MINERAL PROCESSING … IN SPACE

Leslie Gertsch
NASA Glenn Research Center / Missouri University of Science and Technology
Jen Pierce
NASA Glenn Research Center

Abstract

NASA is tasked with exploring the solar system and expanding the U.S. economy into space (among other things). Neither is sustainable over the long term without making use of the natural resources available out there, but the operating environments will be very different from anything encountered in all mineral processing history. This update outlines what's planned, what's being studied, and the crucial part that the mineral industry will play.

INTRODUCTION

The mineral resources of the solar system are orders of magnitude larger than those that have supported human civilization for its entire existence, which has been limited (so far) to the top surface of the Earth's crust. The value of these additional resources will come from the demand generated by extending human activity into space permanently, and by supplying minerals to Earth indefinitely. Both are crucial for the long-term growth of the human economy, and will occur mostly in this order.

Supplying either of these demands requires developing effective ways to extract the natural resources of space (Shaw et al. 2022; Badescu et al. 2023). The terrestrial mineral industries are built on millennia of hard-won experience on Earth, and even though much is different in space, the fundamental requirements remain the same: Find deposits where extractable materials have been concentrated by natural processes, gain control of those materials, extract the desired components, and transform them into forms suitable for downstream use. This paper concentrates on the beneficiation and processing of space-based resources as currently being planned and researched.

The major space-faring nations – the United States, Russia, and China – recognize that mineral extraction is a key part of any plan for permanent, indefinite presence off the Earth. NASA has termed this "in situ resource utilization" or ISRU; the European Space Agency (ESA) calls it "space resource utilization" or SRU. Countries where mineral industries are a major component of the economy, such as Canada and Australia, are applying that expertise in partnership with the space-faring nations. The current version of NASA's plan to return to the Moon and go on to Mars (NASA 2024a) states:

> In-situ resource utilization (ISRU) is the concept of locating, mapping, and estimating extraterrestrial resource reserves and extracting and processing these local resources to generate products instead of delivering the products from Earth. As humans stay longer and go farther into space and the focus turns to more sustainable commercial operations and Earth independence, missions will incorporate ISRU practices. ISRU starts with identifying, characterizing, and mapping the resources at potential sites of exploration. ISRU identifies products that can significantly reduce mission cost and risk or enable new mission options, such as utilizing local resources (both natural resources, such as regolith, water, atmosphere, etc., as well as crew trash, waste, discarded hardware, etc.) to produce water, propellant, and other consumables, and capabilities to excavate and construct structures on an extraterrestrial body. ISRU pathways include commercial-scale water, oxygen, and metals; consumables for humans and food production; feedstock for construction, manufacturing, and energy; and commodities for reusable in-space and surface transportation and depots.
>
> For successful implementation, ISRU systems and capabilities must obtain products and services from other lunar systems and infrastructure, and ISRU systems and operations require customers/users to utilize the products/commodities they produce. Lunar support services and

infrastructure for ISRU systems include material transfer and asset movement between ISRU resource extraction, processing, waste tailing, product storage sites, handling and manipulation of resources and bulk regolith, local navigational aids, communications to/from and within ISRU operational sites, power transmission and management, crew and robotic logistics management, maintenance, and repair capabilities, and construction of roads and infrastructure to/from and on the ISRU operation sites. To achieve the full benefits of using in-situ derived products and to meet the intent of Moon to Mars Objective OP-11, customer/users need to design their systems and concepts of operation around the availability and location of these products and how they can be provided. To minimize the risk to the Artemis campaign and ISRU product customers, NASA and its partners must plan a transition of Earth-delivered to ISRU-derived products, along with adequate resource mapping and demonstration of the ISRU processes and product quality.

Earth's population has reached eight billion, and although growth is slowing, is expected to exceed ten billion by the 2080s (United Nations 2022). The increasing value of an ecologically balanced, human-supportive environment on Earth also will make extra-terrestrial sourcing of some minerals attractive sooner than of others; rare earth elements (due to the environmental risks inherent in their current processing methods) may be economic to produce off-Earth for Earth consumption sooner than, say, construction aggregate (low unit value unable to support long transport distances or delays).

Production Targets

Space exploration efforts such as those planned by NASA and other government space agencies will be the first customers for products made from space resources. These products include propellants (particularly oxygen) for spacecraft, and structural materials for construction of surface infrastructure; a broader range will come into play as human presence off-Earth grows (Zubrin 2023). Currently the main focus is on the Moon as a destination in its own right and also as a stepping stone to Mars. The lunar and martian commodities of current interest, in order of development, are:

1. Oxygen, water, and regolith (bulk and processed)
2. Metals (raw and refined) – aluminum, iron, titanium
3. Manufacturing feedstock; fuels, plastics and hydrocarbons; food/nutrient feedstock

Production levels for the Artemis Program and beyond are estimated in four categories (Werkheiser 2023):

- Commercial scale water, oxygen, metals:
  - Tens of metric tons of commodities per year for initial commercial usage
  - Scalable to hundreds-thousands metric tons per year
- In situ-derived feedstock for construction, manufacturing, and energy:
  - Hundreds to thousands metric tons of regolith for construction
  - Tens to hundreds metric tons of metals, plastics, and binders
  - Materials for multi-megawatts of energy generation and storage
- Commodities (mostly propellants) for commercial reusable in-space and surface transportation and depots:
  - Thirty to sixty metric tons per lander mission
  - Hundreds to thousands metric tons per year for cis-lunar space
  - Hundreds metric tons per year for human transportation to Mars
- Commodities for habitats and food production:
  - Water, fertilizers, carbon dioxide, and other crop growth support
  - Crop production facilities and processing systems
  - Consumables for life support, outdoor activities, and crew rovers/habitats
  - Amounts to be determined

The United Launch Alliance, a major commercial launch provider, has offered to purchase propellant in low-Earth orbit for \$3,000/kg, at the Lagrange point between Earth and the Moon for \$1,000/kg, and on the Moon's surface for \$500/kg (David 2016). A recent study estimated that delivering propellant to low-Earth orbit costs NASA \$10,000 to \$50,000/kg using the current system of fully expendable launch vehicles, depending on tanker size (Tiffin and Friz 2021).

Operating Environments

The major aspects of Earth's environment that have enabled – and constrained – the evolution of mineral processing methods include: Thick, relatively moist atmosphere; liquid water available nearly everywhere; a constant gravity vector; relatively short travel distances; and fundamentally, human beings. These will be different in space, though some things will be more different than others. Space bodies can be divided into two general types. The most familiar are those that are planets or planet-like; in other words, they are large enough to have a consistent gravity vector, like Earth does though the details vary, and a stable surface with enough gravity to work with. Terrestrial techniques can generally be adapted to these bodies. Small bodies, on the other hand, are substantially different from planets. These include asteroids and comets, bodies usually with too little mass to have self-rounded shapes. Their surfaces and interiors may be unstable, and they may consist of unusual materials, thus requiring novel techniques to extract whatever value they contain.

Gaining access to the resources of space has components both familiar and unprecedented in the mineral industry. Long project lead times and shipping routes are facts of life that will be even longer in space. Earth's Moon, nearest in distance, requires several days of very carefully planned travel. Mars, the next further "rock from the Sun," needs seven to eight months for cargo at nearest approach and three years for humans (round-trip). Half of the easiest-to-get-to small bodies are within 5.7 years (round-trip including roughly 1.6 years on-site; Jedicke et al. 2022). The two Voyager spacecraft, launched in 1977 and moving at roughly 58,000 km/hr, will exit the solar system in 14,000-28,000 years.

Getting around in space involves complex mechanics. Instead of constant gravity holding everything against a surface that can be approximated as flat, spacecraft must traverse a three-dimensional gravitational "minefield" that is constantly shifting. Everything exerts gravitational pull in proportion to its mass, thus every solar system body – including spacecraft – orbits the Sun because the Sun contains more than 99% of the mass in the solar system. But bodies are affected also by any mass that is close enough; the difficulty of knowing the location of every body in the solar system at any given moment means that spacecraft must continually adjust their trajectories by expending energy in appropriate directions at appropriate times. Energy to change spacecraft velocity – delta V – is where propellants (fuel and oxidizer) come in.

In the near term, space mineral resources will come from regolith, the fragmented rock[1] that covers the surface of most solar system bodies to some extent[2]. Surface mining is the main focus of current plans, due partly to the expense and difficulty of launching underground mining equipment, but mostly because necessary knowledge of subsurface geology of space bodies is lacking in all but the broadest sense. What we believe we know of their subsurface regions is derived from reflected light (surface composition and roughness) and mass distribution calculations from spacecraft trajectory deviations. These are insufficient for planning mineral extraction, so an urgent priority is to collect data appropriate for prospecting (Neal et al. 2024).

One of the biggest differences between Earth resources and extra-terrestrial ones is that we understand so much more about the former: where they are, how they form, how to process them. Space is still very much an unknown country. In part this is because the surfaces have evolved over much longer timeframes than those on Earth, which are subject to weathering and erosion caused by atmospheric reaction to sunlight. Space regolith major formation mechanisms are impacts and thermal shock. Impacts are well-recognized as a rock fragmentation mechanism. But in vacuum, such as on the Moon and small bodies, thermal shock is equally productive because the nearly instant temperature transition between sunlight and shadow generates skin stresses in rock surfaces.

Other differences that are likely to dissipate in the long term, but will be important on shorter timelines, include low initial production rates (noted in the previous section), the high cost of launching, and the unfamiliarity of the operating environment. Launching a pound of anything from Earth's surface just to low-Earth orbit costs at least $1500 (Aerospace Security 2022).

---

[1] Regolith lacks the organic components to be classified as soil.

[2] Bedrock in the inner solar system consists mainly of silicate minerals, but as distance from the Sun increases, the bedrock becomes ices rather than silicates. (The current distinction between volatile and refractory compounds is based on Earth-surface conditions that are far removed from surface conditions on bodies in the outer solar system.)

The early stages of adapting terrestrial methods to space environments will consist largely of finding substitutes or work-arounds for environmental conditions that our current beneficiation, separation, and concentration methods are based on. Gaining experience in the space environment, however, will certainly reveal unexpected approaches made possible by natural processes that are obscured or have only minor effects on Earth. Recognizing such possibilities at this early stage is handicapped by the fact that most research is conducted on the Earth's surface, and utilizing such processes effectively once they have been identified will require a certain amount of operational experience in the actual space environments.

Earth's Moon

The first mineral processing system demonstrations in space will happen on Earth's Moon. This environment is like the Earth's in that it has constant gravity and a stable surface covered with "soil," but other differences will require modifications to accepted mineral processing methods.

Lunar gravity is widely known to be 83% lower than Earth's, but the inertia is the same, so flowing material and moving equipment will behave non-intuitively. The surface temperature ranges from -290°F to +240°F, with the lowest temperatures occurring in permanently shadowed regions, found mainly near the poles, where water ice is believed to exist. The polar regions – where the Artemis Program, for example, will create a presence –also are subject to extremely irregular light-dark periods due to the high topographic relief combined with low sun angles (Wright 2022).

The lunar surface is exposed directly to the solar wind, cosmic rays, and solar ultraviolet radiation such that the regolith on the sunlit side is positively charged (about 10 volts) and the dark side is negatively charged (usually -200 volts, but reaching -4500 volts during intense solar activity; Calle 2017). This causes some fine regolith particles to jump as the line between sunlight and shadow (the terminator) passes. In fact, electrostatic discharges can occur as deep as one meter into the regolith, so significant attention must be paid to electrostatic charge control and shielding of equipment. Intermittent energy and mass discharges from the Sun are hazardous to humans and machines and the heterogeneity and low strength of the lunar crust magnetic fields provides no practical protection (Wieczorek et al. 2023).

The "soil" is really just regolith (average size of the 1-cm-passing fraction is 70 microns), and gaseous atmosphere is essentially absent. Water is extremely rare, apparently occurring as ice deposited between grains of the regolith (Reach et al. 2023; this has not been confirmed yet with physical sampling, but a mission to do so will land this year). Human monitoring of and intervention in the processes will be very limited.

Mars

Mars is the next human destination beyond Earth's Moon. It is a planet with enough surface area to make local operations essentially flat; its gravity is twice that of the Moon (38% of Earth's) and its atmosphere of mostly carbon dioxide is thicker, though still very sparse (average pressure is about 0.7% of Earth's). Water and carbon dioxide ices are available on the surface, along with minerals that contain water and/or hydroxyl in their structures (clays and sulfates). The atmosphere provides enough thermal buffering to reduce the range of surface temperatures to -225°F to +70°F. The Mars magnetic field is complex in space and time, leading to both under- and over-predictions of its strength (Johnson et al. 2020; Du et al. 2023).

Like most solar system bodies, its orbit is farther from the Sun than Earth's. Depending on the planets' relative positions, communications take 5-20 minutes one-way and are vulnerable to disruption and delay (Chappell et al. 2024). This is too long for direct human control of machines there (it may be possible on the Moon, for some tasks and trained operators, per Panzirsch et al. 2020). The Mars rover controllers instead have developed various techniques, including an increasing use of autonomy, for maximizing the productivity of robot time on the ground that provide some potentially useful lessons for remote mineral extraction (Rankin et al. 2020, Verma et al. 2023).

Small Bodies

Small bodies include asteroids and comets. Comets originate in the outer solar system when their orbits bring them close enough to the Sun that some of their constituent ices are sublimated. Some asteroids are comets that have lost their volatiles. Asteroids can be grouped further into the primitive and differentiated types; early interest is focused on pieces of fragmented differentiated types (for metals) and on hydrated carbonaceous chondrite asteroids (for volatiles, per Britt and Cannon 2023).

Some asteroids are actually easier to get to than Earth's Moon (Rivkin and DeMateo 2018), but most are not. The small size and/or non-cohesive nature of all but the largest asteroids means they cannot be "landed on"; instead, large or active equipment must stand off, keeping station in the vicinity.

Other Solar System Resources

This group includes moons other than Earth's, and the bodies found outside Neptune's orbit (i.e., in the Kuiper Belt and especially the Oort Cloud. The many moons of the giant planets – Jupiter, Saturn, Uranus, and Neptune – vary widely in their sizes, constituents, and origins. Little is known about the trans-Neptunian objects (which include former planet Pluto). Science missions have been sent to some of these bodies, and more are planned, but capabilities for identifying, locating, and extracting their mineral resources are much lower than for the Moon or Mars, so they are not discussed further here. Vacuum, temperature extremes, solar wind, high-energy radiation, etc. can be considered space resources as well; these also are left for other discussions.

CURRENT RESEARCH

The regolith that will be the first target of mining off-Earth is not quite the same as that which forms by weathering and erosion of Earth bedrock. Regolith samples collected from Earth's Moon tend to lock together, impeding flow through openings and hoppers. Although soil mechanics as applied on Earth focuses on moisture content as a major controlling factor, the thin, dry atmosphere of Mars and the thinner, drier atmosphere of the Moon will force a new perspective on electrostatics interactions with highly angular grain shapes instead.

Many hydrometallurgical processes, including electrolysis, rely on the buoyancy of bubbles in liquid to maintain throughput. Reduced gravity decreases buoyancy, and studies conducted with drop towers, parabolic flights, sounding rockets, and the International Space Station (Akay et al. 2022) show that gas bubbles in microgravity stay attached to the electrode for longer times, growing larger and forming an obstructive layer that raises the overpotential of the reaction. It is not clear yet whether current-art buoyancy-controlled processes can be adapted straightforwardly to lunar or Mars gravity or whether completely different processes can be made effective enough for use.

Earth's Moon

Mineral extraction in the near-term on the Moon and Mars is envisioned to be exclusively from regolith in the near term, due to the expense of launching underground mining equipment from Earth's surface. Once mineral extraction has reached an appropriate level in terms of value (technical, geologic, and economic), exploration of deposits in bedrock will certainly begin. Several methods for extracting useful materials from the lunar regolith are being studied: molten regolith electrolysis, molten salt electrolysis, hydrogen reduction, and carbothermal reduction (Hadler et al. 2020).

Linne et al. (2019) outlined the requirements for a (non-optimized) system on a single lunar lander that could produce 10 metric tons of oxygen per year from local regolith. Not a full mission plan, this study explored the plausibility of a system using carbothermal reduction, with power provided by the sun. The result (Figure 1) could nominally produce and store seven metric tons of liquid oxygen during a 7.4-month continuous sunlit period at the lunar south pole. Transfer of the oxygen output from storage tanks to a customer's reusable lander would require separately landed hardware. Fitting the necessary subsystems – regolith excavation, haulage, sorting, heating/reacting, electrolyzing, liquefaction, and storage – within the limited mass, power, and volume available on a fifteen-ton-class commercial lander was non-trivial, but the design did close and serves as a rough template for a lunar regolith-extraction demonstration leading up to a pilot plant design.

Mars

As elsewhere, the first resources of interest are those that can be used to manufacture spacecraft propellants as well as life-support consumables. On Mars that means the carbon dioxide as gas in the atmosphere and ice at the poles, and water as ground ice and components of mineral structures.

The first ISRU demonstration anywhere in space, named MOXIE (Mars Oxygen ISRU Experiment, Figure 2) used a scroll compressor to draw Mars atmosphere into a stack of ten solid-oxide electrolysis cells to produce 99.9% pure oxygen in 2021-2023 (Hecht et al. 2021; Hoffman et al. 2023; Rapp and Inglezakis 2024). A subsequent NASA study (Oleson et al. 2024) expanded on this by evaluating a likely integration of the required subsystems to produce 300 metric tons of liquid oxygen and liquid methane on Mars. As with MOXIE, one of the components would be carbon dioxide from the atmosphere. The other would be 150 metric tons of water.

The first question addressed by Oleson et al. (2024) was whether it would be more efficient to ship the water from Earth, melt subsurface ice, or extract water from hydrated mineral deposits. The first option would be the simplest. The second option would use the most energy and would restrict the site location to near-surface ice concentrations; that is, buried glacier remnants (Perry et al. 2023) that would be accessible by autonomous drilling rigs (Mellerowicz et al. 2022). Surface deposits of hydrated clay mixtures (Du et al. 2023) and hydrated sulfates such as gypsum (Massé et al. 2012; van Susante et al. 2018) are somewhat more extensive, but there may be enough hydrated minerals in “average” regolith planet-wide to extract water through relatively low-level heating of larger ore volumes, in the third option (Abbud-Madrid et al. 2016). This would expand the range of possible landing/mining sites but would require the most new equipment development. Table 1 compares the three cases.

Small Bodies

Working with asteroids and comets is significantly different from working on planetary bodies, and not just because both gravity and consistent atmospheres are absent. Simply staying in the vicinity is not trivial (e.g., Takahashi and Scheeres 2021). Recent science missions have revealed some of the additional issues, such as dodging gas jets from comets (El-Maarry et al. 2019) and rocks spit from asteroids (Agarwal 2020). The resources available in just the near-Earth objects may become attractive once we are able to create reliable models of the interiors of these bodies (Agnan and Vennitsen 2021), though at present our very sparse data comes from meteorites (e.g.,DeMeo et al. 2022), sunlight reflected from surface material (e.g., Korda et al. 2023), and gravitational effects on other bodies (e.g., Scheeres et al. 2020).

NEXT STEPS

Though a crucial part of sustained human economic expansion into space, mineral processing research has waxed and waned with the level of funding support, which is related strongly to public perceptions. Today’s space resources research field is a mixture of projects funded through multiple programs; though NASA does not at present have a single office focused exclusively on ISRU, it does have multiple research and development funding mechanisms that support some of the work needed to reach the initial lunar pilot plant goal by 2033 (Werkheiser 2023). Whether through fundamental or applied research, NASA is committed to work with industry to make mineral production off-Earth feasible both technically and economically.

Most of the programs relevant to ISRU advancement are managed by the NASA Space Technology Mission Directorate (STMD), with some related to science and exploration managed by the NASA Science Mission Directorate (SMD), all in cooperation with the NASA Exploration Systems Development Mission Directorate (ESDMD). Programs are designed to support commercial enterprises (young or mature, small or large) with or without university collaboration; Table 2 lists the main opportunities, which can be explored at https://techport.nasa.gov/opportunities/stmd (overviews of NASA’s technology investment categories are available at https://techport.nasa.gov/framework).

Several companies are already working on developing technology subsystems and procedures for manufacturing propellants on the Moon (NASA 2018; McLaughlin 2019). NASA recently asked the mineral production community for help setting up a “demonstration on the scalable processing of lunar regolith, to produce oxygen as the primary product and potentially other collateral products such as metals from the constituent regolith” (NASA 2023)[3]. This demonstration will be in addition to the resource-related demonstrations already and soon-to-be scheduled to use the launch capabilities available through the Commercial Lunar Payload Services (CLPS) program (NASA 2024b). The data and experience gained from these demonstrations will lead to a lunar pilot plant that is planned to be operational by 2033 (Werkheiser 2023), followed by commercially owned and operated production. NASA and

[3] The information gathered thereby is informing a Request for Proposals (RFP) to be published soon.

potentially other space agencies will be important customers, but the intent is to kick-start a self-sustaining space economy.

REFERENCES CITED

Abbud-Madrid, A., Beaty, D.W., Boucher, D., Bussey, B., Davis R., Gertsch L., Hays, L.E., Kleinhenz, J., Meyer, M.A., Moats, M., Mueller, R.P., Paz, A., Suzuki, N., van Susante, P., Whetsel, C., Zbinden, E.A., 2016. Report of the Mars Water In-Situ Resource Utilization (ISRU) Planning (M-WIP) Study; 90 p, posted April, 2016 at http://mepag.nasa.gov/reports/Mars_Water_ISRU_Study.pptx, accessed December 2023.

Agarwal, J., 2019. "Close-up view of an active asteroid," Science, 6 Dec 2019, Vol 366, Issue 6470, pp. 1192-1193, DOI: 10.1126/science.aaz7129, accessed 7 February 2024.

Agnan, M. and Vannitsen, J., 2021. Scaling uncertainties on asteroid characteristics to prepare datasets for machine learning. Advances in Space Research, 68(8), pp.3225-3232.

Akay, Ö., Bashkatov, A., Coy, E., Eckert, K., Einarsrud, K.E., Friedrich, A., Kimmel, B., Loos, S., Mutschke, G., Röntzsch, L. and Symes, M.D., 2022. Electrolysis in reduced gravitational environments: Current research perspectives and future applications. npj Microgravity, 8(1), p.56.

Aerospace Security, 2022. "Space Launch to Low Earth Orbit: How Much Does It Cost?," Center for Strategic and International Studies, https://aerospace.csis.org/data/space-launch-to-low-earth-orbit-how-much-does-it-cost/, accessed 6 February 2024.

Badescu, V., Zacny, K. and Bar-Cohen, Y. eds., 2023. Handbook of Space Resources. Springer International Publishing.

Britt, D. and Cannon, K., 2023. Resources from Asteroids and Comets. In Handbook of Space Resources (pp. 787-802). Cham: Springer International Publishing.

Calle, Carlos, 2017. Electrostatic Phenomena on Planetary Surfaces. Morgan & Claypool Publishers.

Chappell, M.B., Chai, P.R.P. and Rucker, M.A., 2024. Mars Communications Disruption and Delay. NASA White Paper at https://ntrs.nasa.gov/api/citations/20230012950/downloads/Mars%20Communications%20Disruption%20and%20Delay.pdf, accessed 5 February2024.

David, Leonard, 2016. "Inside ULA's plan to have 1,000 people working in space by 2045," Space.Com, 29 June 2016, https://www.space.com/33297-satellite-refueling-business-proposal-ula.html, accessed 6 February2024.

DeMeo, F.E., Burt, B.J., Marsset, M., Polishook, D., Burbine, T.H., Carry, B., Binzel, R.P., Vernazza, P., Reddy, V., Tang, M. and Thomas, C.A., 2022. Connecting asteroids and meteorites with visible and near-infrared spectroscopy. Icarus, 380, p.114971.

El-Maarry, M.R., Groussin, O., Keller, H.U., Thomas, N., Vincent, J.B., Mottola, S., Pajola, M.A.U.R.I.Z.I.O., Otto, K., Herny, C. and Krasilnikov, S., 2019. Surface morphology of comets and associated evolutionary processes: a review of Rosetta's observations of 67p/Churyumov–Gerasimenko. Space science reviews, 215, pp.1-33.

Hadler, K., Martin, D.J.P., Carpenter, J., Cilliers, J.J., Morse, A., Starr, S., Rasera, J.N., Seweryn, K., Reiss, P. and Meurisse, A., 2020. A universal framework for Space Resource Utilisation (SRU). Planetary and space science, 182, p.104811.

Hecht, M., Hoffman, J., Rapp, D. et al. 2021. Mars Oxygen ISRU Experiment (MOXIE). Space Sci Rev 217, 9. https://doi.org/10.1007/s11214-020-00782-8

Hinterman, E.D. and Khopkar, P.P., 2023. Reliability Optimization of a Mars Oxygen Production Plant. Journal of Spacecraft and Rockets, 60(3), pp.982-990.

Hollist, M., Larsen, D., Gomez, A., Hafen, T., Czernichowski, P., Valdez, S., Lingen, J., Izatt, B., Pike, J., Hartvigsen, J. and Elwell, J., 2023. Scale Up and Coupling of the MOXIE Solid Oxide Electrolyzer for Both Terrestrial and Space Applications. ECS Transactions, 111(6), p.991.

Jedicke, R., Hermosin, P., Sercel, J., Centuori, S., Sciarra, M., Cano, Á. and Peterson, C., 2022. Optimized continuous-thrust round-trip trajectories to ultra-low Δv ISRU targets. Planetary and Space Science, 211, p.105407.

Korda, D., Penttilä, A., Klami, A. and Kohout, T., 2023. Neural network for determining an asteroid mineral composition from reflectance spectra. Astronomy & Astrophysics, 669, p.A101.

Linne, D., Kleinhenz, J., Sibille, L., Schuler, J., Suzuki, N., Moore, L., Oleson, S., Colozza, A. and Turnbull, E., 2019, June. Oxygen Production System for Refueling Human Landing System Elements. In Space Resources Roundtable Planetary and Terrestrial Mining Sciences Symposium (No. GRC-E-DAA-TN69609), https://ntrs.nasa.gov/api/citations/20190029197/downloads/20190029197.pdf, accessed 2 February2024.

Massé, M., Bourgeois, O., Le Mouélic, S., Verpoorter, C., Spiga, A. and Le Deit, L., 2012. Wide distribution and glacial origin of polar gypsum on Mars. Earth and Planetary Science Letters, 317, pp.44-55.
McLaughlin, Haily Rose, 2019. "NASA paying four companies to learn how to make fuel on the Moon," Astronomy, https://www.astronomy.com/space-exploration/nasa-paying-four-companies-to-learn-how-to-make-fuel-on-the-moon/, 3 Oct 2019, accessed 6 February 2024.
Mellerowicz, B., Zacny, K., Palmowski, J., Bradley, B., Stolov, L., Vogel, B., Ware, L., Yen, B., Sabahi, D., Ridilla, A. and Nguyen, H., 2022. RedWater: Water Mining System for Mars. New Space, 10(2), pp.166-186.
NASA, 2018. "NASA selects US companies to advance space resource collection," https://www.nasa.gov/news-release/nasa-selects-us-companies-to-advance-space-resource-collection/, accessed 7 February 2024
NASA, 2023. Lunar Infrastructure Foundational Technologies-1 (LIFT-1) Demonstration Request For Information, https://www.nasa.gov/directorates/stmd/nasa-lift-1-request-for-information/, accessed 2 February2024.
NASA, 2024a. Moon to Mars Architecture Definition Document (ESDMD-001) – Revision A, https://www.nasa.gov/moontomarsarchitecture-architecturedefinitiondocuments/, accessed 2 February2024.
NASA, 2024b. Commercial Lunar Payload Services Providers, https://www.nasa.gov/commercial-lunar-payload-services/clps-providers/, accessed 2 February2024.
Neal, C.R., Salmeri, A., Abbud-Madrid, A., Carpenter, J.D., Colaprete, A., Hibbitts, K.A., Kleinhenz, J., Link, M. and Sanders, G., 2024. The Moon needs an international lunar resource prospecting campaign. Acta Astronautica, 214, pp.737-747.
Oleson, S.R., Kleinhenz, J.E., Johnson, W.L., et al. 2024. Kiloton-Class ISRU Systems for LOX/LCH4 Propellant Production on the Mars Surface. In AIAA SCITECH 2024 Forum (p. 2536).
Panzirsch, M., Singh, H., Krüger, T., Ott, C. and Albu-Schäffer, A., 2020, March. Safe interactions and kinesthetic feedback in high performance earth-to-moon teleoperation. In 2020 IEEE Aerospace Conference (pp. 1-10). IEEE.
Perry, M.R., Russell, A.T., Russell, M.B., Foss, F.J., Chuang, F.C., Morgan, G.A., Bain, Z.M., Campbell, B.A. and Putzig, N.E., 2023. Three-dimensional imaging of martian glaciated terrain using Mars Reconnaissance Orbiter Shallow Radar (SHARAD) observations. Icarus, p.115716.
Rapp, D. and Inglezakis, V.J., 2024. Mars In Situ Resource Utilization (ISRU) with Focus on Atmospheric Processing for Near-Term Application—A Historical Review and Appraisal. Applied Sciences, 14(2), p.653.
Reach, W.T., Lucey, P.G., Honniball, C.I., Arredondo, A. and Malaret, E.R., 2023. The Distribution of Molecular Water in the Lunar South Polar Region Based upon 6 μm Spectroscopic Imaging. The Planetary Science Journal, 4(3), p.45.
Rivkin, A.S. and DeMeo, F.E., 2019. How many hydrated NEOs are there?. Journal of Geophysical Research: Planets, 124(1), pp.128-142.
Shaw, M., Humbert, M., Brooks, G., Rhamdhani, A., Duffy, A. and Pownceby, M., 2022. Mineral processing and metal extraction on the lunar surface-challenges and opportunities. Mineral Processing and Extractive Metallurgy Review, 43(7), pp.865-891.
Takahashi, S. and Scheeres, D.J., 2021. Autonomous exploration of a small near-Earth asteroid. Journal of Guidance, Control, and Dynamics, 44(4), pp.701-718.
Tiffin, D. and Friz, P.D., 2021. Parametric Cost Analysis of Expendable vs. Reusable Refueling Architectures in Cis-Lunar Space. In ASCEND 2021 (p. 4066).
United Nations, 2022. "Global Issues: Population," https://www.un.org/en/global-issues/population, accessed 30 January 2024.
van Susante, P.J., Allen, J., Eisele, T.C., Medici, E.F. and Zacny, K., 2018. Gypsum and other evaporites as a potential source for water extraction on Mars: Experimental update. In 2018 AIAA SPACE and Astronautics Forum and Exposition (p. 5292).
Verma, V., Maimone, M., Graser, E., Rankin, A., Kaplan, K., Myint, S., Huang, J., Chung, A., Davis, K., Tumbar, A. and Tirona, I., 2023, March. Results from the first year and a half of Mars 2020 Robotic Operations. In 2023 IEEE Aerospace Conference (pp. 1-20). IEEE.
Werkheiser, Niki, 2023. In-Situ Resource Utilization (ISRU) Overview, presentation to NASA Advisory Council Technology Innovation and Engineering Committee, May 15, 2023, https://www.nasa.gov/wp-content/uploads/2023/10/werkheiser-and-sanders-isru-tagged.pdf, accessed 2 February2024.
Wieczorek, M.A., Weiss, B.P., Breuer, D., Cébron, D., Fuller, M., Garrick-Bethell, I., Gattacceca, J., Halekas, J.S., Hemingway, D.J., Hood, L.L. and Laneuville, M., 2023. Lunar magnetism. Reviews in mineralogy and geochemistry, 89(1), pp.207-241.
Wright, Ernie, 2023. Illumination at the Moon's South Pole, 2023 to 2030, NASA Scientific Visualization Studio, https://svs.gsfc.nasa.gov/4930/, accessed 2 February2024.

Zubrin, R., 2023. Local Resource Creation on Mars. In Handbook of Space Resources (pp. 669-687). Springer International Publishing.

Table 1. Top-level comparison of water sources for Mars propellant production system

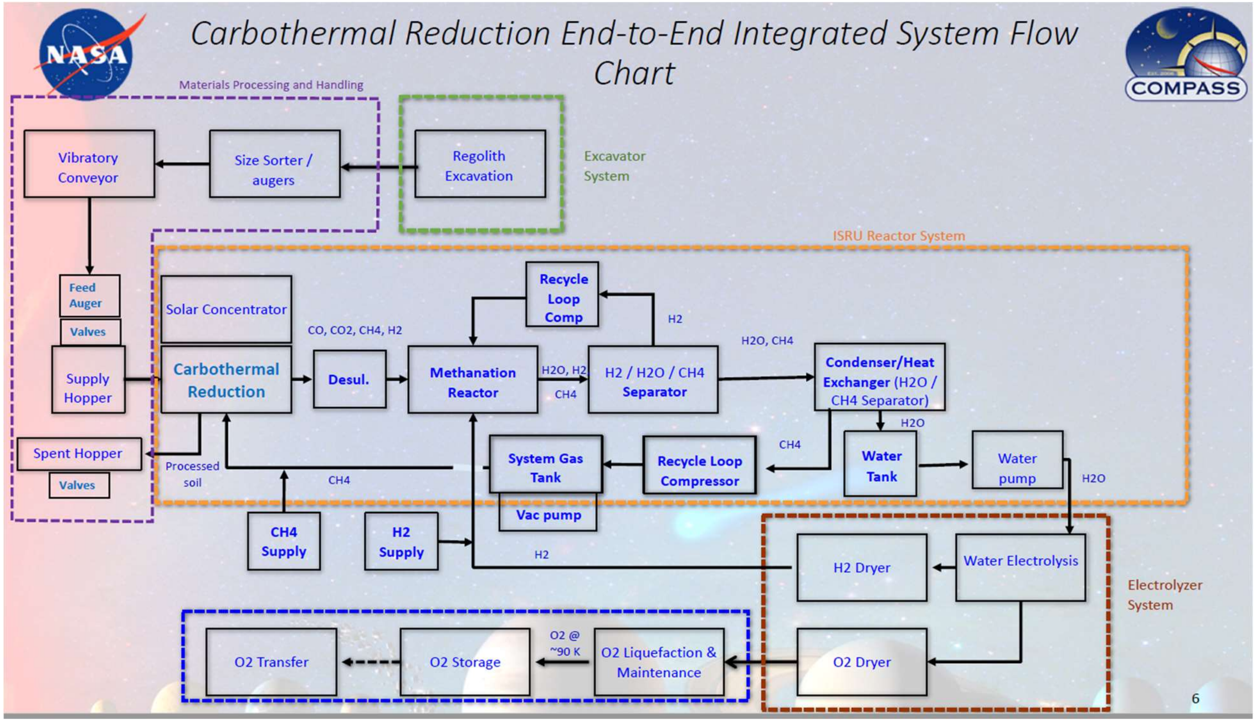
	Pre-crew Cargo Missions	Power for Excavation/ Drilling	Power for Processing	Production Duration	Subsystems to be Matured 1st
	number	kWe	kWe	months	number
Send water from Earth	4	- na -	236	104	4
Borehole mining	3	28	236	78	5
Regolith mining	4	224	236	104	7

Source: Oleson et al. 2024

Table 2. Opportunities for NASA support of technology development, including ISRU topics

	Average Award	Duration	Frequency	Next One	Topic
Funding Opportunity		months			
SBIR Ignite Phase I	$150,000	6	Annual	2023/08	Specified
SBIR/STTR Phase I Contracts	$150,000	6	Annual	2024/01	Specified
NASA Innovative Advanced Concepts Phase I	$175,000	9	Annual	2023/06	Open
Centennial Challenges	$500,000	36	Ongoing	Ongoing	Specified
NASA Innovative Advanced Concepts Phase II	$600,000	24	Annual	2024/11	Open
SBIR Ignite Phase II	$850,000	24	Annual	2024/06	Specified
SBIR/STTR Phase II Contracts	$850,000	24	Annual	2023/11	Specified
Announcement of Collaboration Opportunity	$1,000,000	24	2-3 years	TBD	Specified
SBIR Sequentials	$1,000,000	24	Annual	2023/09	Specified
SBIR/STTR CCRPP	$1,000,000	24	Annual	2023/12	Specified
TechFlights	$1,000,000	18	Annual	2024	Specified
NASA Innovative Advanced Concepts Phase III	$2,000,000	24	Annual	2024/02	Open
Tipping Point	$10,000,000	60	2-3 years	TBD	Specified

Source: https://techport.nasa.gov/opportunities/stmd (may require free registration)



Source: Linne et al. 2019

Figure 1. Carbothermal oxygen production system flowchart for potential lunar ISRU demonstration.

Credit : NASA/JPL-Caltech

Figure 2. The MOXIE oxygen-from-carbon dioxide module being loaded onto the Perseverance rover before its launch to Mars. MOXIE proved the concept by producing 5-10 gram/hr of 99.9% oxygen using less than 300 watts. The experiment ended in 2023 but scaled-up systems are now being designed to prepare for humans landing on Mars.