem
  - How do you land the power systems and other necessary assets BEFORE you have the landing pad?
- Reliability
  - Avoid more complicated processes like gravel raking, sorting and laying.
- Maybe make a Phase 1 landing pad before the final



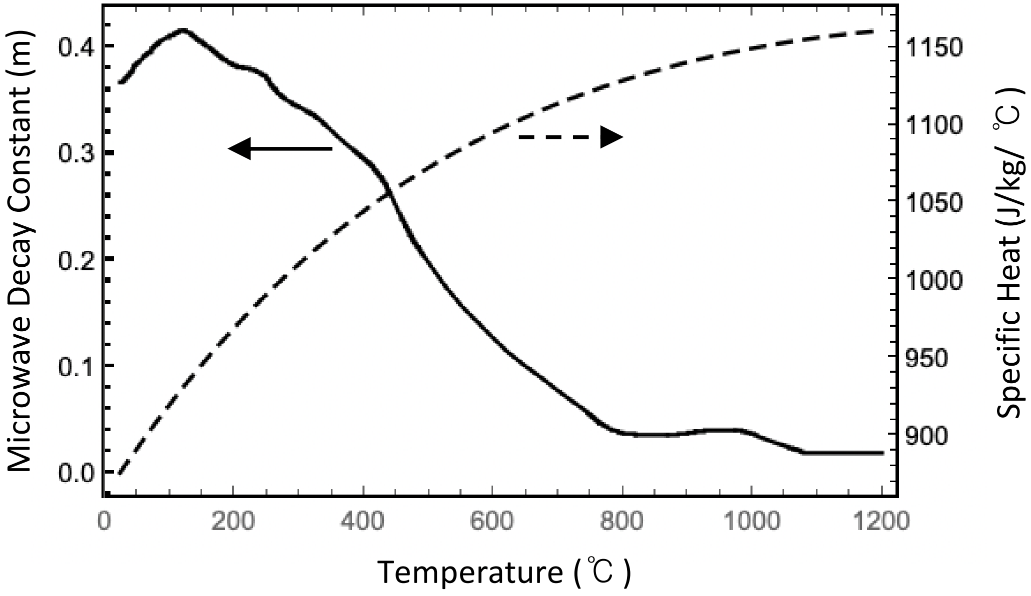
1 All polymer
2 Inner polymer, outer gravel
3 Inner sinter, outer polymer
4 Inner pavers, outer polymer
5 All sinter
6 Inner sinter, outer gravel
7 Inner pavers, outer gravel
8 All pavers

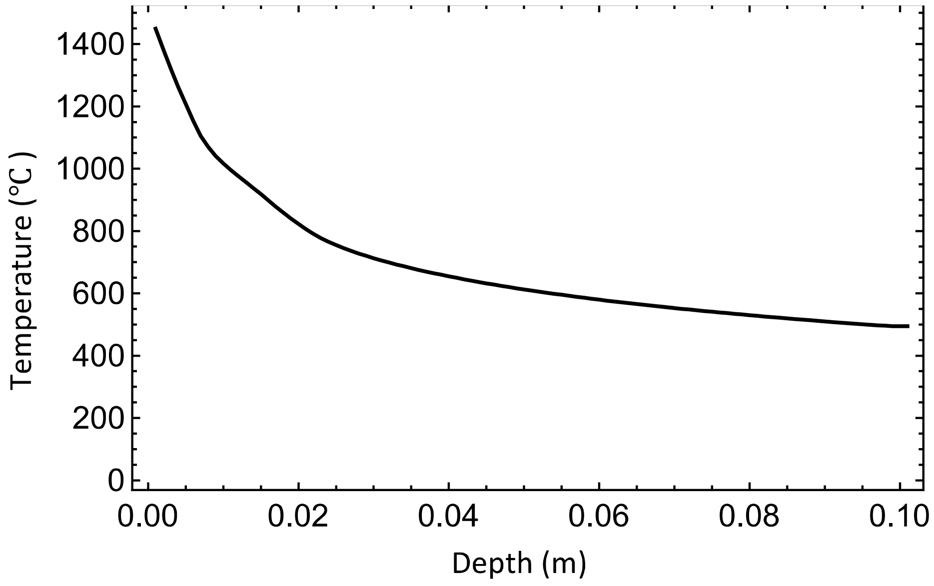


1 All polymer
2 Inner polymer, outer gravel
3 Inner sinter, outer polymer
4 Inner pavers, outer polymer
5 All sinter
6 Inner sinter, outer gravel
7 Inner pavers, outer gravel
8 All pavers

Microwave Sintering Physics

- Microwave absorption by Allan et al. (2013)
- Specific Heat based on basalt by Bouhifd et al. (2007).
- Wrote a finite difference model that predicts temperature versus depth for a given microwave input to the soil



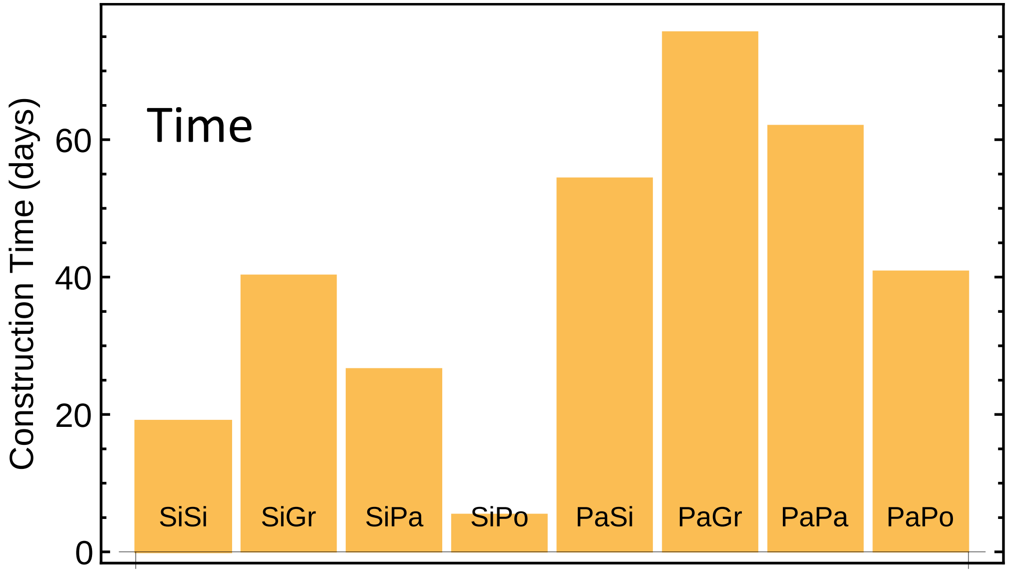


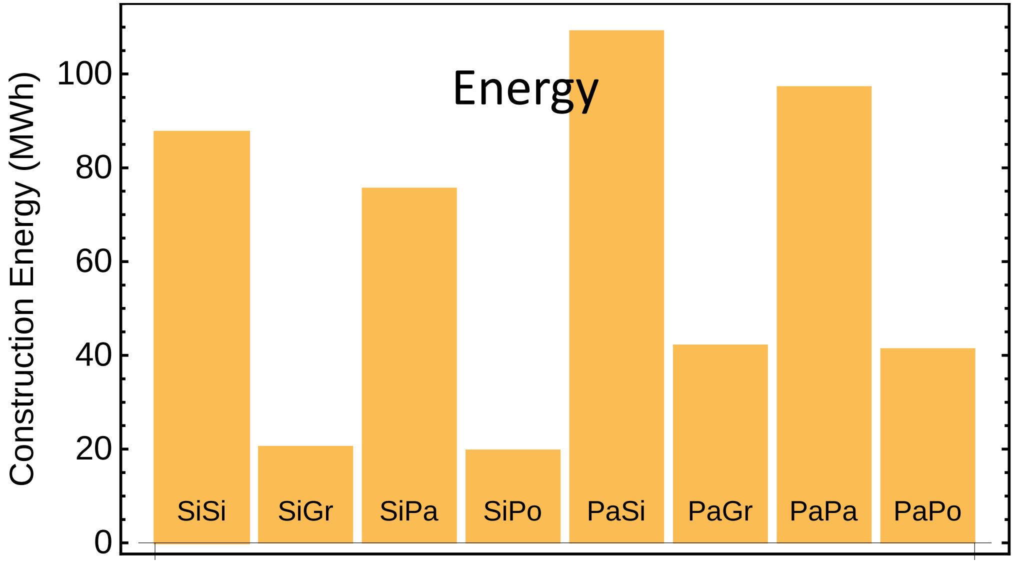
Allan, S. M., et al. (2013) *J. Aerosp. Eng.* 26.4, 874-881.

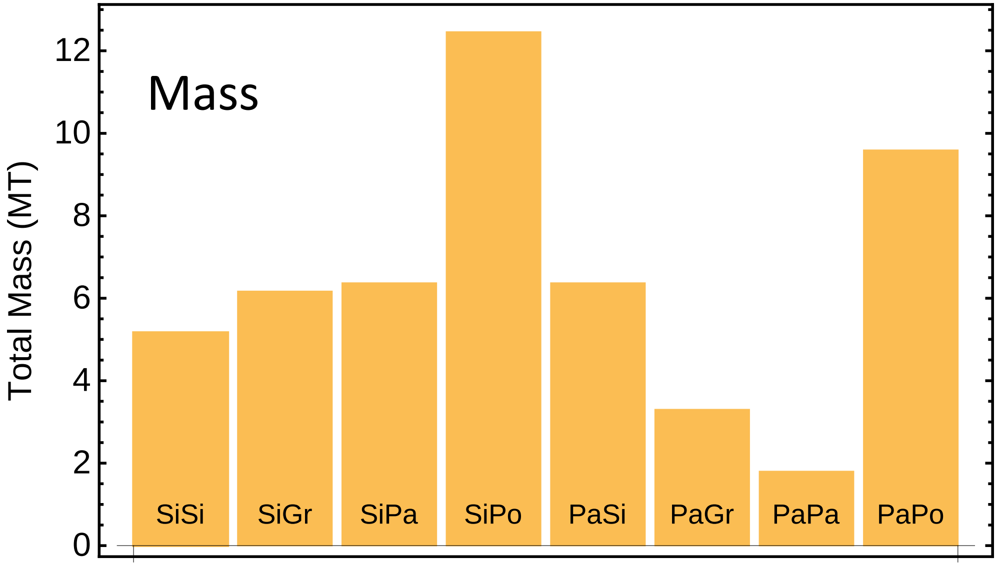
Bouhifd, M. A., et al., (2007), Contrib. Mineral. Petrol. 153.6, 689-698.

Non-Optimized Results

Signifier	Inner Pad	Outer Pad
SiSi	Sintered	Sintered
SiGr	Sintered	Gravel/Rock
SiPa	Sintered	Pavers
SiPo	Sintered	Polymer
PaSi	Pavers	Sintered
PaGr	Pavers	Gravel/Rock
PaPa	Pavers	Pavers
PaPo	Pavers	Polymer



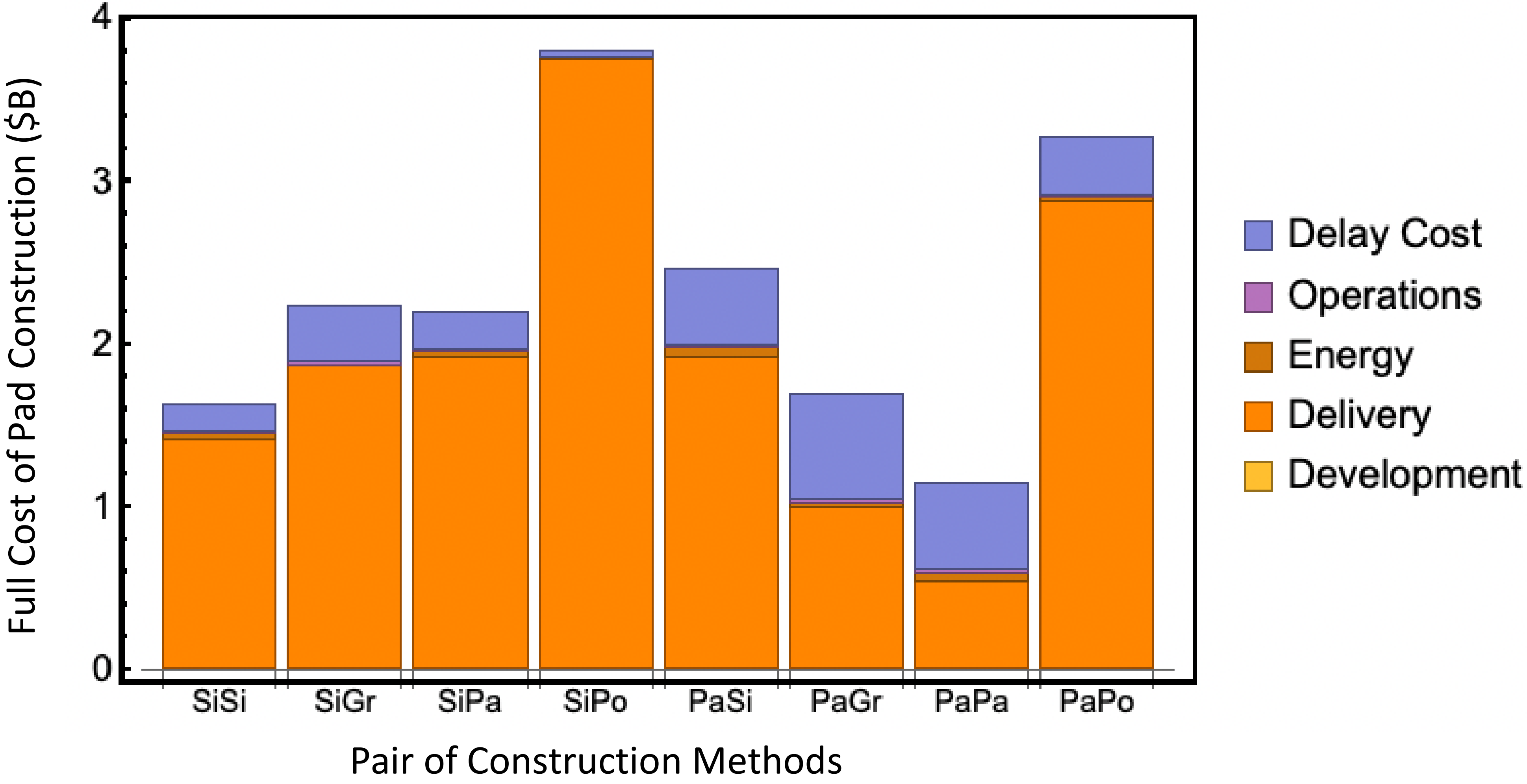




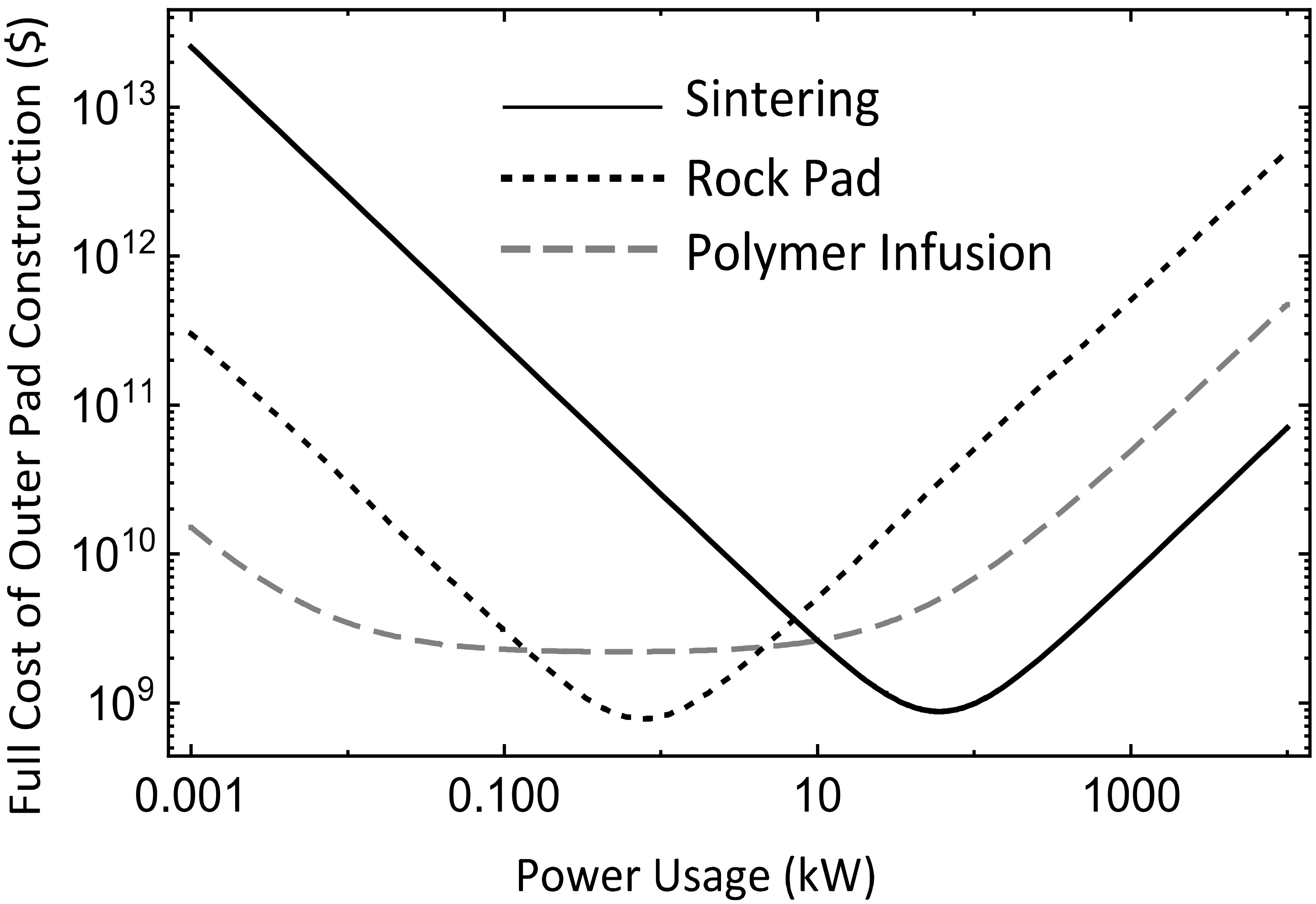
Baseline Economic Assumptions

Parameter	Value	Units
Program Data		
Total Cost of the Lunar Program	100	$B
Program Duration	20	years
Discount Rate for Federal Money	3.5	%
Fraction of Program Reprogrammable (see text)	75	%
Hardware Development Cost Rate	1.684	$M/kg
Transportation Cost to the Lunar Surface	300	$K/kg
Yearly Operations Cost (for pad construction)	124	$M
Energy Systems Data		
Solar Photovoltaic Mass-to-Power Ratio	30	kg/kW
Solar Photovoltaic Lifespan	20	years
Solar Duty Cycle	80	%

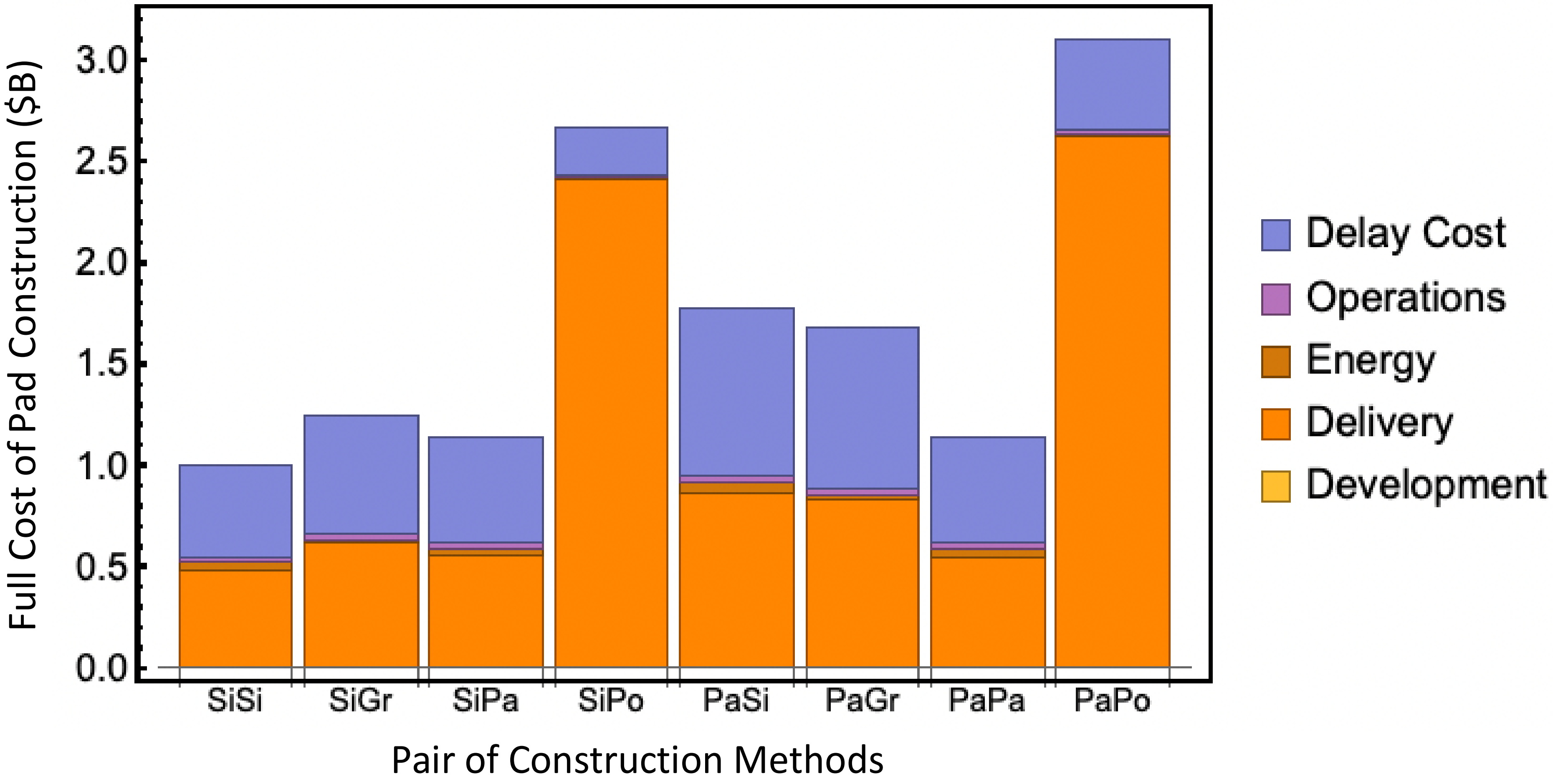
Non-Optimized Costs



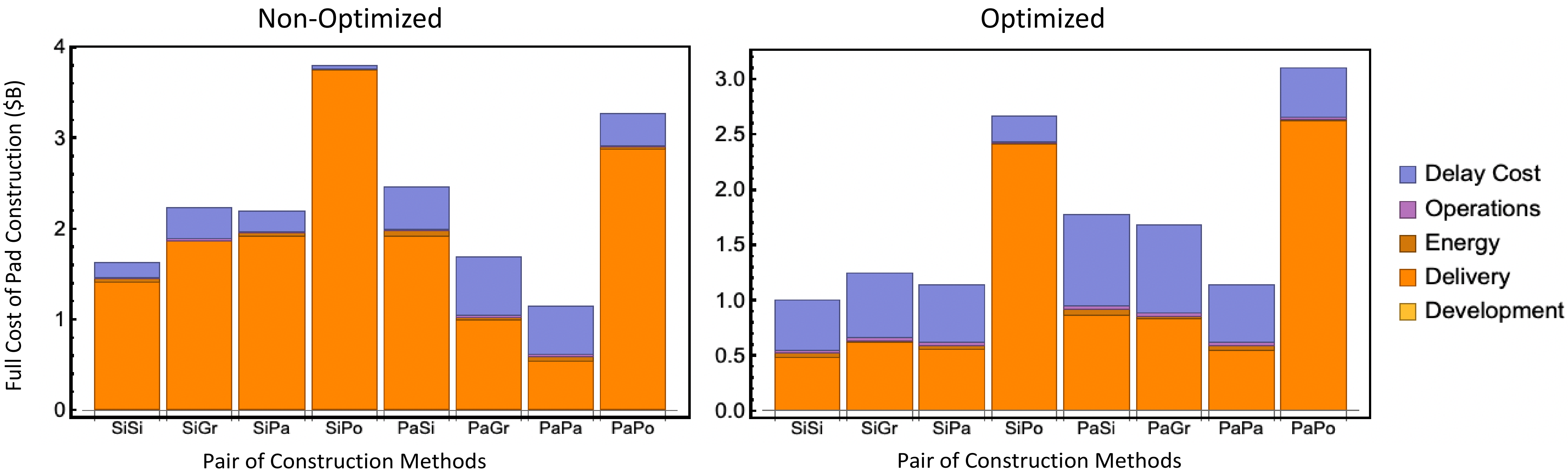
Cost vs. Size of Construction Set



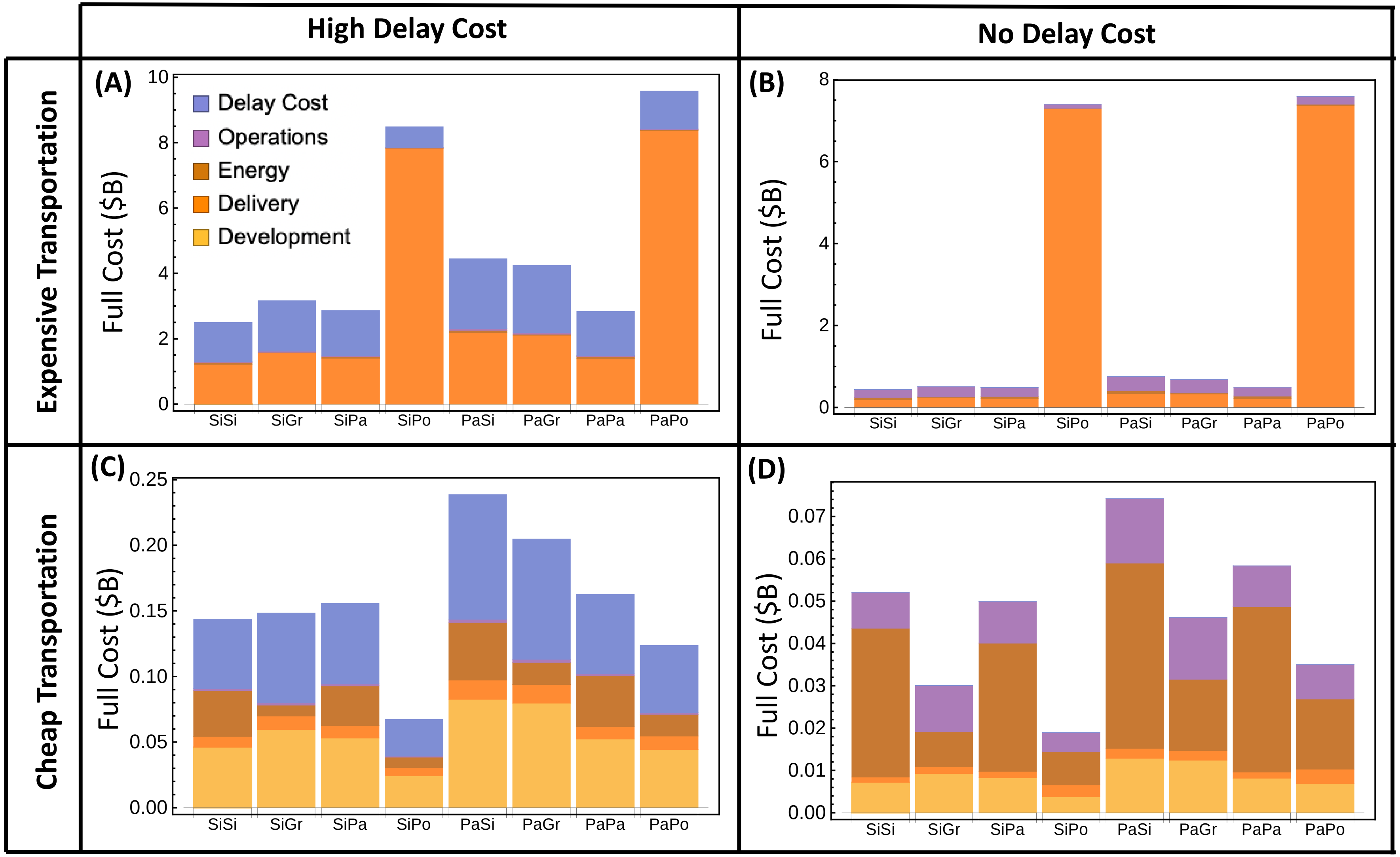
Costs for Optimized Systems



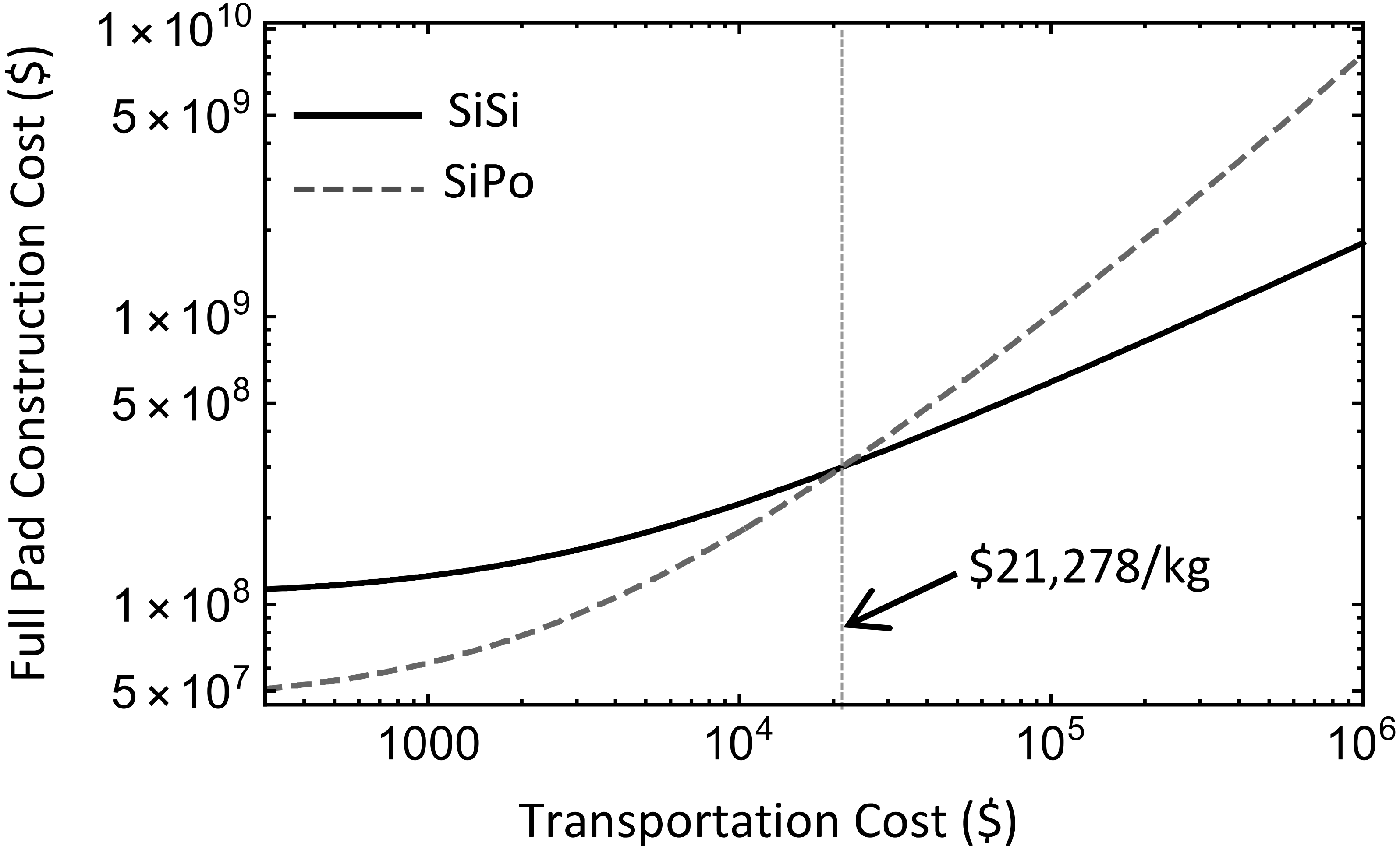
Non-Optimized vs. Optimized



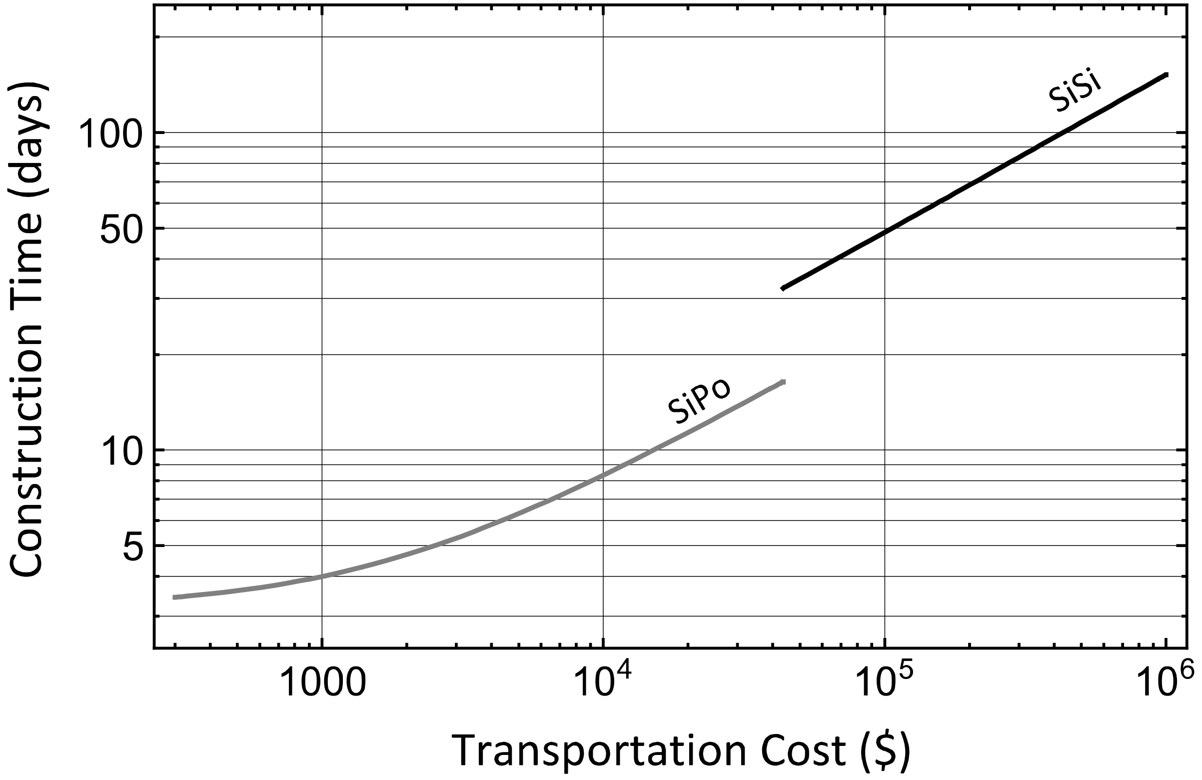
Four Economic Scenarios

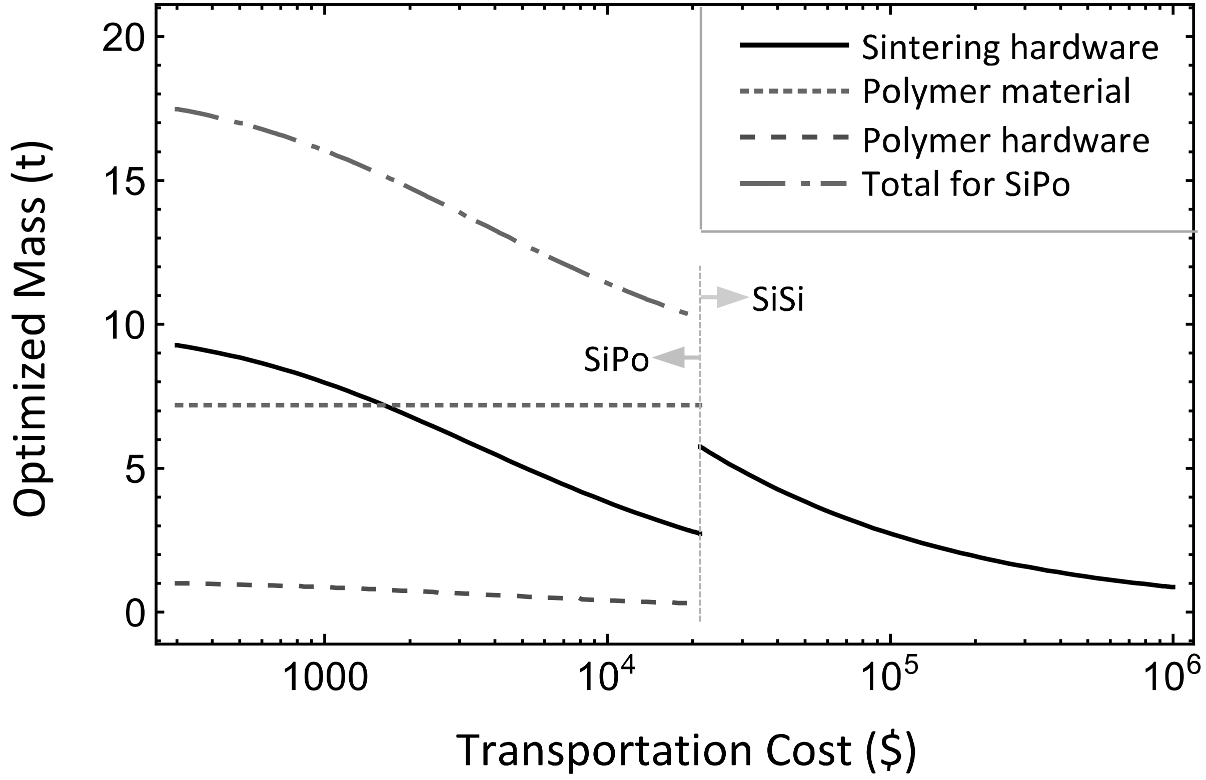


Crossover to Use of Polymer



Crossover to Use of Polymer





Optimized Systems for 4 Transportation Costs

Item	Supporting the Baseline Outpost			
Transportation Cost	\$1M/kg	\$100K/kg	\$10K/kg	\$2K/kg
Method	SiSi	SiSi	SiPo	SiPo
Number of Rovers	1	3	3	5
Total Mass of Rover(s)	201 kg	631 kg	883 kg	1,572 kg
Sintering Hardware Mass	670 kg	2,104 kg	2,942 kg	5,240 kg
Polymer Application Systems Mass	0	0	185 kg	100 kg
Polymer Material Mass	0	0	7.2 t	7.2 t
Max Power Needed	37.3 kW	117 kW	164 kW	291 kW
Total Construction Time	97.6 d	31.1 d	5.5 d	4.1 d
Full Cost	\$1,802M	\$593M	\$107M	\$78.4M
Appropriated Cost (1)	\$914M	\$291M	\$52.0M	\$41.3M

Conclusions

- Several technologies (sintering, pavers, gravel filter) have roughly equivalent cost (within error bars)
- Polymer is not competitive until transport < ~ $20K/kg

- Early in Artemis
  - Delay and transportation costs will dominate
  - Must budget ca. $300M to $900M
  - To sell this cost, we may need to emphasize the inherent good in learning to live off the land by doing construction

- Later, Cheap Transportation
  - Operations and development costs will dominate
  - Only $40M to $50M
  - Ops & development costs are both very responsive to the Experience Curve (Wright's Law)
  - Expect another 10X cost reduction


Questions?
NASA

National Aeronautics and Space Administration

LARGE VEHICLE LUNAR LANDING SURFACE INTERACTION AND IN-SITU RESOURCE BASED RISK MITIGATION

PTMSS / SRR

June 10, 2021

R. P. Mueller[1], N. J. Gelino[1], K. L. Dixon[1], B. T. Vu[1], and L. Sibille[2]

[1]National Aeronautics & Space Administration (NASA), Kennedy Space Center, Swamp Works, M/S: UB-E-2, KSC, Florida 32899

[2] Swamp Works, Southeastern Universities Research Association (SURA), LASSO-013, Kennedy Space Center, FL 32899, USA

NASA ACO with SpaceX

80HQTR19SOA01

Space Technology Announcement of Collaboration Opportunity (ACO)

Focus Area: Entry, Descent and Landing

Game Changing Development Program

Large Vehicle Landing Surface Interaction

Project Schedule: October 1, 2019 – May 30, 2021

Large Vehicle Lunar Landing Risk Mitigation

A key capability required for the exploration of planetary bodies is the ability to land on the surface.

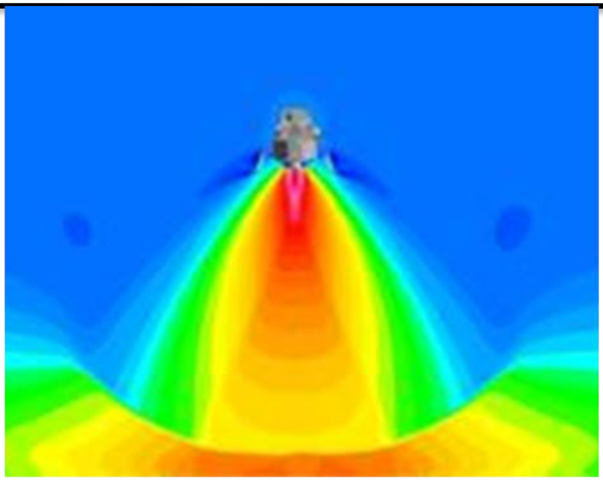
Previous work performed by NASA and other institutions has primarily focused on landing small spacecraft on planetary surfaces and the associated small-to-medium thrusters required for the soft landing.

In the case of human exploration—particularly the establishment of long duration exploration and habitation outposts—**the ability to land large landers, such as the SpaceX Starship (Raptor Engine Thrust ~500,000 lbf, 2,224 kN), is necessary.**

The Apollo Lunar Descent Module had ~10,116 lbf, 45 kN thrust (~50 X less)

An improvement in landing safety and reliability can be achieved by constructing **landing/launch pads (LLP)**, especially with in-situ resources.

Plume Surface Interaction (PSI) Modeling & Materials Testing



Apollo Lander Gas Density at 30 m
Source: NASA

SpaceX Falcon 9 1st Stage Landing
Source: Wikipedia

- **A rocket engine plume has an under-expanded nozzle in a lunar vacuum**
- **The plume spreads rapidly into the vacuum**
- **NASA collaborated with CFD Research Corporation inc. under a Phase III SBIR contract to model the Plume Surface Interaction**
- **This work contained two parts:**

(1) Computer modeling of a large rocket engine plume interacting with regolith on the Moon, using the Granular Gas Flow Solver (GGFS) provided by CFD Research Corporation as well as other computational fluid dynamics codes (CFD) such as Loci/CHEM

(2) Developing landing/launch pad materials that could be used for in-situ construction on the lunar surface in the future, to mitigate the calculated effects of a large vehicle rocket engine landing and launching on the Moon.

Pad Structure Concept Groups

LLP Structure Concepts
Minimal Preparation
Existing Topography
Compacted Regolith Surface
Bedrock Surface
Ice Surface
Rock Piles
Surface Stabilization Applications
Regolith Bags
Ice Bladders
Pavers
Metallic Plates
Deployable Structures
Direct Emplacement of Sintered Structures
Direct Emplacement of Polymer Concretes
Direct Emplacement of a Concrete Pad

Gelino, N. J., Mueller, R. P., Moses, R. W., Mantovani, J. G., Metzger, P. T., Buckles, B. C., & Sibille, L. (2020). Off Earth Landing and Launch Pad Construction—A Critical Technology for Establishing a Long-Term Presence on Extraterrestrial Surfaces. In *Earth and Space 2021* (pp. 855-869).

- There are a wide range of possible solutions, from landing on an unprepared surface to major construction efforts such as sintered or concrete pads
- Each concept has benefits and drawbacks
- There is a timing aspect – initial solutions may be very different from long term, later year, solutions:
  - Should we could accept more risk initially or rely more heavily on materials from Earth?
  - Do we work towards a fully ISRU based comprehensive solution right away?
  - Once we have expanded capabilities on the surface previously infeasible approaches may appear
- Lunar LLPs are a complex problem
- **There are no "silver bullets"**
  - Multiple concepts should be funded to reduce risk

5

Key Criteria

Preparation and Staging Phase	Construction Phase	Operations and Maintenance Phase
Up-Mass of Construction Materials and Systems	Constructability	Performance as a Landing/Launch Surface
Difficulty of Insitu Materials Collection, Handling, and Processing	Versatility	Expected Life
Effort of Site Preparation/Staging Time	Construction Time	Ease of Repairability
Reliance on other Surface Assets	Reliance on other Surface Assets	Reliance on Lunar, Gateway and Earth Crew Interaction
Reliance on Lunar, Gateway and Earth Crew Interaction	Reliance on Lunar, Gateway and Earth Crew Interaction	Robotics and Autonomy
Robotics and Autonomy	Robotics and Autonomy	Required Power
Robustness of process	Robustness of process	Lifecycle cost
Current Technology Readiness Level	Current Technology Readiness Level	
Required Power	Required Power	
	Ability to Verify As-Built Performance	

Gelino, N. J., Mueller, R. P., Moses, R. W., Mantovani, J. G., Metzger, P. T., Buckles, B. C., & Sibille, L. (2020). Off Earth Landing and Launch Pad Construction—A Critical Technology for Establishing a Long-Term Presence on Extraterrestrial Surfaces. In *Earth and Space 2021* (pp. 855-869).

- LLP activities are split into three phases
  - Prep and Staging
  - Construction
  - Operations and Maintenance
- Criteria are intended to be key differentiators that are affected by mission constraints and drive concept of operations
- Weighting of criteria can be adjusted based on the Architecture
- Criteria are quantifiable whenever possible

Examples:

- Use Existing Topology
- Direct Emplacement of Polymer Concrete
- Direct Emplacement of Sintered Structures

Considered Concepts

The trade study produced the following short list of candidate materials concepts that were deemed worthy of testing to observe their performance under engine exhaust plumes.

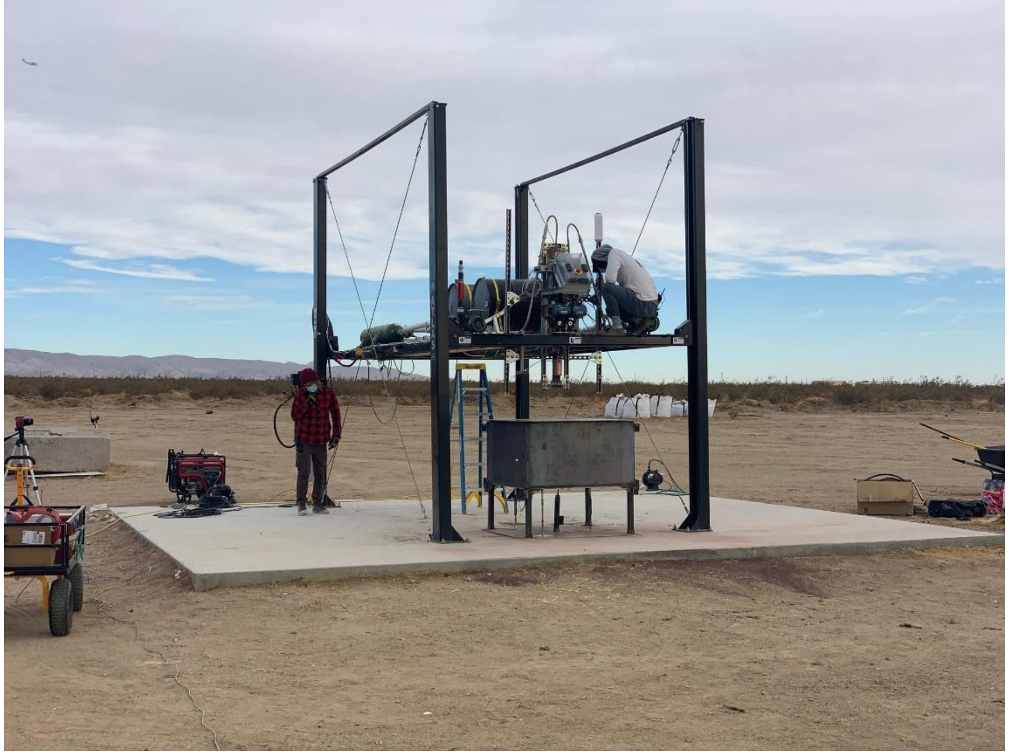
Pad Material Concept	TRL	Test Feasibility Decision
Prepared Regolith Surface (leveled, compacted, and cleared)	5	Previously tested in air under engine plumes by Small Business Innovative Research Contracts (SBIR)
Bedrock Surface	3	Availability of large lunar simulant rock uncertain. Not testable at present.
Rock Piles in Gabion Cages	3	Anorthosite rocks were available and on site at KSC
Regolith bags (Basalt fiber, carbon fiber, Nomex, glass fiber)	3	Materials were available. Low difficulty in design and manufacturing.
Metallic plates	5	Tested during Morpheus test campaign at KSC
Sulfur concrete	4	Not available to project due to schedule constraints.
Synthetic biology concrete	3	Not available to project due to schedule constraints.
Thermally Sintered regolith	4	Available through PISCES partnership
Thermoset polymer binder with regolith	4	Available at KSC GMRO lab with current capabilities
Deployable mat of basalt or carbon fiber textile layers	3	Available COTS materials and feasible manufacturing
Sintered regolith by metal powder combustion	3	Not available to project due to schedule constraints

Selected Concepts for PSI Testing

	Pad Material Concept	TRL	Test Feasibility Decision
1	Thermally sintered Hawaiian regolith pavers	4	Available through PISCES partnership
2	Thermoset ablative polymer binder with regolith	4	Available at KSC GMRO lab with current capabilities
3	Anorthosite Rock Piles in Stainless Steel Gabion Cages	3	Anorthosite rocks were available and on site at KSC
4	High Temperature Textile Regolith filled bags (Carbon fiber woven textile)	3	Carbon fiber woven materials were available. Low difficulty in design and manufacturing.
5	Deployable blanket of carbon fiber woven and non-woven textile layers	3	Available COTS materials and feasible manufacturing (TexTech inc. partner)

Testing Materials with Masten Space Systems

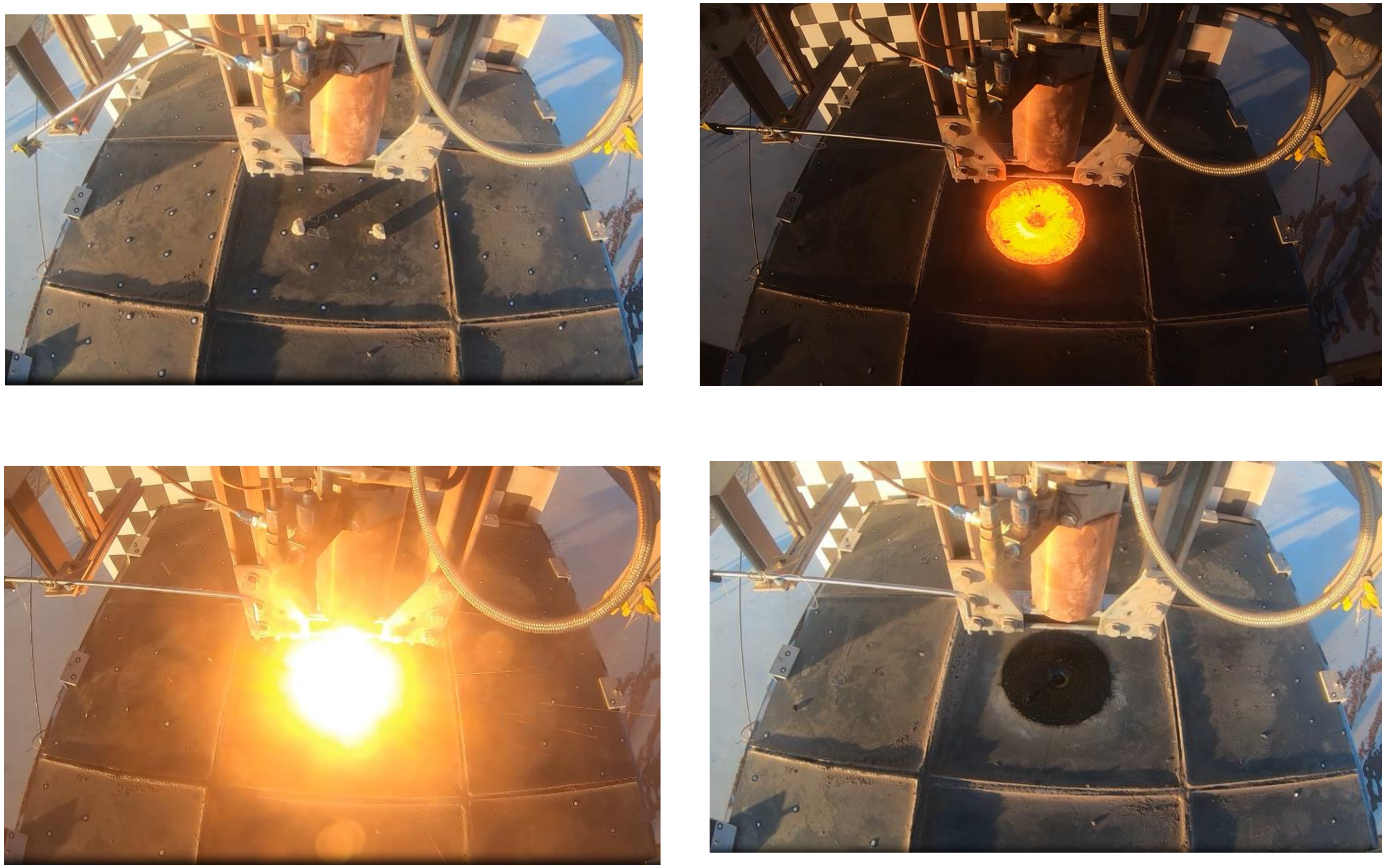
Modeled values of plume impingement surface temperature, stagnation pressure, gas velocity, shear stress and heat flux were then matched as closely as possible in the Earth's atmosphere in a sub-scale rocket engine GO2/CH4 test which was provided by Masten Space Systems in Mojave, California.



Masten Space Systems Rocket engine vertical translation test stand. The pad materials test articles were placed in a regolith bin containing simulated basalt lunar regolith granular material and subjected to a test firing

Regolith bin with pad material test article under the rocket engine test stand

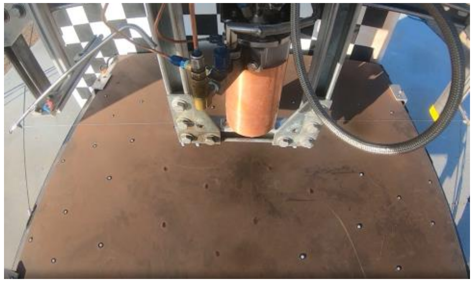
Thermally sintered Hawaiian regolith pavers (with grout)

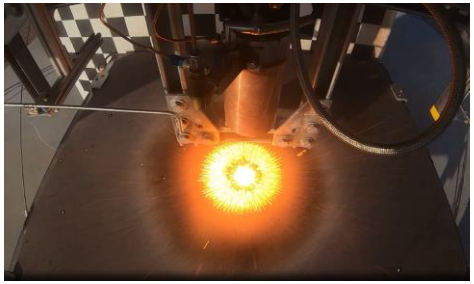


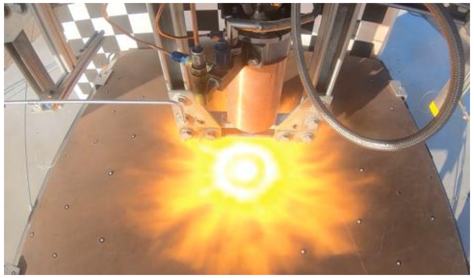
✓

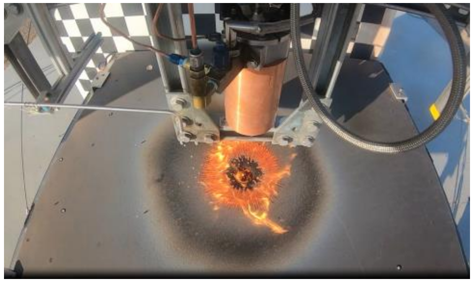
Pass

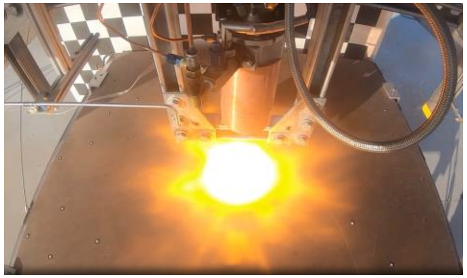
Thermoset ablative polymer binder with regolith

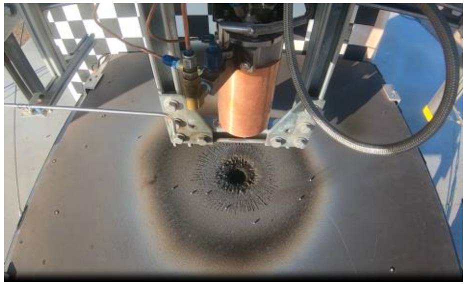












✓

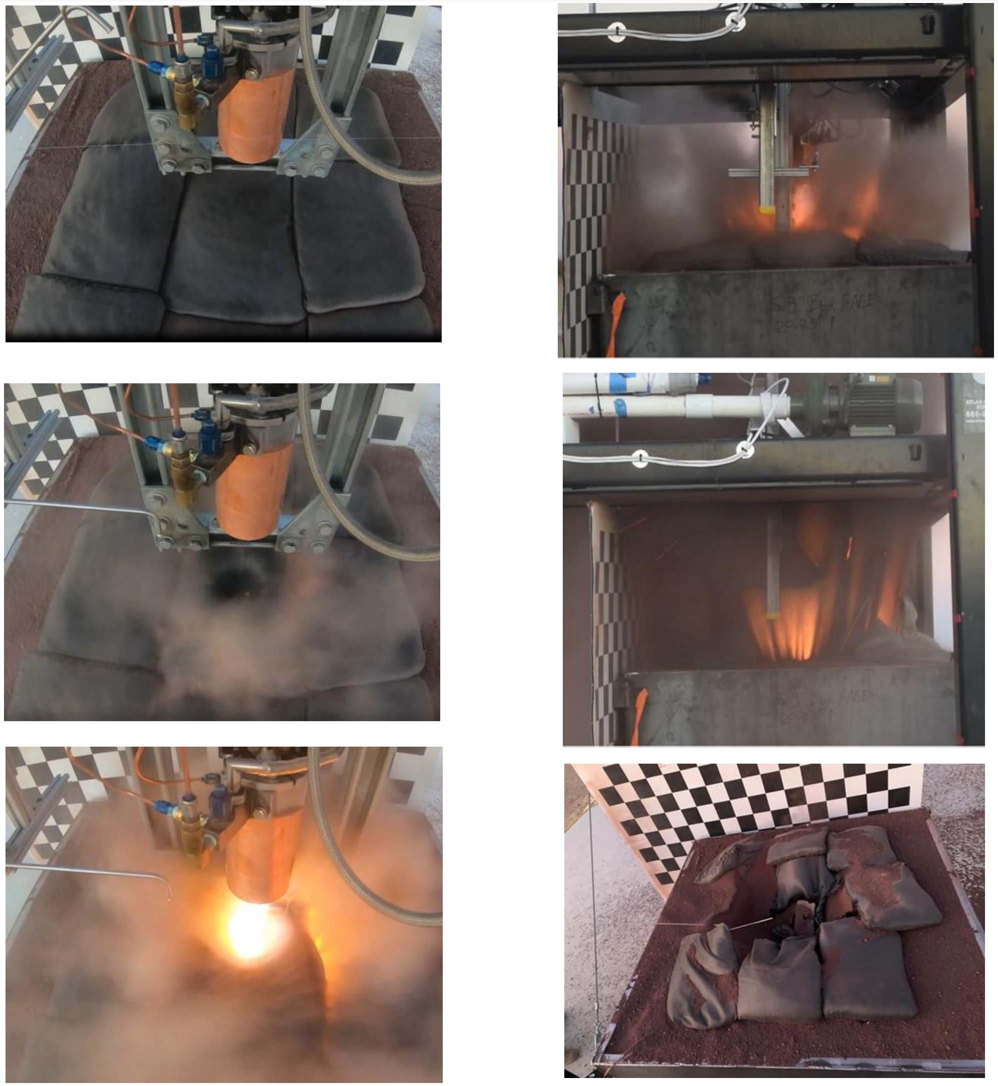
Pass

Anorthosite Rock Piles in Stainless Steel Gabion Cages

✓

Pass

Textile regolith filled bags (Carbon fiber woven textile)



X

Fail

Deployable blanket of carbon fiber woven and non-woven textile layers

?

More work needed

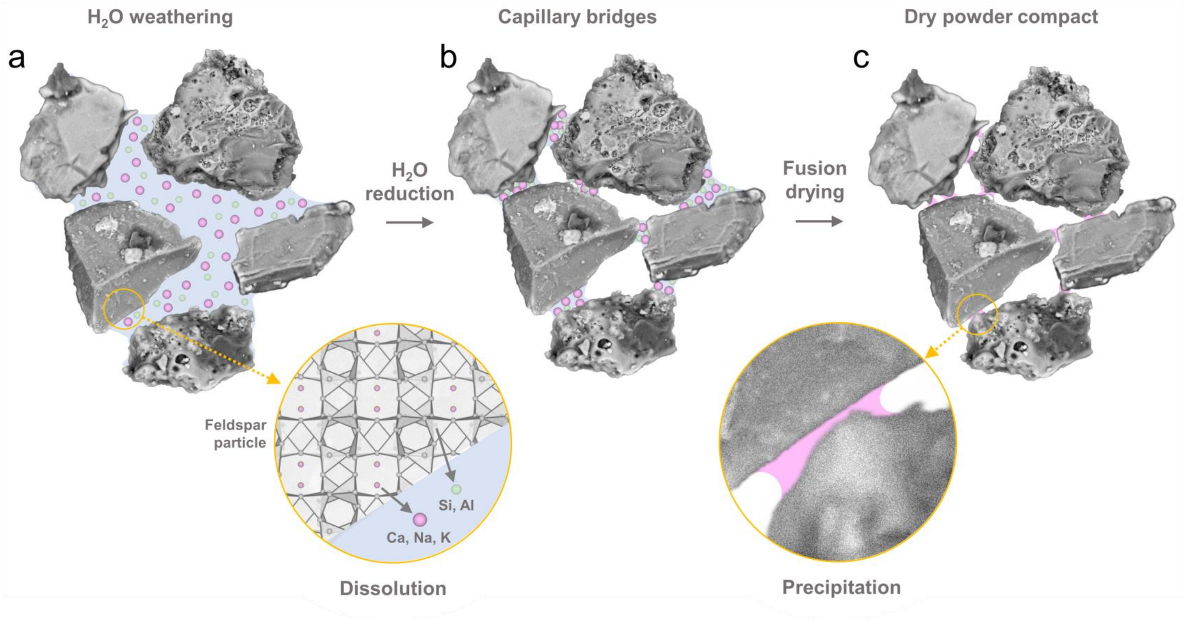
Conclusions

- The computer modeling work was able to predict the Plume Surface Interactions effects of a large O_2/ CH_4 Rocket Engine in lunar vacuum
- Testing in Earth's atmosphere with a small O_2/ CH_4 rocket engine could not accurately replicate a large rocket engine in lunar vacuum
- However, the small rocket engine testing was able to provide a plume with relevant temperatures, pressures, gas velocities and gas densities
- The test program tested 5 LLP materials concepts
- 3 concepts using ISRU passed the testing
- 1 concept failed
- 1 concept showed promise with further development needed

- Building a LLP will depend on feasible materials solutions
- Near term ISRU LLP materials solutions are available

The 11th joint Planetary and Terrestrial Mining Sciences Symposium
And Space Resources Roundtable

Lunar Construction – 10 June 2021, Thursday; 13:00-15:00



Synthetic H_2O weathering and wet-processing of unrefined regolith towards high strength 'sandcastles'.

David Karl[1] and Aleksander Gurlo[1]

[1]Chair of Advanced Ceramic Materials – Technische Universitaet Berlin

Correspondence: **karl@tu-berlin.de**

Previous work: Non-clay Martian simulants

Wet-processing non-clay Martian simulant (JSC Mars-1A) for complex ceramics

Wet-processing:
- Non-clay martial regolith simulant ceramics proof of concept
- Stabil slurries without dispersant (high simulant porosity)
- Slip cast can be used for complex shaped ceramics

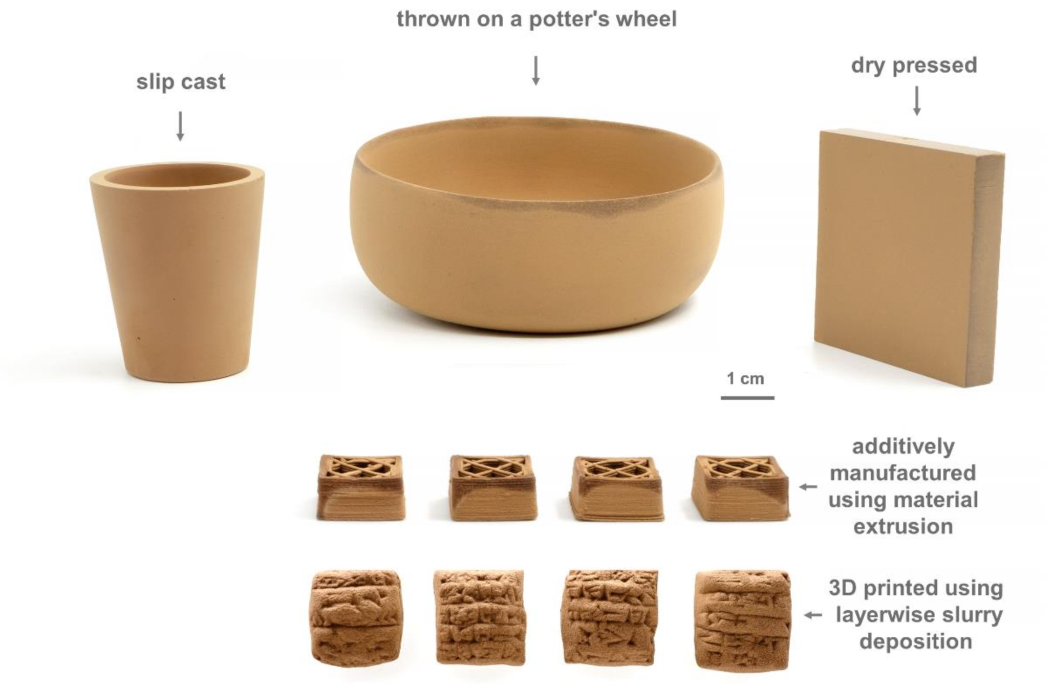
Sintering:
- Good mechanical properties after sintering
- Sinter deformation and remaining porosities

Karl *et al.*, Towards the colonization of Mars by in-situ resource utilization: Slip cast ceramics from Martian soil simulant, PloS one 13 (**2018**) e0204025. https://doi.org/10.1371/journal.pone.0204025.

Previous work: Martian simulants with clay

Wet-processing of clay Martian simulant (MGS-1C) for adobe and ceramics

Green bodies



sintering (firing)

Sintered ceramics

Karl *et al.*, Clay in situ resource utilization with Mars global simulant slurries for additive manufacturing and traditional shaping of unfired green bodies, Acta Astronautica 174 (**2020**) 241-253. https://doi.org/10.1016/j.actaastro.2020.04.064.

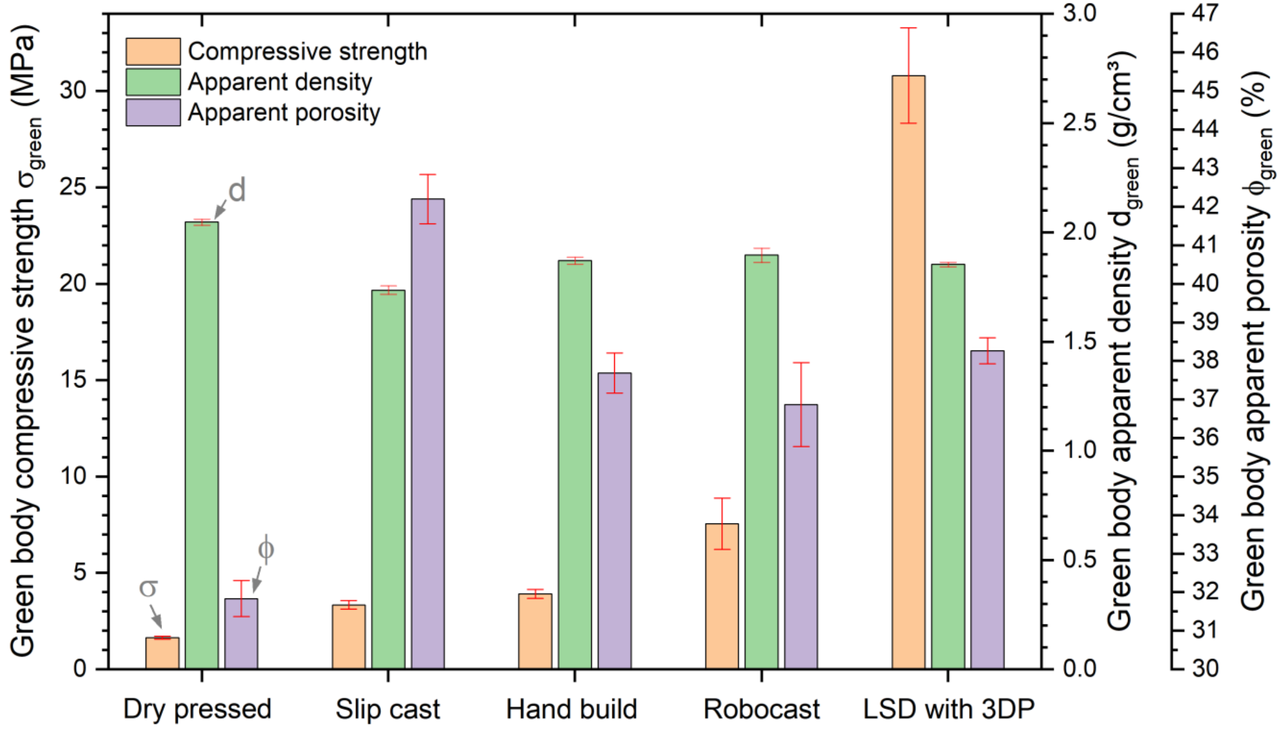
Karl *et al.*, Sintering of ceramics for clay in situ resource utilization on Mars, Open Ceramics 2 (**2020**) 100008. https://doi.org/10.1016/j.oceram.2020.100008.

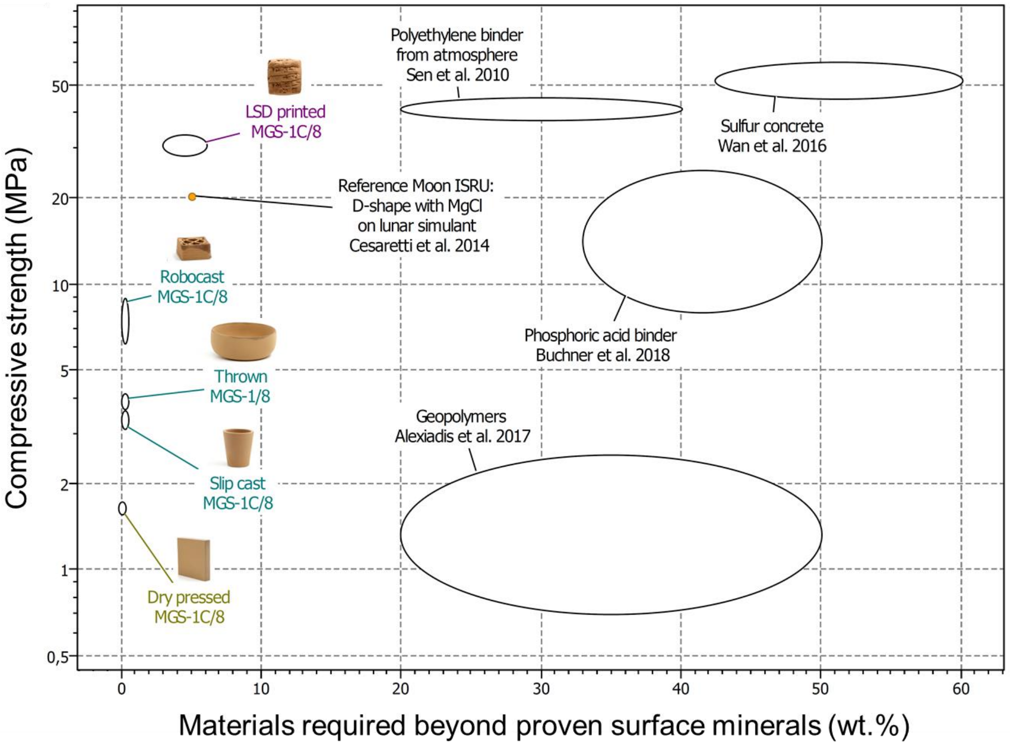
Previous work: Green body/adobe compressive strength

Wet-processing for unfired clay structures using MGS-1C

Proof of concept for adobe

- Good mechanical properties for direct use of regolith
- Sufficient strength for habitat and landing pad building





Karl *et al.*, Clay in situ resource utilization with Mars global simulant slurries for additive manufacturing and traditional shaping of unfired green bodies, Acta Astronautica 174 (**2020**) 241-253. https://doi.org/10.1016/j.actaastro.2020.04.064.

Keramische Werkstoffe

Previous work: Sintered ceramics - flexural strength

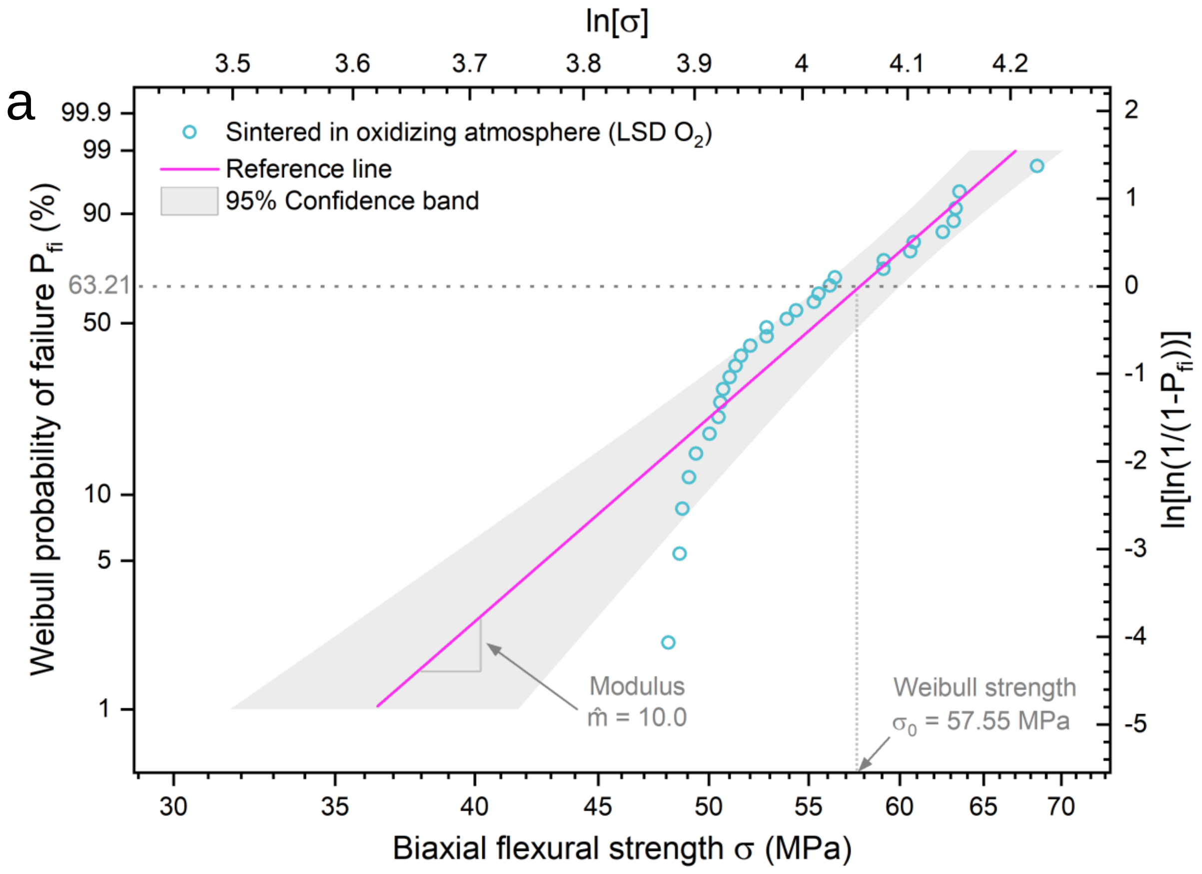
Clay green body sintering using MGS-1C

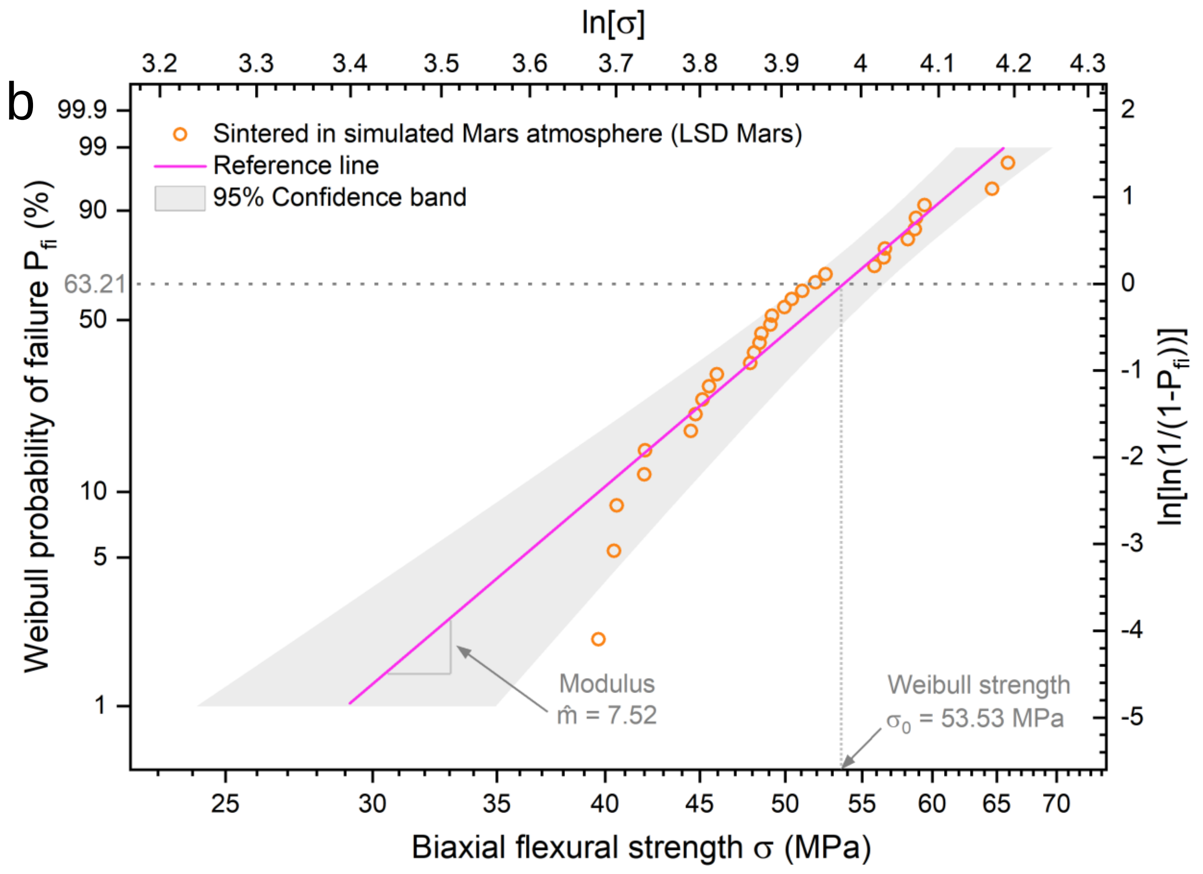
Sintered in oxidizing atmosphere

- Biaxial flexural Weibull strength 57.55 MPa
- Weibull modulus m = 10.0

Sintered in simulated Martian atmosphere

- Biaxial flexural Weibull strength 53.53 MPa
- Weibull modulus m = 7.52





Karl *et al.*, Sintering of ceramics for clay in situ resource utilization on Mars, Open Ceramics 2 (**2020**) 100008. https://doi.org/10.1016/j.oceram.2020.100008.

Previous work: Sintered ceramics

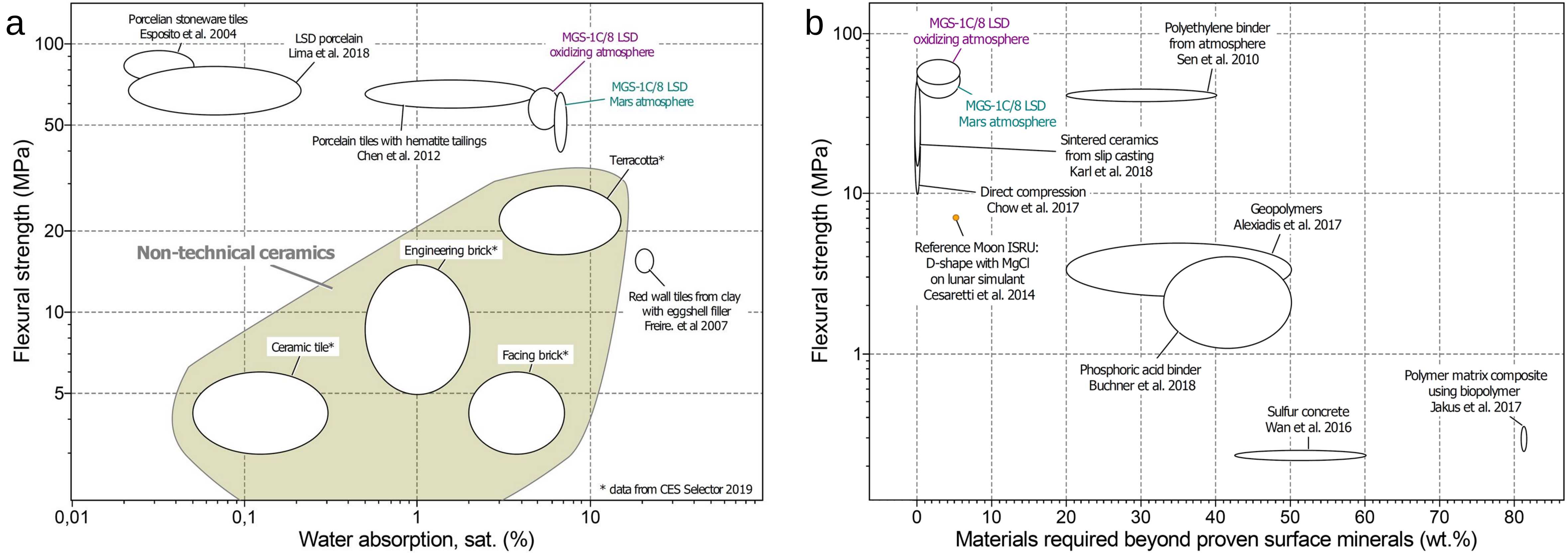
Clay green body sintering using MGS-1C

Sintering in oxidizing and Martian atmosphere:

- Sinter schedules developed
- Bloating hinders dense sintering, due to oxygen release

Characterize sintered materials:

- Iron phase changes observed; **some atmospheres produce metallic Fe phase**
- Excellent flexural strength with remaining porosities
- All shaping approaches generally similar sintering behavior



Karl *et al.*, Sintering of ceramics for clay in situ resource utilization on Mars, Open Ceramics 2 (**2020**) 100008. https://doi.org/10.1016/j.oceram.2020.100008.

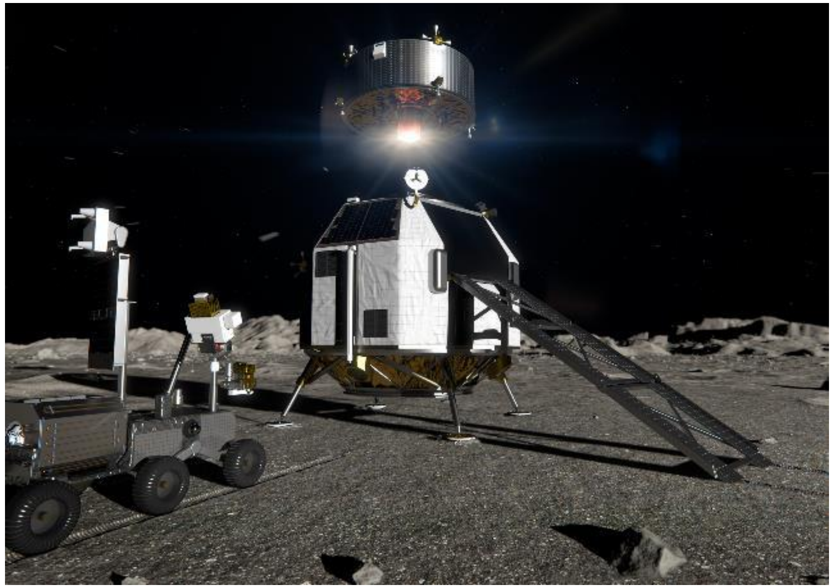
Idea: Lunar regolith wet-processing?

Concept: Proposal wet-lab for EL3 open call

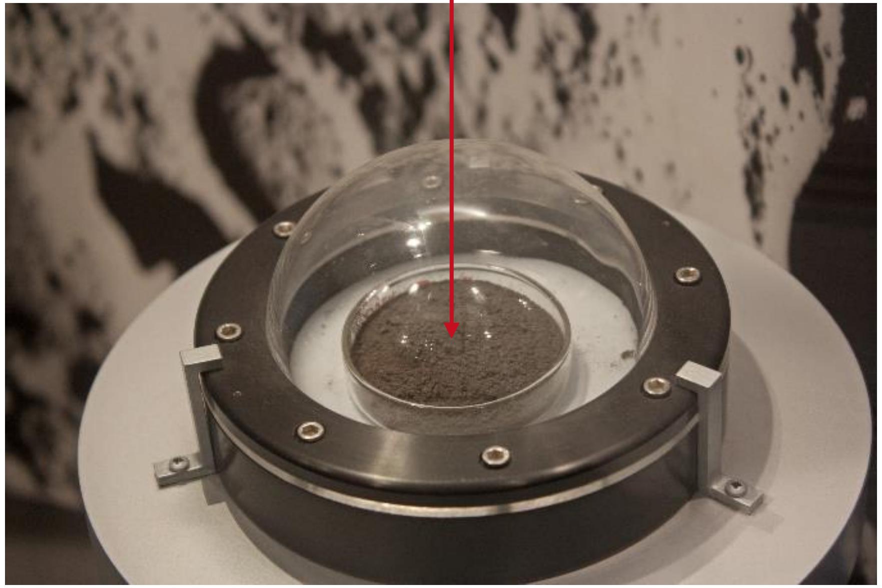
Technische Universität Berlin

Lunar regolith reaction to water?

+ H_2O



European Large Logistics Lander (EL3) return.
Image courtesy of ESA.



Lunar Regolith 70050 sample, collected from the Moon by the Apollo 17 mission, on display in the National Museum of Natural History.

- It has even been proposed that **no other know natural silicate is as reactive in water as Lunar regolith** (Whitney, 1989).
- **Mineral dissolution is inversely proportional to particle size** and water will dissolve primary lunar minerals (e.g., anorthosite, glass).

↓

Regolith water interaction is a real research need for a large number of issues (topic already identified after Apollo)

https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Exploration/European_Large_Logistics_Lander
https://commons.wikimedia.org/wiki/File:Lunar_Regolith_70050_from_Apollo_17_in_National_Museum_of_Natural_History.jpg

Keramische Werkstoffe

Wetting of Lunar Regolith from Apollo (Cooper *et al.*)

Lunar regolith (Apollo 14) H_2O/IPA/pH 4 buffer reaction

Technische Universität Berlin

Table 1. Dissolution of lunar soil 14003 in water, isopropanol, and in a pH 4 buffer solution. Controls were H_2O, isopropanol (IPA), and pH 4 Buffer soltuion without soil or other solute.

Element (mg/L)	H_2O	H_2O Control	Isopropanol (IPA)	IPA Control	pH 4 buffer Solution	pH 4 buffer Solution Control
Silicon (µg/L)	304.5	9	1280	1500	~35,000	~700
Calcium (mg/L)	0.53	0.14	0.1	0.2		
Aluminum (µg/L)	3	2	8	8	~22,500	~100
Magnesium (mg/L)	0.32	0.04	0.04	0.04		
Iron (µg/L)	5	8	20	20	~17,000	~100
Sulfur (mg/L)	0.7	0.7	1.6	1.6		
Titanium (µg/L)	1	1	4	4	~1700	~100

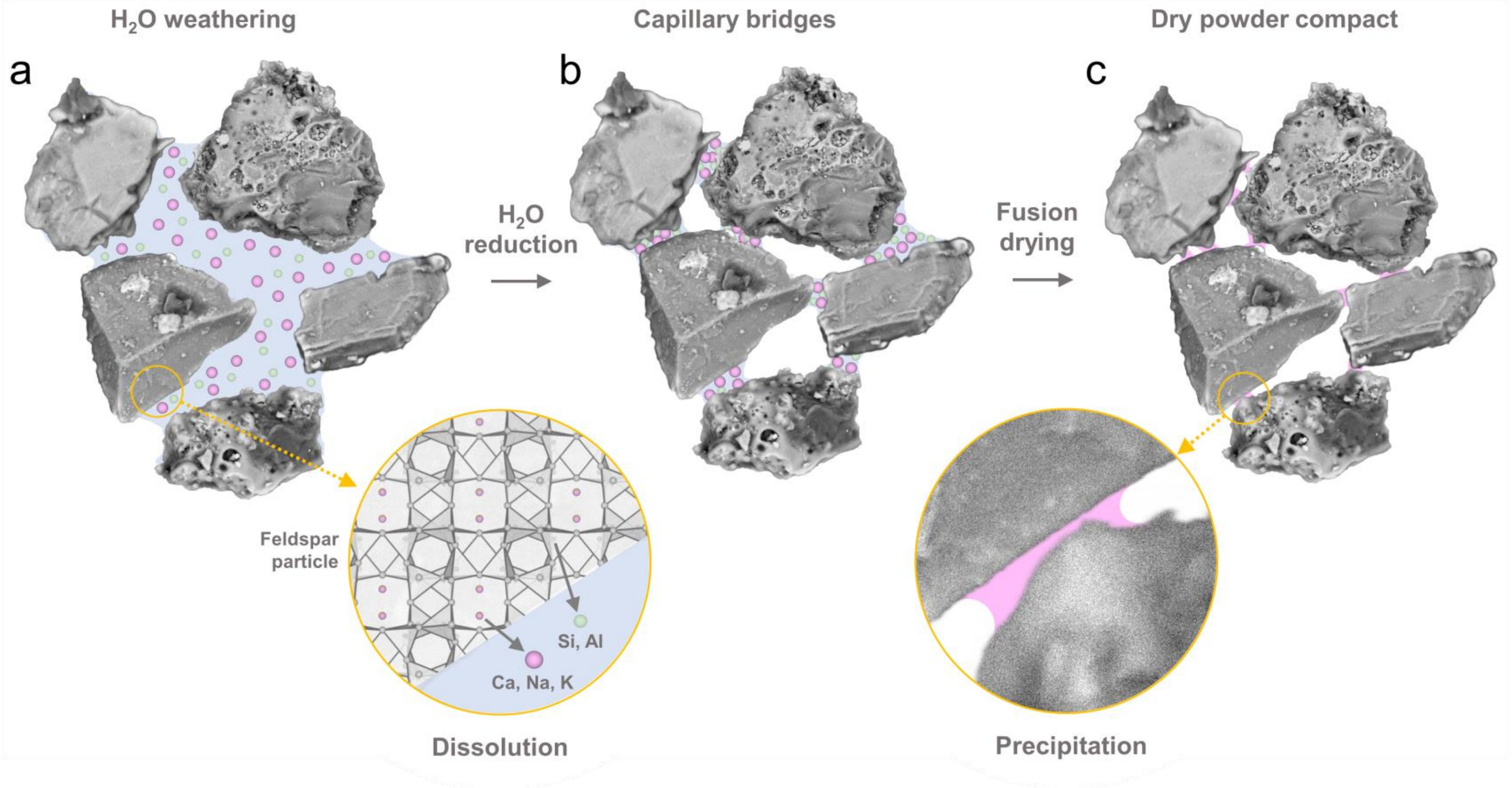
- Dissolution of primary minerals and glass: Olivine, pyroxene and anorthite (the most common lunar minerals) are among the most easily dissolved silicate minerals under weathering conditions (Whitney 1989).
- From the dispersion of Apollo 14 samples (Cooper et al., 2011), it is known that regolith is highly reactive to H_2O (McKay et al., 2015).
- Precipitation of colloids and secondary minerals; Process could be used to produce phyllosilicates.

Cooper BL, McKay DS, Wallace WT, Gonzalex CP. Fluids and their Effect on Measurements on Lunar Soil Particle size Distribution (**2011**); Available from: https://ntrs.nasa.gov/search.jsp?R=20110008012.

Keramische Werkstoffe

Concept: Lunar regolith H_2O weathering and fusion drying

Why are sandcastles hard after they dry?



(a) During weathering, mineral ions are dissolved in the water.

(b) After water reduction, capillary bridges between particles form (this mechanism gives wet sandcastles their strength).

(c) Precipitation of dissolved ions leads to solid interparticle necks.

↓

Dry powder compacts (sandcastles) could be useful for a number of processes and structures

Karl and Gurlo, Synthetic H2O weathering of simple feldspar lunar regolith simulants aiming to build high strength 'sandcastles' using fusion drying, in: Earth and Space 2021 (**2021**) 958-969. https://doi.org/10.1061/9780784483374.087.

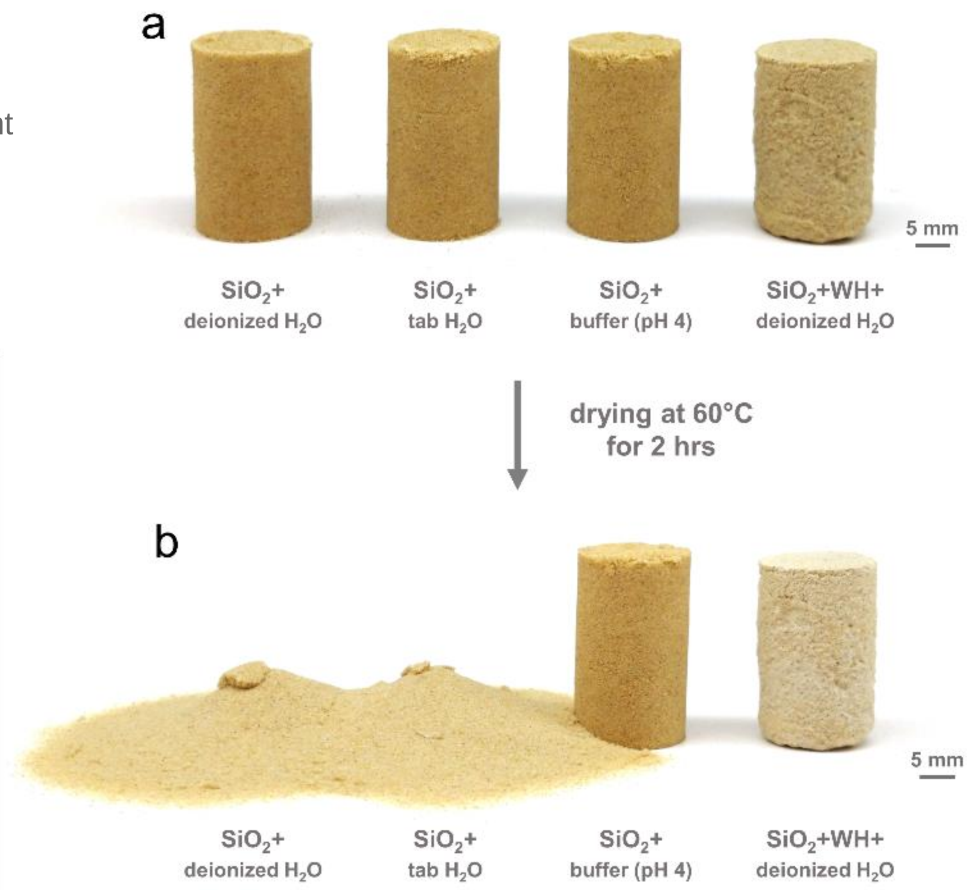
Keramische Werkstoffe

Sandcastles – SiO_2 cylinders

Fusion drying using quartz sand (with feldspar)

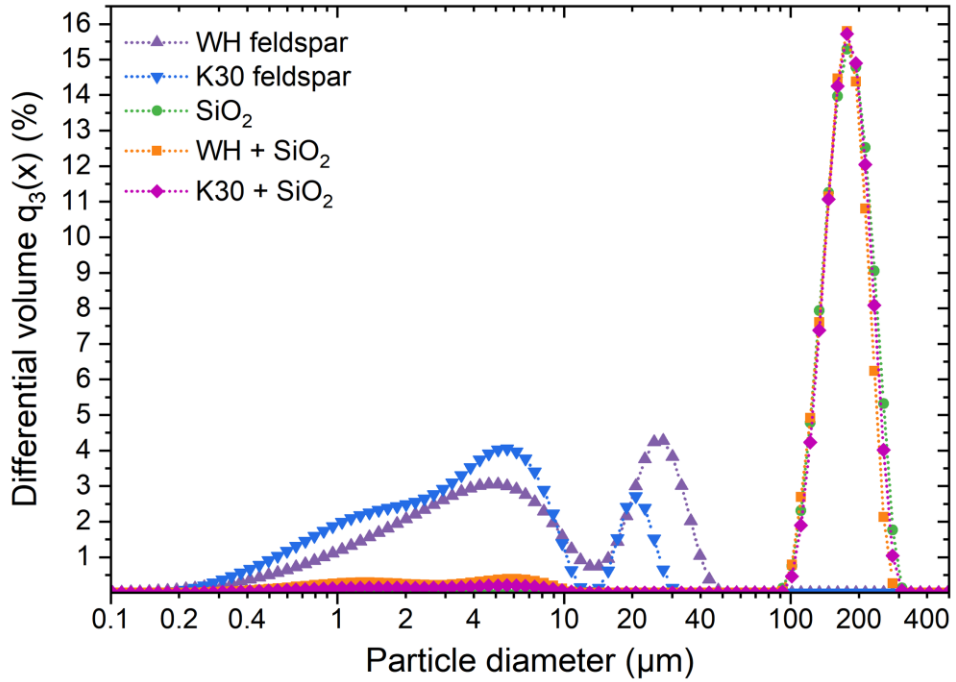
(a) **Wet cylindric** 'sandcastles' with different liquid media (10 wt% liquids) - for the sample on the right a K-feldspar (WH) has been added to the SiO_2 sand.

(b) **After drying**, only samples prepared from liquids with a significant number of ions (or small feldspar particles) produced solid powder compacts.



K-feldspar (WH)

Na-feldspar (K30)



Karl and Gurlo, Synthetic H2O weathering of simple feldspar lunar regolith simulants aiming to build high strength 'sandcastles' using fusion drying, in: Earth and Space 2021 (**2021**) 958-969. https://doi.org/10.1061/9780784483374.087.

Keramische Werkstoffe

Simple feldspar ‘simulants’

Chemical elements of Lunar regolith and feldspars simulants

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Compound	Lunar highlands	Lunar KREEP	K-feldspar (WH)	Na-feldspar (K30)
	Apollo 14 14003 [a]	Apollo 15 15417B [b]	Previous analysis [c]	Previous analysis [c]
SiO2	48.5	53.4	82.3	70.6
Al2O3	19.8	12.9	10.4	17.9
Fe2O3	7.5	12.8	0.1	0.2
MnO	0.11	n.a.	n.a.	n.a.
MgO	7.2	3.8	0.1	< 0.1
CaO	12.8	10.0	0.1	1.3
Na2O	0.63	1.2	0.2	7.2
K2O	0.55	1.7	5.2	2.4
TiO2	2.1	3.5	n.a.	n.a.
P2O5	0.34	2.3	n.a.	n.a.
Cr2O3	0.19	n.a.	n.a.	n.a.
SO3	n.a.	n.a.	n.a.	n.a.
Cl	n.a.	n.a.	n.a.	n.a.
LOI	n.a.	n.a.	1.6	0.3
Total	99.72	99.9	100	100

- While the simple preliminary feldspar simulants used in this work have their closest chemical match on the Moon in KREEP soils, there might be strong dissolution/precipitation reactions of regolith from anorthositic highland regions in water, but also basaltic maria regolith is worth to consider.

[a] Unground Apollo 14 sample 14003 used by McKay et al. for dissolution study (McKay et al., 2015).
[b] Apollo 15 samples 15417B of KREEP basalt (Irving, 1977).
[c] Averaged values of analysis given by DKG (Salmang and Scholze, 2007)

Karl and Gurlo, Synthetic H2O weathering of simple feldspar lunar regolith simulants aiming to build high strength 'sandcastles' using fusion drying, in: Earth and Space 2021 (**2021**) 958-969. https://doi.org/10.1061/9780784483374.087.

Keramische Werkstoffe

Leaching experiments

Ion concentrations (all in mg/l) in supernatants

Compound (mg/l)	K-feldspar (WH) this work		Na-feldspar (K30) this work		Apollo 14 14003 [a]	
	deionized H_2O	pH 4 buffer	deionized H_2O	pH 4 buffer	deionized H_2O	pH 4 buffer
Si	0.37 ± 0.03	0.63 ± 0.03	0.24 ± 0.01	0.69 ± 0.03	0.30	~35
Al	0.72 ± 0.01	1.83 ± 0.01	0.38 ± 0.01	1.52 ± 0.03	0.003	~22.5
Ca	0.02 ± 0	2.44 ± 0.01	0.06 ± 0.01	5.02 ± 0.06	0.53	n.a.
K	0.89 ± 0.07	1.7 ± 0.12	0	0	n.a.	n.a.
Mg	0	0.04 ± 0	0	0.15 ± 0	0.32	n.a.
Na	1.91 ± 0	1859.58 ± 8.33	3.52 ± 0.23	1845.68 ± 9.38	n.a.	n.a.

[a] Results from Cooper et al. dissolution study of Apollo 14 sample 14003 (Cooper et al., 2011; McKay et al., 2015).

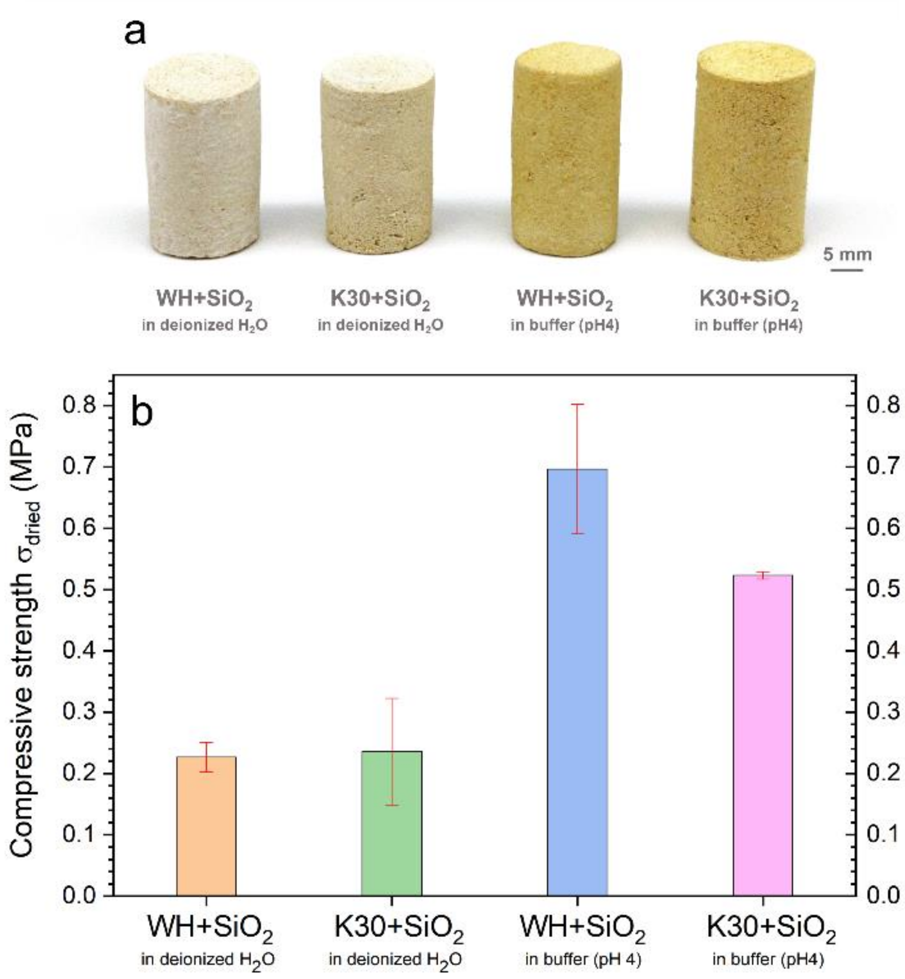
- Ion concentrations (all in mg/l) in supernatants from leaching experiments of feldspar powders in deionized water and buffer solution (for 3 days) and dissolution results for Apollo 14 soil from the same procedure by Cooper et al. (Cooper et al., 2011).

McKay et al. 2015. Acta Astronautica:163–76, 107. p. 163–176. doi:10.1016/j.actaastro.2014.10.032.

Karl and Gurlo, Synthetic H2O weathering of simple feldspar lunar regolith simulants aiming to build high strength 'sandcastles' using fusion drying, in: Earth and Space 2021 (**2021**) 958-969. https://doi.org/10.1061/9780784483374.087.

Compressive strength

Compressive strength of feldspar/quartz powder compacts



Processing approach:

4 feldspar slurries on roller bank for 3 days

- 50 wt% slurry mixed with 50 wt% quartz sand
- High amount of water reduced by heating to 250 °C while stirring
- Pastes were molded into shape by hand-pressing
- Cylinders were left to dry at 60 °C

Karl and Gurlo, Synthetic H2O weathering of simple feldspar lunar regolith simulants aiming to build high strength 'sandcastles' using fusion drying, in: Earth and Space 2021 (**2021**) 958-969. https://doi.org/10.1061/9780784483374.087.

Recent results - leaching experiments with Lunar simulants

Ion concentrations (all in mg/l) in supernatants

On-going work with M. Lappe, K. Cannon and A. Gurlo

Compound (mg/l)	LHS-1 (highl.)		LMS-1 (mare)		ORPH2N (nearside highl.)		ORPL2N (mare)		TUBS-M (mare)		Apollo 14 14003 [a] (highl.)	
	deionized H_2O	pH 4 buffer	deionized H_2O	pH 4 buffer	deionized H_2O	pH 4 buffer	deionized H_2O	pH 4 buffer	deionized H_2O	pH 4 buffer	deionized H_2O	pH 4 buffer
Si	0	1.65	0	3.26	0.01	17.93	0	18.27	0	8.82	0.30	~35
Al	0	0.71	0	0.32	0	6.63	0	6.77	0.02	2.86	0.003	~22.5
Ca	0.87	2.52	0.21	1.35	0.52	9.45	0.49	9.52	0.11	4.1	0.53	n.a.
K	0.28	0.81	0.24	1.01	0.24	2.35	0.22	2.68	0.26	2.04	n.a.	n.a.
Mg	0.02	0.29	0.11	3.2	0.05	5.59	0.04	5.65	0.02	4.26	0.32	n.a.
Na	1.15	2356.35	0.06	2374.73	0.11	2386.63	0.11	2400.28	0.53	2367.05	n.a.	n.a.
Fe	0	0.47	0	2.18	0	12.73	0	13.12	0	5.92	0.005	~17
Ti	0.01	0.02	0.05	0.03	-	1.44	0.01	1.52	0.01	0.08	0.001	~1.7

[a] **McKay** et al. 2015. Acta Astronautica:163–76, 107. p. 163–176. doi:10.1016/j.actaastro.2014.10.032.

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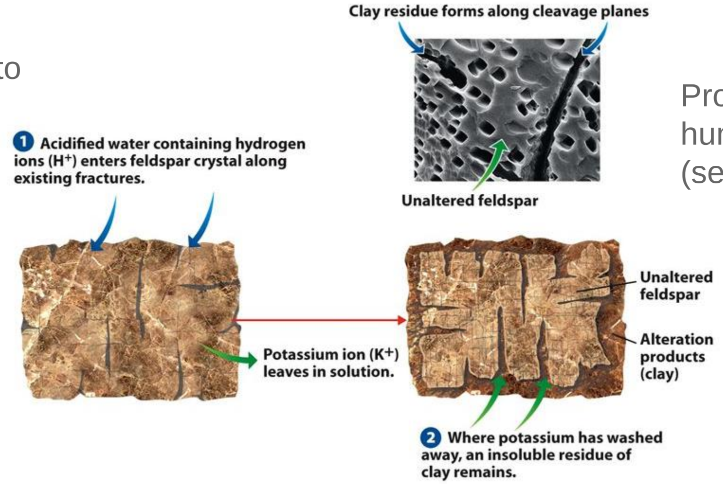
Clays on Earth

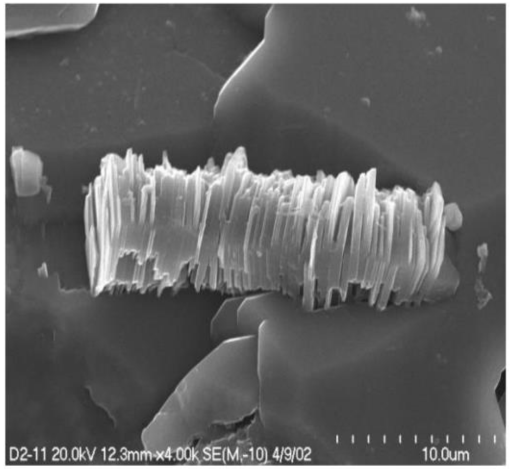
H_2O weathering of rocks on Earth towards clay minerals

Mineral dissolution is inversely proportional to particle size!

Ion exchange an the chemical breakdown of feldspar.



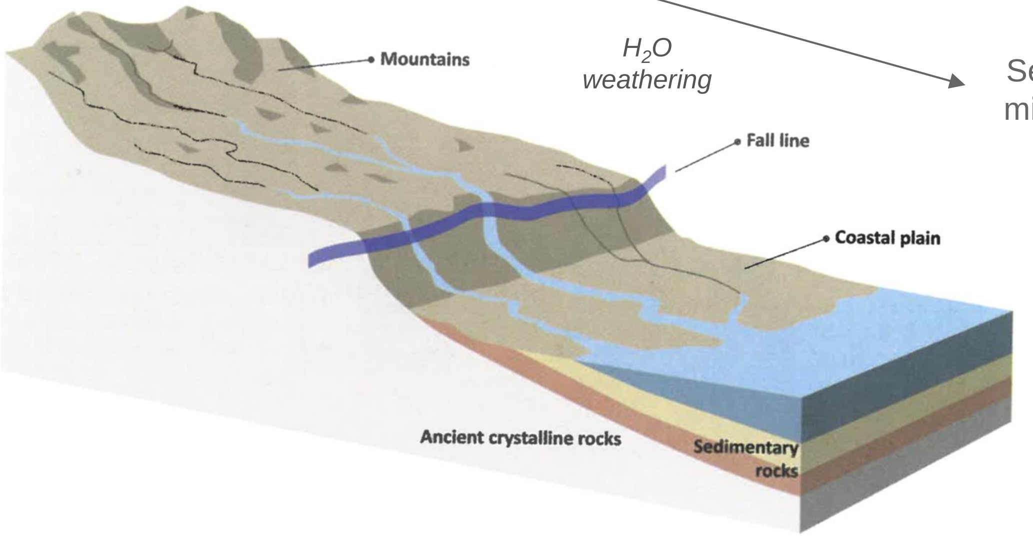
Process happens in human timescales (see silver mines).



Layer structure of kaolin clay

Primary minerals and glass (**in form of solid rock**)

H_2O weathering



Sediments of secondary minerals (phyllosilicates)

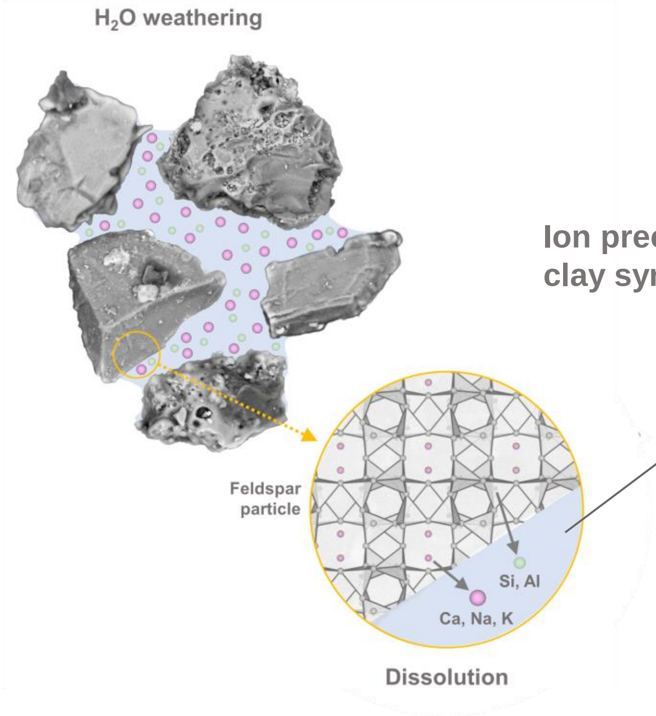
Clays are **functional materials** with hundreds of applications on Earth!

Clay materials show plasticity

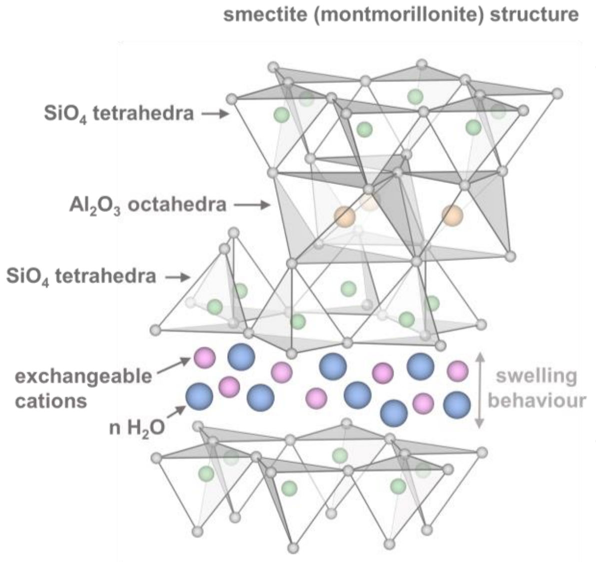
Bloomfield. Science for potters. Westerville, ACERS **2017**. http://slideplayer.com/slide/7474646M.
Kracker, Skript „Tonkeramik und Porzellan, Otto-Schott-Institut
https://www.azonano.com/article.aspx?ArticleID=3080

Clay on the Moon?

H_2O weathering of lunar regolith towards clay minerals

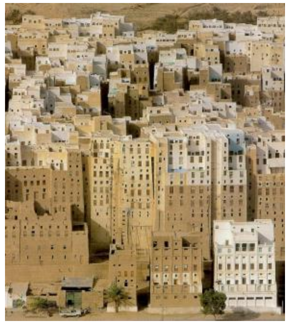


Ion precipitation and clay synthesis



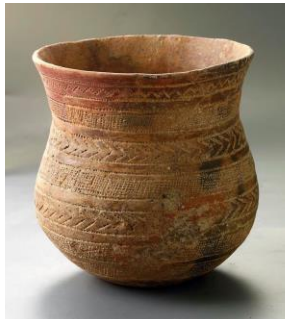
Clays

Building materials



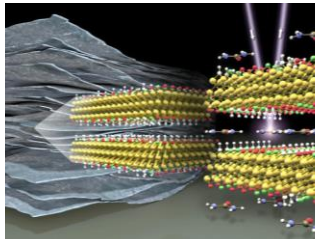
Shibam, Jemen Skyscrapers from clay earth

Ceramic tools



Bell beaker culture Neolithic and Early Bronze Age

Functional materials in general



2D materials forming multi-layered particles (Mxenes)

Bloomfield. Science for potters. Westerville, ACERS **2017**.
http://hiddenarchitecture.net/shiba/
https://labbacallee.weebly.com/trading.html
https://www.helmholtz-berlin.de/pubbin/news_seite?nid=21128;sprache=en;seitenid=74699

Outlook for lunar regolith weathering

Wet-processing and fusion drying

- Wet-processing has some advantages such as increased packing densities, particle interlocking and can produce stabile powder compacts through fusion drying via dissolution /precipitation.
- Water is an expensive resource on the Moon and should be recollected during fusion drying and reused.
- It might be possible to produce simple bricks using fusion drying, which could be employed for infrastructure constructions, such as landing pads, road, habitats.

- Agglomerated powder compacts from fusion drying (green bodies) could either be sintered in heating element or in microwave furnaces.
- Fusion drying for agglomerated powder compacts could be used at all locations on the Moon (if the water is brought).
- In case regolith with water ice is available, (possible) phyllosilicate mineralogy should be utilized.
- Water ice regolith might be used 'right out of the cold trap.' – if water concentrations are low (or water is lost during mining), concentrations might have to be increased.

- In general, basic research on the dissolution/precipitation of individual lunar minerals and glasses is a fundamental research need.
- Work would benefit all efforts which involve lunar dust/regolith in contact with water (water ice, astrobiology, habitat construction, greenhouses, dust inhalation etc.).
- Technologically, a regolith weathering pit on the Moon would involve a sealable container filled with regolith and water.
- In containers with controlled conditions and self-cycling it might be possible to produce synthetic phyllosilicates for ISRU in weathering pits.

List of publications and scientific contributions

Publications on regolith simulant processing:

(1) **D. Karl,** F. Kamutzki, A. Zocca, O. Goerke, J. Guenster, A. Gurlo, Towards the colonization of Mars by in-situ resource utilization: Slip cast ceramics from Martian soil simulant, PloS one 13 (**2018**) e0204025. https://doi.org/10.1371/journal.pone.0204025.

(2) **D. Karl**, F. Kamutzki, A. Zocca, P. Lima, O. Goerke, J. Guenster, A. Gurlo, Ceramics from wet-processing of Martian soil simulant using slip casting or AM for ISRU on Mars: Proc. of the 8th Europ. Conf. for Aeronautics and Space Sci. in Madrid Spain, 1-4 July (**2019**). https://doi.org/10.13009/EUCASS2019-769.

(3) **D. Karl**, T. Duminy, P. Lima, F. Kamutzki, A. Gili, A. Zocca, J. Günster, A. Gurlo, Clay in situ resource utilization with Mars global simulant slurries for additive manufacturing and traditional shaping of unfired green bodies, Acta Astronautica 174 (**2020**) 241-253. https://doi.org/10.1016/j.actaastro.2020.04.064.

(4) **D. Karl**, F. Kamutzki, P. Lima, A. Gili, T. Duminy, A. Zocca, J. Günster, A. Gurlo, Sintering of ceramics for clay in situ resource utilization on Mars, Open Ceramics 2 (**2020**) 100008. https://doi.org/10.1016/j.oceram.2020.100008.

(5) **D. Karl**, A. Gurlo, Synthetic H_2O weathering of simple feldspar lunar regolith simulants aiming to build high strength 'sandcastles' using fusion drying, in: Earth and Space 2021 (**2021**) 958-969. https://doi.org/10.1061/9780784483374.087.

Acknowledgements

Chair of Advanced Ceramic Materials (TU Berlin) – Thank you all!

Special thanks to Prof. A. Gurlo, F. Kamutzki, Dr. O. Görke, J. Wild, A. Gili, T. Duminy, K. Weisser, Harald Link, Peter Schneppmüller, H.Sap, D. Kober.

To our collaborators in Berlin:

Bundesanstalt für Materialforschung und –prüfung
Prof. J. Günster, Dr. A. Zocca, P. Lima, H. Marx, D. Nicolaides

3D Lab at TU Berlin

International facilitators/supporters:

Exolith Lab at Center for Lunar & Asteroid Surface Science (UCF, Florida, USA)

Advanced Light Source (Berkeley, CA, USA)

We thank our founding agencies:

Thank you very much

Roundtable Thursday June 10

What are the obstacles for technology development? Are they:

- Environment we are going to
- Steps we forgot about like beneficiation
- Simulants – can we simulant the environment
- Infrastructure – power, mass, volume, comms etc

- Could it be the culture of the community? Dreamer culture, going for technologies that might not have been so well tested on earth – assess TRL of existing technologies as opposed to developing new ones
- Can work with simulants all we want but when you get to space, it can be different
- The lexicon of different sectors is different – in order to collaborate, need to understand each other
- Be cautious not to discard things that don't work on earth, because it might work very well on the moon
- How would various things work in micro-G? – does LOE really matter for what is being done in ISRU
- Is there an appetite for developing a LOE laboratory for testing?
- Blue Origin is currently offering single shot experiment flights
- Getting there is biggest hurdle – funding is hurdle before getting there
- We have different requirements in space than on earth – ex big excavator in space won't work – on earth, dig fast and move on – in space, time to dig
- Terrestrial industry just now getting in to automation as it wasn't worth the investment – in space, we HAVE to automate – opportunity for synergy
- If a govt agency is running a program then there is little motivation to fast in and out – in private industry, idea is get in, dig hole, get out – investors are looking for fast return
- Risk needs to be retired in a lunar environment but systems integration seems to be where a lot of technologies fail – field trials offer low cost, integration checks and opportunity to excite the public
- ISRU is a complicated problem, significant risks to many steps along the way – in the NASA culture, perhaps also academic and industry – tries to look for the perfect solution rather than a solution that works
- Should a technology be more highly valued and invested in based on how broadly it could be applied? – ex radiators required by all powered systems, wear and abrasion affecting all equipment
- Enemy of good is perfect
- Any system, especially in new environment there is some kind of a limit – used to be mass – now we may be able to make more massive things based on transport available – something else will become a limiting factor – ex power – this is a learn as you go
- Mining industry becomes reactive, they are not proactive
- Spend years solving only a current bottleneck and stagnate on development

- What about scaling up from demonstrations?
- Regulatory regime issue after demos
- As soon as you try to scale up, will run into issue with outer space treaty, Artemis Accords, geo-politicization of ISRU
- base on the moon will not be the same as the ISS
- LEO – operational system, 20 years in existence – trying to create LEO ecosystem – struggle to find resources needed – funding mechanisms, business model – moon development 15 years out
- Are we ready to scale up? If not now, then when? Private sector emergence in transport to space, geo-political push to fund makes this a great time
- Had to redesign hand hammers more than once – we've been making them on earth for a long time – similar with hand drills – it's a little more difficult than you might think – there are a lot of failures that will happen
- NASA racing as fast as it can before others – therefore they will crawl, they know it, and then will do better
- Next phase should not count too much on govt – govt gets tired, public gets tired – when a couple of missions accomplish their goals, it will be difficult to keep going
- Govt as anchor tenant – lease will be short
- SpaceForce – would protect commerce and interest of industry- cannot drive the interests
- Academia interested in proving something new – now we need to think about what is going to make money and drive the economy
- We can't predict a political landscape 5 or 10 years in the future – yes public could get tired, gov't could lag, but China may be enough competition to push greater involvement
- NASA as risk taker for following industry - this is the stage we are in now?
- Are we going to the moon to develop technologies to us on Mars – is this reasonable, valid?
- Is there a potential for kickstarter efforts?
- Systems level design is important development from Moon work that is applicable to mars in addition to individual technologies (some of which are applicable in both environments)
- Moon can be practice for operations on mars as well
- Moon technologies re-adapted to mars
- Water on moon and how much is there – can you close the business case – architectures being developed – is mining water on the moon just an intermediate phase till we figure out the next thing we want to do with the moon
- Power distribution would need to be considered – swarm rovers for mining require power – power beaming?
- Nuclear or solar power stations on orbit or lagrange points – prospect, set up plants for ISRU, use remote power source then when sure of reserve/resource, can then set up power system on moon – needs to be something more valuable than water on the moon - go to the moon to create water to DO something else – what is that something else?
- Level of optimism in the community is high