AIAA ASCEND 2023

Lunar Mining and Processing: Considerations for Responsible Space Mining & Connections to Terrestrial Mining

Gerald B. Sanders[1]
NASA Johnson Space Center, Houston, TX. 77058, USA
Julie E. Kleinhenz[2]
NASA Glenn Research Center, Cleveland, OH. 44135, USA
and
Dale Boucher[3]
Independent, Sudbury, ON, Canada

The National Aeronautics and Space Administration (NASA) of the United States of America (US) has initiated the Artemis Moon to Mars program to send astronauts (the first woman and person of color) back to the lunar surface, create a sustainable human lunar exploration program, and lead the first human exploration mission to the Mars surface in the late 2030's [1]. Besides reinvigorating human exploration beyond low Earth orbit not seen since the Apollo program and enabling new scientific activities and discoveries, a major objective of this program is to characterize the resources that exist on the Moon and Mars, and learn how to utilize them for human exploration and the commercialization of cis-lunar space. Commonly known as In Situ Resource Utilization (ISRU), the search for, acquisition, and processing of resources in space has the potential to greatly reduce the dependency on transporting mission consumables and infrastructure from Earth, thereby reducing mission costs, risks, and dependency on Earth. With the launch of Artemis I in November 2022 and the anticipation of several robotic missions to the Moon under the Commercial Lunar Payload Services (CLPS) program, greater recognition and excitement about NASA's Artemis program and lunar exploration activities is growing in the public. With the recognition that past statements and concept videos of human exploration of the Moon are actually becoming real, there is also a growing awareness of the possible positive and negative consequences and impacts these exploration activities may have on the Moon and Mars. On the positive side, the development of ISRU and lunar mining and processing can enable and grow lunar surface exploration and cis-lunar commercial activities, as well as provide benefits to terrestrial industries through spin-in and spin-back of advanced technologies and autonomous operations. On the negative side, there is a perception that space mining will impact the lunar surface and environment negatively for science, and that cultural beliefs about the Moon need to be addressed and considered before these operations occur. This paper will begin to explore the potential driving attributes and guidelines that will address how best to maximize the lessons and connections to terrestrial mining to reduce the risk and cost of lunar ISRU and space commercial activities, enhance efforts to achieve the terrestrial 'mine of the future', and provide viable markets for space-derived technologies until commercial space mining is established. This paper will also begin to explore the potential driving attributes and guidelines that could address how to minimize the environmental and surface impacts of lunar ISRU and foster 'responsible' space mining that can be implemented until more official agreements and treaties are signed. The existing robust mining regulations adopted globally will be used as a basis for this examination and suggestions will be presented to adopt these agreements for use in space mining.

---

[1] ISRU System Capability Lead, NASA STMD, and AIAA Senior Member
[2] ISRU System Capability Deputy, NASA STMD, and AIAA Senior Member
[3] Independent ISRU Consultant.

I. NASA's Plans for In Situ Resource Utilization (ISRU) – Envisioned Future

The National Aeronautics and Space Administration (NASA) of the United States of America (US) has initiated the Artemis Moon to Mars program to send astronauts (the first woman and person of color) back to the lunar surface, create a sustainable human lunar exploration program, and lead the first human exploration mission to the Mars surface in the 2030's. A major objective of this program is to characterize the resources that exist on the Moon and Mars, and learn how to utilize them for sustained and affordable exploration. Commonly known as *In Situ* Resource Utilization (ISRU), the search for, acquisition, and processing of resources in space has the potential to greatly reduce the dependency on transporting mission consumables and infrastructure from Earth, thereby reducing mission costs, risks, and dependency on Earth. In situ resources can encompass natural resources, as well as human-made resources such as crew waste and trash, discarded landers and tanks, and anything brought from Earth that has completed its nominal mission use. Through the extraction and processing of resources into mission commodities such as rocket propellants, life support consumables, and fuel cell reactants, ISRU enhances and evolves the cis-lunar, lander, and surface transportation systems required for human exploration; expanding and enhancing HOW humans get to, explore, and return from the Moon. Through the extraction and processing of resources into metals, silicon, and other manufacturing and construction feedstock, ISRU enhances and allows for the expansion of critical infrastructure through in situ manufacturing and construction capabilities needed for WHAT humans do on the Moon and in cis-lunar space.

To support the development of critical technologies and capabilities for the Artemis program, such as ISRU, the NASA Space Technology Mission Directorate (STMD) created a strategic framework and process for understanding, organizing, coordinating, prioritizing, and infusing technologies and capabilities into the Artemis architecture [2]. This framework and process starts with organizing all work under four major Thrusts (Go, Land, Live, and Explore) and identifies the driving Outcomes for each of these Thrusts. From the Thrusts and Outcomes, all work can be categorized and linked between Capability Areas, and Technology Gaps can be identified and addressed. To drive the development of technologies and capabilities, this process starts with establishing an 'envisioned future' of where each Outcome and Capability is aiming to be considered complete; sometime in the next 20 to 40 years. For ISRU, the Envisioned Future is "Scalable ISRU production/utilization capabilities including sustainable commodities on the lunar and Mars Surface" [3]. While our only experience to date with acquiring and processing extraterrestrial materials has occurred with limited hardware and small samples on Surveyor and Apollo lunar missions in the 1960's and 70's and more recently with Mars science landers and rovers, the ISRU Envisioned Future considers the evolution of initial small scale demonstrations and systems to being able to acquire, process, and produce 100's to 1000's of metric tons of products from in situ resources, such as oxygen, water, propellants, metals, and construction feedstocks [4].

II. Terrestrial and Space Mine of the Future

The term 'Mine of the Future' is used to both denote that (i) large scale/commercial lunar resource exploration, mining, and processing is in its infancy, and (ii) terrestrial mining needs to go through a major transformation in the next 20 years (see Section IV). With Lunar ISRU being new and terrestrial mining needing a significant transformation, there is an opportunity to explore the differences and potential similarities to see if there are possible solutions and approaches that advance both simultaneously and collaboratively.

As is the case with terrestrial mining and processing, ISRU does not exist on its own. To be successful, ISRU systems and capabilities must obtain products and services from other systems and infrastructure, and it requires customers/users to use the products/commodities it produces. Just like a terrestrial mine, lunar ISRU will require support services and infrastructure including transportation to/from the mine site, local navigational aids, communications to/from and within the mine site, power transmission and management, crew support, logistics management, maintenance, and repair capabilities, and construction of infrastructure to/from and on the mine site. An infrastructure requirement for space mining operations that also translates to terrestrial mining operations is local/on-site generation of energy (electrical/thermal) through 'green' (solar, green fuels, regenerative fuel cell, and/or geothermal) or nuclear energy generation systems. The elements and capabilities that make up the space mine of the future (Figures 1 and 2) as well as the lunar exploration elements that utilize ISRU products must be designed with Space Mining processing and product usage in mind from the start to maximize benefits. To ensure this occurs the Artemis architecture and commercial operations need to include ISRU systems and product usage, and ISRU and surface infrastructure must be guided by an overarching Site Master Plan. To minimize risk, the Artemis architecture should consider transition from Earth-supplied to ISRU-supplied products when they have been adequately demonstrated. Besides identifying important element and capability linkages, Figure 1 also highlights the important infrastructure elements required to evolve an initial Artemis base camp for short duration lunar robotic and human surfaces missions into sustainable human and commercial surface operations. It is also the goal of NASA that lunar

ISRU resource extraction, processing, and product storage systems and the infrastructure and services needed to support their operation be commercialized.

While Figure 1 provides an overview of the infrastructure elements and interdependencies for the space mine of the future, Figure 2 provides details on the elements and operations associated with characterizing, acquiring, preparing, and processing in situ resources into products and delivering those products to nearby customers. Before commercial mining and processing operations begin, it is expected that local resources have been mapped, orebody characterization has been completed, the site infrastructure and operation location has been defined, and the excavation plan has been established (which minimizes the extraction and processing footprint). As production begins and grows, it is expended that multiple coordinated excavators/haulers will operate between the Excavation, ISRU Processing, and Waste Dump sites. These assets will be working autonomously together and in sync with the overall extraction/processing value chain to minimize downtime and maximize performance. These capabilities may evolve into conveyors or other material transportation methods as production further increases. Resource preparation (crushing, size sorting, mineral separation) may occur at either the Excavation or Processing site. It will be essential to optimize around available energy and product production rates. For example, to mine for required materials, extraction and transport systems will be optimize against available energy types and amounts and achievable processing/production rates. It is currently desired to minimize the distances between the Extraction, ISRU Processing, and Waste sites and especially the Resource Processor and Product Storage units at the ISRU Processing site. For early systems, pre-integration to minimize assembly and set up before operations can begin and to enable data integration across the value chain is expected to the maximum extent possible within lander payload volume/mass capabilities. Larger operations and separate product depots are expected as production quantity increases. Throughout all ISRU operations, it is imperative to characterize all resource, product, and waste streams and stockpiles, to ensure optimum performance and enable efficient future processing. Product transfer from the ISRU system to the customer(s) will occur initially on a periodically basis. For cryogenic fluid products, minimum losses of cryogenic fluids during transfer and transit operations is desired. To support semi to full autonomous operations, local and/or orbital navigation and communication capabilities support is needed. While initial operations will occur over unprepared surfaces, prepared paths (roads, rail, tram, etc.) will be created over time to minimize wear and increase efficiency as extraction/production amounts and distances increase.

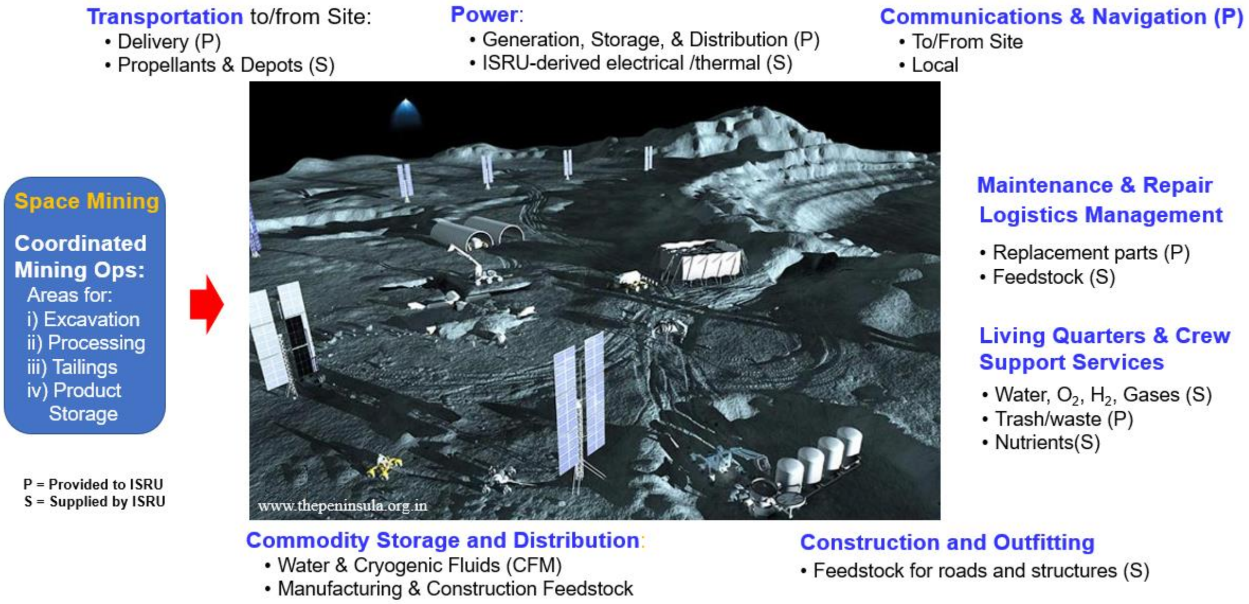


Figure 1. ISRU as Part of a Larger Architecture

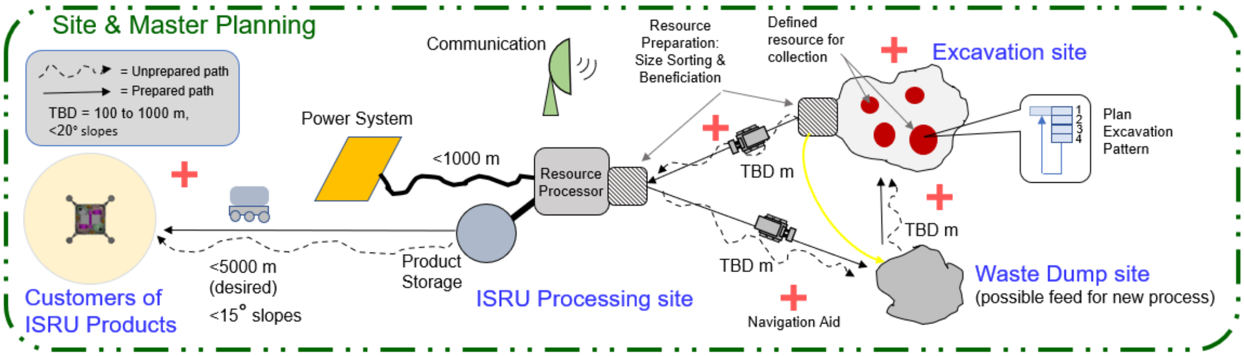


Figure 2. Lunar ISRU System and Concept of Operations

III. Space Resource Exploration and Mining/Processing Design and Operation Considerations

In an effort to document NASA's Moon to Mars strategy and top-level goals and objectives needed to achieve the vision for sustained human presence and exploration throughout the solar system, NASA released the Moon to Mars Objective document at the International Aeronautical Congress (IAC) in Paris in September 2022. An updated version, titled *Moon to Mars Strategy and Objectives Development*, was released in April 2023 [5]. The document describes 63 major objectives covering four major areas of emphasis: Science (26), Infrastructure (13), Transportation & Habitats (12), and Operations (12). The document also captures common themes that are broadly applicable across all the objectives, known as Recurring Tenets. It states that neglecting any of these recurring tenets could hinder or even prevent successful execution of NASA's Moon to Mars endeavor. Upon examining the objectives and recurrent tenets in the document, eighteen objectives spread across the 4 major areas of emphasis involve or enhance ISRU implementation, as well as 6 of the 9 Recurring Tenets. For better clarity, these eighteen objectives were sorted into the following categories and depicted in Figure 3:

Resource Assessment: While 5 objectives were identified, two are considered key drivers for future needs and missions. **AS-3**: Characterize accessible lunar and Martian resources, gather scientific research data, and *analyze potential reserves* to satisfy science and technology objectives and enable In-Situ Resource Utilization (ISRU) on successive missions. **OP-3**: Characterize accessible resources, gather scientific research data, and *analyze potential reserves* to satisfy science and technology objectives and enable use of resources on successive missions.

ISRU and Usage: While 5 objectives were identified, two are considered key drivers for future lunar ISRU missions and implementation: **LI-7**: Demonstrate industrial scale ISRU capabilities in support of continuous human lunar presence and a robust lunar economy. **OP-11**: Demonstrate the capability to use commodities produced from planetary surface or in-space resources to reduce the mass required to be transported from Earth.

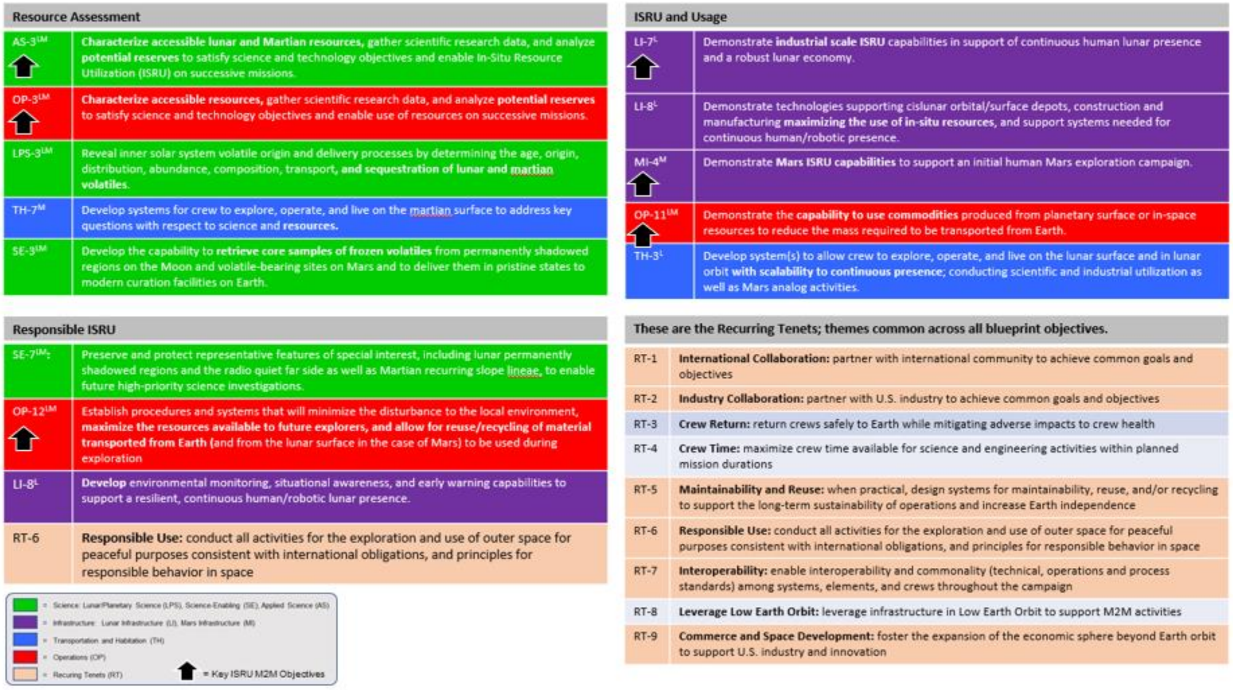
Responsible ISRU: The following objectives can be considered as a start toward performing lunar ISRU ethically and in an environmentally responsible manner. **OP-13**: Establish procedures and systems that will minimize the disturbance to the local environment, maximize the resources available to future explorers, and allow for reuse/recycling of material transported from Earth (and from the lunar surface in the case of Mars) to be used during exploration. **RT-6**: Responsible Use: conduct all activities for the exploration and use of outer space for peaceful purposes consistent with international obligations, and principles for responsible behavior in space. **SE-7**: Preserve and protect representative features of special interest, including lunar permanently shadowed regions and the radio quiet far side as well as Martian recurring slope lineae, to enable future high-priority science investigations.

Recurring Tenets that Enhance ISRU: Six of the 9 recurring tenet objectives can be associated with ISRU missions and implementation (RT-1, 2, 5, 6, 7, & 9). These deal with promoting international and commercial partnerships, interoperability, maintainability, and reuse, and especially the responsible use of space.

When examining the hardware and operations depicted in Figure 2 along with the ISRU-related Moon to Mars objectives in Figure 3, future ISRU systems and operations need to consider the following Design Recommendations and Considerations.

- ISRU resource processing systems should be modular for scale-up/growth and repairability in mind. They will ideally support more than one commodity production and operations (ex. oxygen and metal; water and other volatiles)
- Modularity and maintenance & repair design features/capabilities need to be applicable to being performed by both humans and robotic assets. A two-phase maintenance and repair strategy should be considered. Phase 1 is a

fast repair via module and orbital replacement unit (ORU) level exchanges to minimize the downtime/shutdown of operations. Phase 2 is an off-line repair down to the component level to refurbish the module/ORU back to operational status for future use.



Resource Assessment	
AS-3^{LM} ⬆	**Characterize accessible lunar and Martian resources,** gather scientific research data, and analyze **potential reserves** to satisfy science and technology objectives and enable In-Situ Resource Utilization (ISRU) on successive missions.
OP-3^{LM} ⬆	**Characterize accessible resources,** gather scientific research data, and analyze **potential reserves** to satisfy science and technology objectives and enable use of resources on successive missions.
LPS-3^{LM}	Reveal inner solar system volatile origin and delivery processes by determining the age, origin, distribution, abundance, composition, transport, **and sequestration of lunar and martian volatiles**.
TH-7^{M}	Develop systems for crew to explore, operate, and live on the martian surface to address key questions with respect to science and **resources.**
SE-3^{LM}	Develop the capability to **retrieve core samples of frozen volatiles** from permanently shadowed regions on the Moon and volatile-bearing sites on Mars and to deliver them in pristine states to modern curation facilities on Earth.

ISRU and Usage	
LI-7^{L} ⬆	Demonstrate **industrial scale ISRU** capabilities in support of continuous human lunar presence and a robust lunar economy.
LI-8^{L}	Demonstrate technologies supporting cislunar orbital/surface depots, construction and manufacturing **maximizing the use of in-situ resources,** and support systems needed for continuous human/robotic presence.
MI-4^{M} ⬆	Demonstrate **Mars ISRU capabilities** to support an initial human Mars exploration campaign.
OP-11^{LM} ⬆	Demonstrate the **capability to use commodities** produced from planetary surface or in-space resources to reduce the mass required to be transported from Earth.
TH-3^{L}	Develop system(s) to allow crew to explore, operate, and live on the lunar surface and in lunar orbit **with scalability to continuous presence**; conducting scientific and industrial utilization as well as Mars analog activities.

Responsible ISRU	
SE-7^{LM}:	Preserve and protect representative features of special interest, including lunar permanently shadowed regions and the radio quiet far side as well as Martian recurring slope lineae, to enable future high-priority science investigations.
OP-12^{LM} ⬆	Establish procedures and systems that will minimize the disturbance to the local environment, **maximize the resources available to future explorers, and allow for reuse/recycling of material transported from Earth** (and from the lunar surface in the case of Mars) to be used during exploration
LI-8^{L}	**Develop** environmental monitoring, situational awareness, and early warning capabilities to support a resilient, continuous human/robotic lunar presence.
RT-6	**Responsible Use:** conduct all activities for the exploration and use of outer space for peaceful purposes consistent with international obligations, and principles for responsible behavior in space

These are the Recurring Tenets; themes common across all blueprint objectives.	
RT-1	**International Collaboration:** partner with international community to achieve common goals and objectives
RT-2	**Industry Collaboration:** partner with U.S. industry to achieve common goals and objectives
RT-3	**Crew Return:** return crews safely to Earth while mitigating adverse impacts to crew health
RT-4	**Crew Time:** maximize crew time available for science and engineering activities within planned mission durations
RT-5	**Maintainability and Reuse:** when practical, design systems for maintainability, reuse, and/or recycling to support the long-term sustainability of operations and increase Earth independence
RT-6	**Responsible Use:** conduct all activities for the exploration and use of outer space for peaceful purposes consistent with international obligations, and principles for responsible behavior in space
RT-7	**Interoperability:** enable interoperability and commonality (technical, operations and process standards) among systems, elements, and crews throughout the campaign
RT-8	**Leverage Low Earth Orbit:** leverage infrastructure in Low Earth Orbit to support M2M activities
RT-9	**Commerce and Space Development:** foster the expansion of the economic sphere beyond Earth orbit to support U.S. industry and innovation

🟩 = Science: Lunar/Planetary Science (LPS), Science-Enabling (SE), Applied Science (AS)
🟪 = Infrastructure: Lunar Infrastructure (LI), Mars Infrastructure (MI)
🟦 = Transportation and Habitation (TH)
🟥 = Operations (OP)
🟧 = Recuring Tenets (RT)
⬆ = Key ISRU M2M Objectives

Figure 3. NASA Moon to Mars Objectives Relevant to ISRU Implementation

- ISRU and support service elements and systems should maximize the use of common elements: motors, controllers, sensors, connectors and interfaces, latches/attachment points, etc. Identify and promote common standards and interfaces.
- Designs and operations need to consider both i) that deployment, operation, and maintenance/repair of ISRU systems will be performed without crew present or for only a limited amount of time, and ii) the capabilities and limitations of teleoperation/autonomy with respect to software, space computers/avionics, situational awareness and performance sensor data processing and transmission, local navigation capabilities and aids, and local and Earth to Moon communications. Due to time delays on the order of several seconds for the Moon to many minutes for Mars, teleoperation of ISRU assets should be limited to supervised autonomy and not real-time operation and control, especially for mobile assets. Increased levels of autonomy should be added as confidence and understanding of ISRU asset operation increases. For maintenance and repair, robotic and ISRU systems will need to be designed around common modules, interfaces, fasteners, and tools. This will be especially important for minimizing/eliminating crew involvement in hazardous and/or extreme environments, such as in permanently shadowed regions.
- Power systems may be dedicated to ISRU operations. While end-to-end pilot plant operations are expected to require modest levels of electrical/thermal energy (5 to 10 kilowatts), initial 'full scale' production systems are expected to be in the 40 to 100 kilowatts range, and systems beyond that will require 100's to 1000's of kilowatts. These power demands far exceed the 10's of kilowatts needed for initial lunar surface crew exploration elements. Because ISRU processing and extraction methods often require heating resources to drive off water/volatiles or promote reduction/electrolysis reactions, dedicated solar thermal energy generation and transmission may be desired over electrical-to-thermal energy conversion. Placement of electrical and thermal power generation capabilities and transmission distances are important factors to consider in option selection and processing site planning.
- ISRU system designs will be strongly influenced by the payload size, transportation system frequency, and cost to deliver hardware and infrastructure to the Mining and Processing sites. Initial ISRU processing design and use of modularity needs to take into consideration scalability to future production levels as well as transportation size/volume, mass, and offloading capabilities. Initial ISRU systems should consider complete integration and

checkout on Earth, with minimal offloading, deployment, and setup needs. This approach minimizes both operational/performance risk and the need for preplaced infrastructure. Once ISRU processes, products, and infrastructure support surfaces are adequately demonstrated and established, larger scale systems can be delivered in sections/modules and assembled on-site. While the two-step design/deployment approach can increase design and testing costs, it may better allow for initial lessons-learned to be incorporated into the next generation of production systems thereby increasing performance and longer-term return on investment.

- ‘Right-sizing’ of all operational elements and sequences (excavation, transport, processing, product delivery) is very important to minimize any ‘slack’ or ‘oversizing’. There is a need to balance underutilized invested capital versus the ability to grow with demand. This includes optimizing around power generation and usage as well. Initial end-to-end pilot plant scale operations will be more about demonstrating the processes and validating the products than providing a cost-effective commodity. However, when full-scale production begins for commercial operations, the end-to-end value chain needs to be examined, and asset size/modularity is scaled to consider material flow, redundancy/reliability, and future production growth in each step in the value chain.

For most traditional space hardware, designs are optimized around minimizing mass and power while meeting mission life and operation requirements. However, since ISRU systems need to operate for extremely long durations under harsh abrasive regolith and environmental conditions, optimizing to minimize mass and power should not be the primary criteria for evaluating and selecting designs. To meet the design recommendations and considerations discussed above, Lunar ISRU systems need to focus on reliability and long-term economical operation first and foremost, and mass and power second.

IV. Terrestrial Resource Exploration, Mining, and Processing Issues That Influence Lunar ISRU

[Information in this section references material from 6, 7, & 8]

The terrestrial resource exploration, mining, and processing (REM&P) industry is at a critical transition point. The world needs an order of magnitude growth in extraction of critical minerals/metals to meet Green Energy/Net-Zero Emissions goals by 2050 [9]. However, to meet UN Sustainability Goals [10] and achieve the order of magnitude growth in capabilities, the resource exploration, mining, and processing sectors need to address the following significant challenges:

Remaining ore concentrations are dropping requiring greater extraction efficiency. Due to remaining ore concentrations dropping, more efficient extraction and processing is required. To reduce the impact on local terrains and the environment, efforts are underway toward achieving smaller mining footprints and to minimize the movement of material.

There is an increasing need to operate in remote and extreme environmental conditions. Besides ore concentrations dropping, new sources of critical minerals/metals are located in more remote and extreme environments. This requires hardware and infrastructure to be more robust, but also requires greater levels of maintainability and logistics to support these operations. To reduce logistic and maintainability impacts, greater use of common parts and on-site manufacturing is required. Establishing cost effective access and infrastructure at the remote locations and extreme environments is also a significant challenge, especially when trying to minimize impacts to the environment and local/indigenous communities. Addressing the challenges below can significantly reduce this challenge.

Finding new resources to mine requires increasing the speed of resource exploration and orebody knowledge. It has been mentioned that the time from identifying a potential resource location to initiating mining operations at a site can easily take over a decade. Significant time is often lost between taking samples at sites, analyzing the samples, mapping the location with known information, and then replanning and executing the next set of operations. These operations involve humans traveling to remote, often unprepared, locations. To meet the demand for critical minerals/metals for a Green Economy, increasing the speed and accuracy of finding, characterizing, and mapping ore bodies for site selection, mine site planning, and efficient extraction is critical. To achieve this goal, there is a strong need to significantly decrease the timeline from initial interest from orbital data to detailed mapping to start mining operations through increased and more rapid data collection, transmission, and modeling. This can only be achieved if the REM&P industry promotes innovation and applies new/disruptive technologies in current approaches and operations, such as Artificial Intelligence/Machine Learning (AI/ML), robotics, automation, ‘big data’ (i.e. the collection and analysis of large amounts of data), and Edge computing.

Removing humans from hazardous operations and/or remote locations is important. Resource exploration, mining, and processing operations are currently very human intensive. Many of these operations, especially underground mining, raise significant health issues and operational safety concerns. To remove or minimize human involvement, a greater infusion in automation and remote operations is needed. While there may be a significant initial cost impact to add remote and/or autonomous operations to existing human-centric operations, a longer-term benefit and return on investment will occur in human health costs, operational performance, and retaining & attracting new talent.

Transmitting, collecting, managing, and analyzing large amounts of data. With an increase in remote and autonomous operations comes the need for increased levels of data collection, transmission, and analysis (including need for greater Artificial Intelligence/Machine Learning – AI/ML). Besides controlling remote/autonomous assets, understanding and tracking the location of the ore body and the content of all resource/product/waste streams throughout the end-to-end value chain of operations in near real-time is essential for optimizing performance and energy usage and maximizing a circular economy approach (see Section V. Circular Economy). While a significant investment cost to implement the new remote/autonomous hardware, sensors and instrumentation, and communication infrastructure will be needed, it is expected that implementation of this capability and others will optimize operations and reduce costs, labor, and time.

Reducing the impact on the environment. Resource extraction and processing operations currently have a significant impact on the environment, through carbon dioxide emissions, water usage, environmentally hazardous chemicals, reagents, and emissions, and processing waste/tailings. Decarbonization of equipment, reducing energy expenditure through mining and extraction process optimization, and greater usage of green/renewable energy sources for infrastructure and equipment is needed. Reduced water usage and better recycling/cleaning of water used in extraction and processing operations is also needed, especially to expand the potential sites for future mining where water limitations may currently exclude those locations from consideration. As was previously mentioned, to reduce the impact on the environment, it is important to incorporate more focused mining techniques to achieve smaller mining footprints and minimize the movement of material. To further reduce environmental impact and to reduce longer-term logistics and costs, there is a greater need to regenerate and recycle reactants/reagents used in extraction and processing operations or even change the processes themselves to reduce discharge and emissions (ex. use of non-carbon electrodes and biologically based mining to replace environmentally hazardous reagents). It is now critical to plan for the end of mining/processing operations with remediation/removal plans before operations begin. Remediation does not need to wait until the end of operations, but can be performed on a continuous basis as operations continue and expand so that the overall footprint of operations is kept to a minimum.

To promote and effect the changes needed requires significant coordination between government, industry, and academia. While there is an overarching incentive to increase operations and performance to meet the global and societal demands mentioned at the start of this section, developing new technologies/capabilities, and implementing change at on-going operations is difficult. Investment and change requires a stable, predictable, balanced, and agreed upon regulatory regime between government, industry, and society. Government support and incentives to attract investment and maintain competitiveness (esp. when involving short duration contracts) is needed. Finally, to attract, retain, and retrain the workforce to the new approaches, it is essential that the REM&P industry create closer ties with universities to obtain a skilled, diverse, and inclusive workforce.

Retain and attract skilled, diverse, and inclusive workforce. It was mentioned that at the World Mining Congress (WMC) in Brisbane, that a recent survey showed that up to 70% of students were somewhat or completely against taking a job in the mining industry, and that some universities have banned mining companies from recruiting on their campuses. While traditional mining operations are physically demanding and potentially hazardous, thereby limiting the applicable workforce pool, introduction and incorporation of remote/autonomous assets and processes, and collecting, managing, and analyzing large amounts of data for ore body delineation and process and product/waste steam management opens up opportunities for a larger pool of talent and involvement. Besides the physically demanding/hazardous aspect of employment in the REM&P industry, the stigma and societal perception of having a significant negative impact on the environment and local/indigenous communities is also a substantial barrier to attracting new talent. A keynote presenter at the WMC in Brisbane mentioned that just trying to tell ‘a better story’ is not sufficient to build the trust and overcome the perception with society. Instead, engagement and recognition of past/on-going issues and concerns is required, and work must be performed in a collaborative manner to address them.

It should be noted, that while each of these challenges considered separately may seem like a daunting task and huge investment, by considering all of them simultaneously and holistically can significantly reduce the investment while increasing the longer-term benefits. For example, while developing new decarbonized equipment and vehicles with electric motors/systems, it is possible to simultaneously add instrumentation, computational, and communication capabilities to enable remote/autonomous operation and optimize energy usage and performance. Also, while introducing new technologies and approaches into an existing operation is not the optimum approach, it provides an opportunity to examine the benefits and weaknesses before full implementation. The overarching goal is to utilize all of these new approaches, technologies, and capabilities in new mining and processing operations that will need to be initiated in the near future to meet the Green Energy/Net-Zero Emissions goals by 2050.

V. Role of NASA/Government Agencies in Lunar Mining and Processing

As emphasized in NASA's Moon to Mars Strategy and Objectives Development document [5], there are three fundamental pillars as to why humans explore and go into space: Science, National Posture, and Inspiration, As US Space Policy Directive 1 (SPD-1), states, NASA is directed to "lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities" [11]. A critical aspect of both the NASA Moon to Mars Strategy and SPD-1 is promoting commercial involvement, investment, and partnerships. As such, a primary objective of NASA's Space Technology Mission Directorate (STMD) is to ensure American global leadership in space technology by 1) Advancing U.S. space technology innovation and competitiveness in a global context, 2) Encouraging technology driven economic growth with an emphasis on the expanding space economy, and 3) Inspiring and developing a diverse and powerful U.S. aerospace technology community [12]. To achieve these goals and objectives, the primary driver for STMD In Situ Resource Utilization (ISRU) technology and flight development activities, as documented in the ISRU Envisioned Future Priorities strategic plan [3], is to "Enable Industry to Implement ISRU for Artemis, Sustained Human Presence, and Space Commercialization". The plan to achieve this primary driver involves the following:

Market Transparency. Define initial and long-term customer needs for ISRU-derived products. To do this, NASA ISRU personnel work internally with other Artemis element developers and technical disciplines, as well as externally with international partners and industry to identify where ISRU-derived products could enhance or enable current elements and systems, and what modifications or changes (if any) would be required to maximize the benefits of utilizing these products instead of bringing them from Earth. An important partner in defining initial and long-term customers and product amounts is the NASA funded Lunar Surface Innovation Consortium (LSIC) run by the John Hopkins University (JHU) Applied Physics Laboratory (APL). An example of this effort is the Supply and Demand Workshop, held in Sept. 2020 to better understand the state-of-the-art (SOA) and needs of the ISRU developers making oxygen propellants and lunar human and robotic transportation and lander developers [13].

Technology Innovation. NASA STMD will advance ISRU technologies and systems for future lunar applications and missions by utilizing the full range of STMD internal and external solicitations, and through public-private partnerships. To help developers understand and focus their efforts, an extensive review of the SOA of ISRU technologies and systems and gap analyses was performed (and continuously updated), with results and subsequently defined development priorities documented and released in the ISRU Envisioned Future Priorities strategic plan [3] and in recent presentations. The STMD solicitations and selected development efforts cover the full range of Technology Readiness Level (TRL) from extremely low in the NASA Innovation Advanced Concepts (NIAC) program to Flight Opportunity and Commercial Lunar Payload services (CLPS) mission flight activities.

Scale-up Investment. Besides advancing critical technologies, it is essential for NASA/government agencies to reduce risk and promote investment in ISRU systems and products in advance of customer usage and purchases. This starts with identifying and coordinating requirements, standards, and interfaces within and to/from ISRU systems. It also involves identifying, promoting, and coordinating the development of the infrastructure required to support ISRU operations. When appropriate, NASA/government agencies need to provide key and enabling technologies, capabilities, facilities, and expertise to advance and enable industry and future commercial operations to be successful. To reduce risk and promote investment, it is critical for NASA/government agencies to perform and/or support lunar resource assessment and technology/system lunar flight demonstrations using actual lunar regolith and under real lunar environmental conditions. This support could potentially include data buys for lunar resource understanding and ISRU technology/system performance.

Readiness for Disruption: The ability to acquire and process resources at the site of exploration to create products that can be utilized instead of bringing everything from Earth is a **disruptive capability**. Often mission elements and mission architectures need to be modified or changed when considering ISRU product availability (ex. degree of life support system closure if ISRU water/oxygen is available, or propellant type and depot locations with ISRU-derived propellants). To minimize overall infrastructure mass and to achieve the greatest return on investment, lunar ISRU systems must operate for extremely long periods of time (most of the time without crew), in harsh environments, and with extremely abrasive lunar regolith/extraterrestrial soils. When considering the communication delays between Earth and Mars, ISRU systems also need to operate autonomously with minimal human supervision. As with any new technology, before it can be utilized in a mission critical role for human spaceflight, it needs to have undergone significant ground development, as well as demonstrate its performance in the actual flight environment. Therefore, a key step in developing ISRU capabilities for human exploration and commercialization of space is to demonstrate and validate ISRU systems and products at human mission relevant scale and duration to extend or enhance a robotic and/or crewed mission (i.e., 'Pilot Plant' operation). Besides production, it is essential to demonstrate the use of ISRU products initially in a non-mission critical role (ex. provide propellant to a CLPS lander to enable a propulsive hop or provide extra oxygen for EVA/crew usage above the Earth provided mission supply). By NASA encouraging, supporting, or leading development, deployment, and flight operations of an end-to-end Pilot Plant production and product usage mission, commercial risk is reduced, and customer trust and market viability is increased.

Transition to Commercial Production. Terrestrial and space mining cycles can be divided into 4 major phases: Exploration, Development, Production, and Remediation. The Exploration Phase covers both Reserve Definition and Mining Recovery Technology Readiness, The Development Phase covers feasibility studies, contractual and legal aspects, and financing. The Production Phase covers three subphases: Build-up (startup and initial production), Plateau (production rate remains steady), and Decline (Reserves begin to dwindle). The Remediation Phase covers Shutdown/removal of mining equipment, and final mine site reclamation. Figure 4 [based on Ref 14] depicts the value of a mining company over time as a function of the mining cycle phase. The largest negative cash flow for a company is during the Exploration Phase. By focusing on supporting and promoting lunar resource characterization, mapping, and site evaluation/selection and ISRU pilot plant development and operation on the lunar surface during the Exploration Phase, NASA/government agencies can reduce the negative cash flow and risk of transition into the Development Phase where investors and future customers will have greater confidence in achieving commercial production.

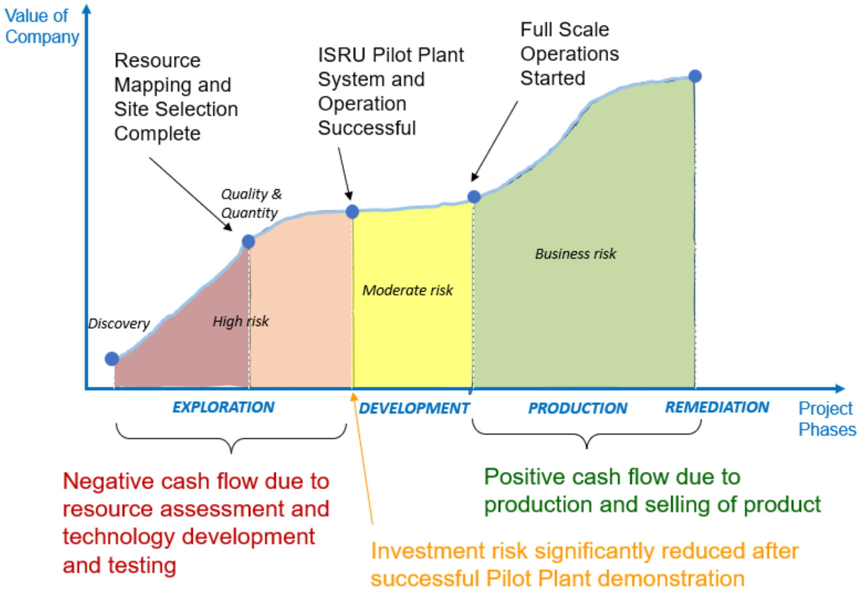


Figure 4. Mining Economics and Mining Phases

Circular Economy. To date, most ISRU architecture and system studies consider a single resource input and one or two main products extracted from that resource. The remainder is considered 'waste'. To promote and advance ISRU to support sustained human presence and commercial operations on the Moon requires a broader perspective considering multiple resources, processes, products, and waste streams, and how they may interact with each other, i.e from a Circular Economy perspective. Circular Economy can be defined as "an economic system based on the reuse and regeneration of materials or products, especially as a means of continuing production in a sustainable or environmentally friendly way" [15]. To support and promote a lunar circular economy, NASA and LSIC will support and promote the tracking and usage of all resource/reactant/product/waste streams, and will work to minimize waste and promote recycling, refurbishment, and reuse of hardware and material streams. To be successful, the lunar circular economy needs to take into consideration not just the flow of the mining-processing material streams and products, but also the hardware and infrastructure associated with both the production and consumption sides (ex. excavators and propulsive hoppers). The overall objective is to minimize disposal amounts and mining/processing wastes. Figure 5 depicts a lunar ISRU circular economy approach which was inspired by two different graphics/concepts [6, 16].

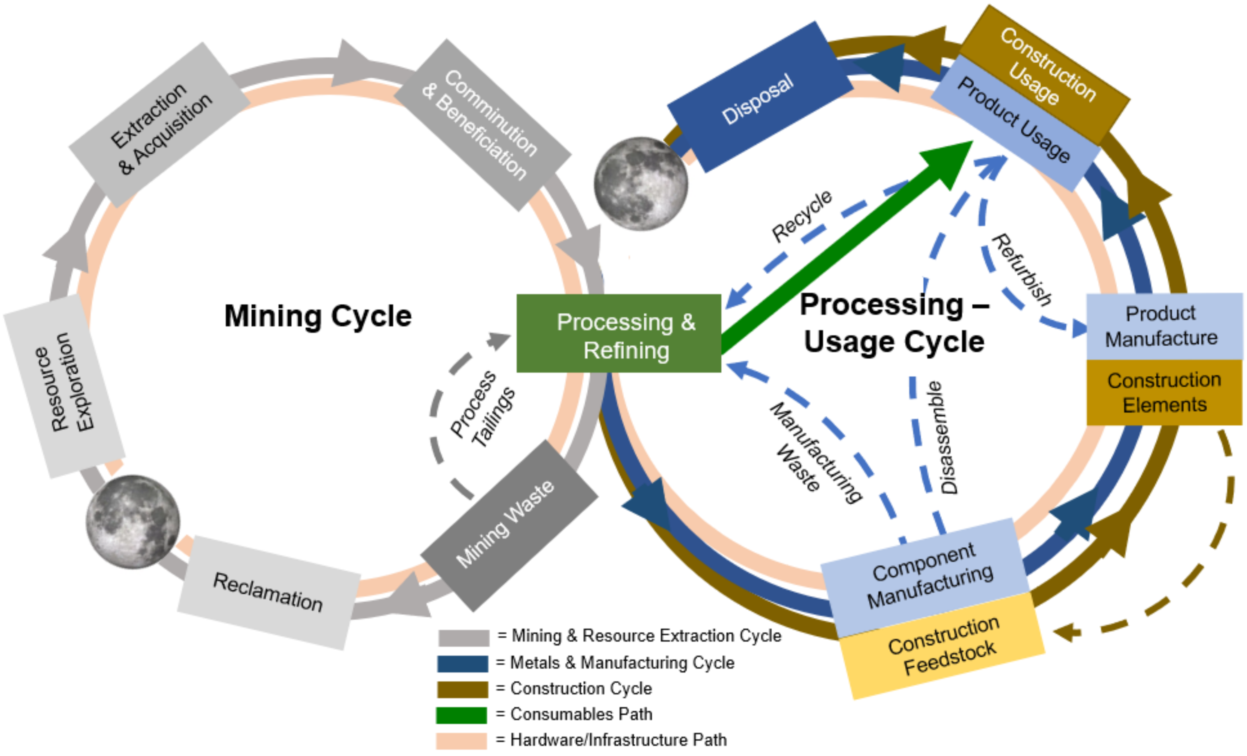


Figure 5. Lunar Mining and Processing Circular Economies

VI. Areas of Commonality between Terrestrial & Lunar ISRU to achieve the 'Mine of the Future'

Based on Lunar architecture and Resource Exploration and Mining/Processing Design and Operation Considerations discussed in Sections II and III, and Terrestrial Resource Exploration, Mining, and Processing Issues That Influence Lunar ISRU in Section IV, fifteen (15) areas of commonality were identified that should be considered in future development activities and collaboration/partnerships between government agencies, space and terrestrial industries, and academic institutes. Figure 6 depicts the interconnectivity of some of these commonalities.

Resource Assessment – Mapping – Valuation

1. High confidence in resource reserves

Infrastructure for Mining and Processing

2. Continuous renewable power at multiple and remote locations
3. High accuracy positioning, navigation, and timing (PNT) in non-GPS environment
4. Secure, distributed, high bandwidth communication network
5. Rugged on-board processing and Edge computing.

Operations for Mining and Processing

6. Data rich environment with near real-time measurements
7. High level of autonomy for all operations (esp. remote)
8. Minimize logistics and ease maintenance/On-site manufacturing
9. Electrification of all mechanisms and platforms

Safety

10. Minimize on-site human/crew involvement, esp. high-risk operations
11. Minimize number and severity of safety and response time critical operations

Environmental Impact

12. Minimize release/exposure of corrosive/hazardous reagents and fluids to crew/space suits and environment
13. Mitigate environment impacts on hardware/operations and vice versa
14. Continuously and distributed environmental monitoring
15. Remediate sites at completion of operations

Resource Assessment – Mapping – Valuation

1. High confidence in resource reserves

To obtain high confidence in resource reserves, sufficient measurements (number/frequency, resolution, accuracy) are needed to mitigate uncertainties, as well as being to define risk/uncertainty for decision makers. The instruments need to be able to operate remotely and under potentially harsh environmental and operating conditions, and the measurements taken need to be able to assess surface and subsurface geotechnical and mineral characteristics to higher degrees of measurement numbers, accuracy, and resolution than may be currently available. These measurements are needed to validate reserve and economic models which characterize the "orebody" for mapping and planning decisions to a much greater extent and accuracy than has been done in the past. To achieve these measurements, the following are needed:

- Surface and subsurface geotechnical and mineral measurement instruments (contact and non-contact)
- Robotic surveying and automation of sampling and information collection and transmission
- Expert systems/AI for data collection and real time analyses
- Remote and real-time analysis, interpretation, and operation support (geologists, operation specialists, etc.) for on-site human and/or robotic resource assessment instruments, coring devices, etc.

The end result is to make resource assessment more efficient and shorten the time to adequately map resources to perform economic assessment and site planning with high confidence. The ability to achieve this objective is tied to implementation of many of the subsequent areas of commonality and will result in more dynamic mine and process modelling and control.

Infrastructure for Mining and Processing

2. Access to continuous renewable power at multiple and remote locations (utilizing electrical energy and use of natural and waste thermal energy)

The type of power generation will depend on the amount, timing, and type of mining/ISRU capabilities utilized. In general, local/on-site power generation with minimal logistics/fuel delivery is desired. The type of power transmission selected will be based on transmission distance, processing power needs, and terrain. Power conditioning and charging stations will be required. Operations may need to be optimized/scheduled around available power generation and storage levels and battery charging rates/station usage (maintain steady load). Power generation and power usage will need to be considered together to optimize hardware and overall performance and operations. Because of the large power demands for resource extraction and processing, there may be opportunities to share local/on-site power generation, storage, and transmission capabilities with local communities/infrastructure, with extra environmental benefits associated with utilizing renewable energy approaches (solar, wind, thermal, and renewable fuels)

For lunar ISRU, solar arrays and power cables delivered from Earth are the preferred initial electrical power generation and transmission capabilities, especially at locations of long-duration (near continuous) solar availability at the lunar poles. One kilometer length cables have been initially identified to mitigate damage from lander engine plume debris to previously landed/delivered non-mobile elements. For water mining operations in permanently shadowed regions (PSR) at the lunar poles, power beaming into the PSR has been identified as a potential option to deliver energy 5 to 10 kilometers into the PSR from sunlit locations nearby. While the ratio of delivered power to initial power is very low compared to cables, the ability to transmit power over greater distances and avoid extreme environments and terrains may be more important. In situ production of solar arrays and electrical transmission lines can significantly enhance the growth and profitability of ISRU systems and operations. Pending decisions on locations, power generation and storage systems, and when maximum power usage is required, concepts of operation designed to maximize available power during lunar day/sunlit periods are preferred.

3. High accuracy positioning, navigation, and timing (PNT), especially in non-GPS environments

To map resources for reserve estimation and planning mining operations, to enable remote and autonomous operations, and to optimize operations with respect to time and energy, highly accurate position knowledge of mobile assets and precise timing of all sequential operations is required. While Global Positioning System (GPS) signals can be accessed readily at most places on Earth, there are locations that they are not at the accuracy level needed, are degraded, or not available, especially underground. While there are plans to deploy and implement cis-lunar/lunar orbit based PNT assets in the future, their capabilities and availability are currently being defined. Besides understanding the relative location of assets to the terrain, it is also critical to understand and measure the position and alignment of mobile assets with each other and to fixed processing and infrastructure hardware the assets may need to interact with. For example, regolith delivery systems will need to align and position themselves with a hopper to enable regolith transfer operations to the processing unit. To achieve highly accurate PNT for resource extraction and processing operations requires the following:

- Need to define PNT measurement beacons/receivers types, accuracy requirements, and locations (orbital/local)
- Need to define passive/active sensors for engagement operations (ex. dumping in bins, positioning vehicles to receive material, engaging interfaces, etc.)
- Need to define communication & avionics capabilities for near real-time understanding of positions for all mining elements.

PNT requirements and capabilities are highly dependent on autonomy (#7) and local and on-board computational capabilities (#5), and therefore implementation must be coordinated with these capabilities. For early lunar ISRU commercial operations, a combination of orbital and local PNT assets should be established as early as possible to allow for achieving high levels of autonomy.

4. Secure, distributed, high bandwidth communication network

The ability to address many of the challenges facing the terrestrial resource exploration, mining, and processing industry with respect to high confidence in resource reserves (#1), remote/autonomous operation (#6), PNT (#3), and a data rich operation environment (#10) is predicated on deploying a secure, distributed, high bandwidth communication network. Communication network capability needs are also closely linked to the level of video imagery and data required for control of remote assets. The amount of data that needs to be transmitted for remote control is directly correlated to the rugged on-board computing/processing capabilities (#5) that are available, as this capability will determine how much autonomy and data evaluation and manipulation can be performed on the fixed/mobile asset versus the amount of measurement and information that needs to be transmitted to a central location for processing and operation management. As the number of remote assets requiring control and management increases, especially mobile assets with video and/or detailed 3-dimensional (3-D) scanning imagery, the need for greater communication throughput will be needed. Since resource extraction, processing, product storage and delivery assets and operations are distributed over multiple kilometers on Earth (and planned for on the lunar surface), the communication network will also need to be distributed. Since the measurements and information transferred need to be reliable and may also be proprietary, the communication network needs to also be secure. While it is expected that high bandwidth communication capabilities will be established for early human lunar activities associated with Extra-Vehicular Activities (EVA), operation of unpressurized and pressurized rovers, and operating initial crew habitats, it can be expected that large scale lunar surface resource exploration, extraction, processing, and product generation will require significantly greater bandwidth and data transmission needs than what is currently planned. With the transmission time delays expected for lunar (and future Mars missions) as well as the criticality of the data being transmitted, Delay Tolerant Network (DTN) protocol usage will be essential. It will be important to work with terrestrial and space resource extraction and processing companies to identify communication network needs as early as possible to prepare for this growth in capability.

5. Rugged on-board processing and Edge computing

To perform remote and especially autonomous operation requires acquiring, processing, analyzing, and displaying a significant amount of information/data. For autonomous operations to be implemented successfully requires rugged on-board processing capabilities to collect, process, analyze, and make decisions rapidly, and to manipulate and transmit the ‘optimal’ amount of raw and processed data need for remote supervised operations while at the same time attempting to minimize communication bandwidth needs.

To maximize the end-to-end value chain performance and product generation of the complete mining/processing cycle, and to minimize cost, material movement, and waste generation, measurements, information, and performance data needs to be transmitted, collected, and analyzed near-real time on i) the material being excavated, transferred, and processed, ii) the terrain being modified and environment being impacted, and iii) on the hardware performing these operations. The large amount of data collected and analyzed can be used to track the ore body size and location, assess the product/waste streams to potentially manipulate and optimize operations, and to fully characterize the hardware operation so that it can be used for predictive maintainability and process improvements (Digital Twins). To collect, process, analyze, and display this vast amount of information and data may require Artificial Intelligence/Machine Learning (AI/ML) approaches combined with new Edge computing capabilities. Edge computing can be defined as a distributed information technology architecture in which data is processed at the periphery of the network, as close to the originating source as possible. It has been mentioned that the traditional computing paradigm built on a centralized data center isn't well suited to analyzing extremely large amounts of distributed data, and that bandwidth limitations, latency issues, and unpredictable network disruptions can impair and degrade such efforts, leading to the need for this new computing capability [17]. It should be noted that computers/processors designed to operate in space are not as capable as those available commercially on Earth, and these limitations will need to be considered when linking terrestrial to space application development activities.

Operations for Mining and Processing

6. Data rich environment with near real-time measurements

To achieve high confidence in resource reserves (#1), high levels of autonomy and remote operation (#7), and to optimize performance and minimize logistics (#5 & #9) requires an ever growing need to collect, process, analyze, and display vast amount of information, commonly referred to as a 'data rich environment'. Reducing the time it takes from collecting the data to making decisions, is also extremely important to increase the efficiency and cost effectiveness of the operations being monitored and controlled. For time sensitive operations such as control of mobile assets or hazardous operations, as close to real-time data transmission and usage is desired within the limits of communication latency and processing capabilities. With the increasing use and importance of the data collected, also comes an increasing need for accuracy and reliability of the measurements and data collected. Benefits gained from utilizing a data rich environment with near real-time measurements include the ability to:

- Collect and analyze performance and maintenance trends. To do so, sensor redundancy and dissimilar measurements need to be performed to ensure measurement accuracy
- Reduce orebody uncertainty (post orebody characterization model) through active/passive ore sensing and removed material measurements
- Optimize the end-to-end value chain through mineral/material stream and process operation measurements and control.

To maximize the benefits of utilizing a data rich environment, the process should start with creating an initial digital model/simulation (based on past experience) and identifying the instrumentation/measurements needed for all the elements in the value chain within a collaborative environment. Using past experience along with new concepts/technologies, the digital model can be used to initially evaluate design and operation choices with respect to important overall critical attributes, such as cost, performance, energy, footprint, environmental impacts/waste generation, and infrastructure required. The end goal of a data rich environment is to be able to operate a digital model/simulation of the complete value chain, that is verified with past data and updated continuously to enable automated decisions. Creating a digital model/simulation of both the lunar surface and ISRU operational hardware will be important for planning and execution of lunar operations as well as helping to assess potential lunar surface terrain and environmental impacts. It will be important to work with element/asset developers on what level of digital model can be used for simulation and control without compromising intellectual property.

7. High level of autonomy for all operations (esp. remote)

As was discussed in Section IV, to meet the challenges facing terrestrial resource exploration, mining, and processing that exist today requires a greater need to operate in remote and extreme environmental conditions, while at the same time remove humans from remote and hazardous operations. The only way to do both is to increase the level of platform/asset on-board autonomy (decision making and operation). This requires coordination and collaboration with PNT (#3), communications (#4), and computing/processing (#5), especially when considering the roundtrip communication time delay of approximately 5 to 6 seconds between the Earth and the Moon (8 to 40 minutes for Earth to Mars). Attributes of a high level of autonomy include:

- Human supervision only when needed
- Reduced number of personnel in central and onsite control rooms (move away from typical Shuttle/ISS NASA mission control room approach), enabling distributed decision making (manual – semi automated – automated)
- Precision mining/reduced footprint when additionally coupled with high confidence in resource reserves (#1)
- More diverse workforce and human safety is possible with removal of direct human control/operation

When dealing with multiple platforms/assets, especially mobile assets, a major question to address with the level of desired/allowed autonomy is 'how much do the assets coordinate with each other autonomously without human supervision or limited insight?'. Adoption of AI/ML for having assets learn and coordinate better and more independently can increase the efficiency and speed of operations but can lead to non-intuitive or predicted solutions. Since, achieving a high level of autonomy does not happen immediately or quickly, there is time to perform extensive testing, under realistic operational conditions to develop both the capability and the trust that operations will be performed/executed as planned. Extra time and reduced performance should also be expected when these capabilities are first introduced into active/on-going mining/processing operations to ensure autonomy, PNT, communications, and processing/control are all working properly together.

8. Minimize logistics and ease maintenance/On-site manufacturing

While significant attention is given to the platforms/assets involved in resource exploration, extraction, transfer, processing, and the infrastructure needed to support these operations, it should be noted that the efficiency and cost effectiveness of resource mining and processing operation itself is highly dependent on both the level of maintenance and repair these assets and infrastructure require and the timeliness and availability of the logistics required to keep these operations going. A colleague is fond of saying that ‘big mining companies are really logistics companies’. To reduce logistics issues and needs, there are two major factors that must be considered: how to reduce the number/mass of items needing to be shipped, and how to optimize/plan logistics shipments. It should be noted that energy-related logistics can be reduced by access to continuous renewable power at multiple and remote locations (#2), and electrification of mechanisms and platforms (#9), and crew-related logistics and infrastructure can be reduced by minimizing on-site human/crew involvement (#11). Since platform and mobile unit logistics needs are largely based on the level of maintenance and repair needed, it is important to: 1) reduce the time and effort associated with maintenance and repair, and 2) focus on preventive maintenance versus repair after failure. The following six attributes should be considered from the start in the design of the hardware/assets used in resource exploration, extraction, and processing, and the infrastructure and operations performed on-site to reduce logistics and maintenance issues and increase operation productivity.

a. Modularity/Orbital replacement unit (ORU)
b. Commonality of parts/interfaces
c. Two-phase maintenance approach
d. On-site manufacturing
e. Understanding of high wear/failure components, tied to predictive and prescriptive maintenance philosophies
f. Automated supply chain

The first three attributes, modularity, commonality, and two-phase maintenance, were previously discussed in Section III. Use of common parts, and especially use of common modules can significantly reduce overall logistics and inventory complexity. Modularity, also known as orbital replacement units (ORUs) in the space industry, and the two-phase maintenance approach where failed modules are quickly replaced to keep the hardware/asset operational while the failed module is then repaired off-line can allow for reduced down-time of hardware/assets leading to increased operation productivity. While the International Space Station has utilized ORU repair from the start, failed hardware needs to be returned to Earth vs repaired there. A driving requirement for this effort as well as minimizing human/crew involvement (#10) will be the ability to perform remote robotic maintenance, especially for hazardous and extreme environments such as cramped underground coal seams and lunar permanently shadowed regions (PSRs). Modularity, commonality of parts/interfaces, and fasteners/tools used in maintenance will be key for successful robotically performed maintenance.

The benefit of the two-phase maintenance approach is maximized by the ability to repair and reuse modules on-site. To aid with this capability and simultaneously reduce logistics needs is the ability to manufacture replacement parts on-site. For lunar operations, this capability not only can reduce logistics delivered from Earth, but also may strongly influence/change the design of the hardware used in lunar ISRU operations if the parts can be produced from in-situ resources. For example, parts that may fail due to wear or repeated contact with regolith could be designed around fast replacement and on-site manufacturing vs designing with a high wear resistant metal/material that can’t be produced on the Moon.

A major benefit of the digital model/simulation of all the elements in the value chain discussed in Rugged on-board processing and Edge computing (#5) and Data rich environment with near real-time measurements (#6), is the ability to better understanding what parts tend to fail first as well the ability to monitor trends and performance to predict where failures might occur if left unchecked. This ability, tied to predictive and prescriptive maintenance philosophies, can significantly reduce major failures/downtime in operations and allow for a more automated supply chain where logistics and prescriptive maintenance are coordinated in advance.

9. Electrification of all mechanisms and platforms.

Transition from diesel motors and hydraulic actuators to all-electric motors/actuators raises significant design and operational challenges and opportunities. Current terrestrial mobile operations are often dominated by utilizing mass, large amounts of stored energy in diesel fuel, and the significant force capabilities of hydraulic actuators. Electrification, combined with automation, can allow for greater control with more consistent outcomes, while increasing productivity and safety. However mobile asset designs and operations will need to be redesigned and optimized around energy storage capabilities, energy usage, electric motor/actuator force capabilities, and recharging/refueling capabilities. There is also value in unifying electrical storage with on-site regenerable/ISRU produced reactants. On-site production of energy/fuel cell reactants and power systems for backup and mobile assets may also allow for greater flexibility and ready growth of operations. A trade-off between fuel cells versus batteries on mobile assets for providing electrical and thermal energy will need to be performed for each class of mobile asset and operation, since one approach may not be appropriate for all possible operations. To maximize the benefits of electrification of mechanisms and platforms, the following is needed:

- Standardize power interfaces, batteries, power conditioning units, motors, etc.(tied to #2 & #8)
- Common ISRU-derived/regenerated and energy system fluids (fuel cell and flow battery reactants)

For terrestrial applications, electrification of mechanisms and platforms, along with use of renewable/regenerable energy (#2) are major factor in mitigating environment impacts associated with resource exploration, extraction, and processing hardware and operations.

Safety

Safety of on-site personnel and astronauts in space is paramount in all hardware/asset design and operations for terrestrial and space resource exploration, extraction, and processing systems and support infrastructure. Two aspects of increasing personnel/crew safety are discussed below: minimizing crew on-site involvement (#10) and minimizing the number and severity of safety and response time critical operations (#11).

10. Minimize on-site human/crew involvement, esp. high-risk operations

The simplest method for increasing on-site personnel and astronaut safety is to remove humans from direct involvement with potentially hazardous hardware and operations. Since astronauts will only be available on the lunar surface for limited durations until sustained surface presence is established, lunar ISRU systems need to be designed from the start with the assumption that operations and maintenance/repair tasks will not be performed by astronauts, but instead controlled from Earth and maintained by robotic assets to the maximum extent possible. Humans/astronauts would only be utilized in situations where existing robotic capabilities are not sufficient to correct the problem on their own. With this in mind and as a potential guide, the ultimate goal of lunar ISRU and new terrestrial operations should be to design for zero human entry for all mining and processing sites from the outset. To achieve this goal requires the following:

- Tele-operation and on-site asset control/oversight (tied to #4, #5, & #6)
- Autonomous operation of on-site hardware/assets (tied to #7 and subsequently #3, #4, & #5)
- On-site robotic maintenance (tied to #8)

While zero human/crew entry is not expected to be possible for some time, working on these aspects can significantly reduce the number of personnel required to maintain and grow on-site operations. This is extremely important since the cost of accommodating and supporting crew at remote locations as well as retaining and attracting new personnel (Section IV) are significant challenges that can be mitigated/reduced.

11. Minimize number and severity of safety and response time critical operations

While the primary purpose of developing and incorporating all of the areas of commonality discussed above is to mitigate the challenges facing the terrestrial resource exploration, mining and processing industry while simultaneously enabling an increase in productivity and cost effectiveness, these new technologies and operations can also introduce new safety issues to on-site personnel and the local community, as well as unintended hazards to hardware/assets and the environment. Besides standard Environmental Impact Studies (EIS) and Occupational Safety and Health Administration (OSHA) type studies and considerations for terrestrial operations, a more holistic evaluation and analysis of the overall operational architecture and hardware/assets may be desired. This holistic evaluation should be linked to the Digital Twin - model/simulation of all the elements in the value chain discussed in Rugged on-board processing and Edge computing (#5) and Data rich environment with near real-time measurements (#6). In performing the hazard analysis for these new approaches, it will be important to minimize both the number and severity of time critical safety operations. The analysis will need to consider two important factors:

a. Increased time between actual operation and decision/response by a remote operator
b. Level and decision authority/approach of autonomous/supervised control

With incorporation of remote operations and time delays associated with communications and analysis of collected data (especially for lunar/Mars ISRU), there may be a significantly greater amount of time between what is occurring and the decision making/response time of a remote controller vs someone directly operating the system/asset. Once safety related issues are identified, for human operators nearby (or the local environment and community) and/or the hardware itself, designers and operators need to assess the criticality of the response time in mitigating/eliminating the hazard. An important aspect to consider in the mitigation approach will be the response approach philosophy. One approach is to immediately halt operations and attempt to enter a ‘safe’ state mode until a human operator can assess the situation and decide what the appropriate response should be to the detected anomaly/hazard that caused the shutdown. For assets/systems that aim to have a high level of autonomy for all operations (#7), decision authority for the response to hazards/anomalies will need to be designated to the on-board processor with notification to remote human operators after the action/response has occurred. Achieving this latter state of capability will most likely require extensive testing and operation to achieve this level of trust, especially if humans/crew are in close proximity. Note, these capabilities and control approaches need to consider both nominal operating conditions as well as phase one maintenance and repair operations (#8).

Environmental Impact

12. Minimize release/exposure of corrosive/hazardous reagents and fluids to crew/space suits and environment

Reduction of minerals to extract oxygen and metals (terrestrially and in lunar ISRU) can i) involve the use of corrosive and environmentally hazardous reagents such as hydrochloric and sulfuric acids, ii) produce hazardous gases/liquids as intermediate/secondary products in the overall resource processing system, and/or iii) release or create undesired contaminants (example, production of hydrogen fluoride, hydrogen chloride and hydrogen sulfide during hydrogen reduction of lunar regolith). For lunar ISRU systems and operations, it will be important to perform demonstrations on the lunar surface with actual lunar regolith not only to understand the performance of the process and the quality of the product desired, but to also identify any potential and/or unintended contaminants released or produced during regolith processing so that these can be eliminated or mitigated in subsequent larger scale designs and operations. It is also critical to regenerate and recycle reactants to the maximum extent possible in lunar ISRU processes to both minimize replenishment logistics from Earth as well as to minimize release and impact to the lunar environment. Before considering venting/releasing any gas/liquid (hazardous or not) to the lunar environment in full scale/commercial operations, alternative uses for these waste products should be considered (waste to wealth/circular economy) or capture approaches should be considered. The three most likely operations that could lead to venting to the lunar environment are 1) when regolith is feed into processing units, 2) when processed regolith is removed from processing units, and 3) is during maintenance and repair. It is extremely important to consider the third operation in the design and mitigation of hazards since this operation might require crew/astronaut involvement. While on-site regeneration/recycling of reactants may not be a normal approach for terrestrial operations, it should be considered as a future approach to minimizing environmental impacts. Another form of mitigation to release/exposure of corrosive/hazardous reactants and fluids is to replace hazardous reactants with non or less hazardous approaches, such as use of ionic liquids (with extremely low vapor pressure) or biological reactants. More work in this area is needed to match the extraction efficiency and processing time possible with current reactants.

13. Mitigate environment impacts on hardware/operations and vice versa

Developing and incorporating many of the capabilities discussed in this section will either directly or indirectly reduce environmental impacts associated with current terrestrial mining and processing operations. For example, high confidence in resource reserves can lead to more precise extraction of resources and smaller mining footprint, thereby reducing the terrain being modified and remediate, as well as the amount of dust generated that could impact hardware and the local environment. Use of renewable energy and electrification of motors, mechanisms, and actuators reduces or eliminates carbon emissions. Optimizing operations around minimum energy and material movement reduces overall energy consumption. Recycling reactants and minimizing venting/waste may reduce water usage or promote water recycling. When all of these are taken into consideration together, a significant reduction in environmental impact is possible.

14. Continuously and distributed environmental monitoring

While zero emissions, wastes, and dust generation are the ultimate goal for terrestrial resource excavation/processing and lunar ISRU operations, this will most likely not be possible for the foreseeable future. Therefore, it will be important to understand the immediate and long-term impacts of these terrestrial and lunar operations on the local and global environments. To do this, it will be critical to establish a distributed environmental monitoring capability that provides continuous monitoring capability before full-scale commercial operations are initiated on the Moon. In accordance with what was discussed in Minimizing the release/exposure of corrosive/hazardous reagents (#12), it is recommended that ground analog and lunar environmental chamber testing and early lunar ISRU demonstrations and pilot plant operations include environmental monitoring capabilities to understand and characterize the possible contaminants and waste products that could be generated and released into the lunar environment. This network would also be critical in performing Responsible Lunar ISRU discussed in Section VII.

15. Remediate sites at completion of operations

A significant social issue with regard to both terrestrial and space mining and processing operations is the modification and visual impact to the terrain and lunar surface, and the generation of waste. It is, therefore, extremely important to consider both how to minimize the impact to the terrain during these operations as well as how to remediate the site at the conclusion of the operations. One approach used currently at some mining sites is to perform remediation on an on-going basis as mining operations progress. Another approach previously discussed is to perform more focused/precise extraction. A third option to consider is to minimize the generation of waste by considering and implementing a more circular economy for terrestrial and lunar activities. To achieve this, waste/tailings need to be initially characterized and stored at designated locations, with promotion and incentives for subsequent reprocessing and generation of new products (waste to wealth). Finally, as is stated later in the paper, remediation/reclamation of a site does not require the site to be modified back to its original state, only to an agreed upon desired end state. Therefore, it will be important to discuss and plan for what are acceptable end states for these operations. In a recent visit to coal mining sites outside of Emerald in Australia, sites that were originally hostile/unusable before coal mining operations started were converted into farming and cattle grazing sites at the completion of the reclamation process in agreement with the local/indigenous community.

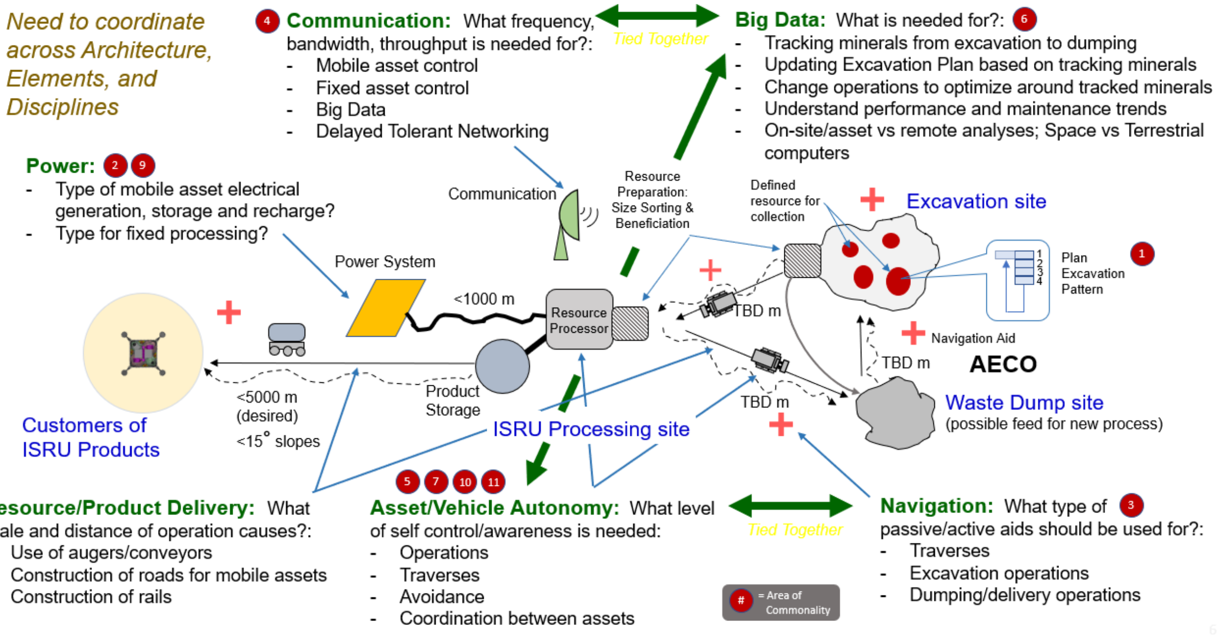


Figure 6. Interconnectivity Associated with Implementing Commonalities for the Mine of the Future

VII. Considerations for Development and Implementation of Responsible Lunar ISRU

There are growing concerns about the lack of governance and regulation over lunar surface exploration and commercial operations, especially with respect to operations that may impact the lunar environment. As will be discussed in the section below, lunar resource extraction and processing operations are likely to result in potential environmental impacts, including but not limited to dust generation, landscape modification, atmosphere/regolith contamination, and waste generation. A sustainable future for humans in space requires consideration of the long-term implications of all space activities before they are carried out. Identifying the environmental impacts of resource extraction and processing should be done by considering the characteristics of the hardware and operations themselves, along with the data from baseline environmental and operational measurements. Terrain and environmental impact measurements and modeling will be important to understand the extent of spatial and temporal impacts on the lunar surface and environment. To limit/mitigate potential environmental impacts, the following prioritized steps should be considered when designing and operating resource extraction and processing hardware and systems: 1) impact prevention, 2) reduction of impacts, 3) restoration and finally, 4) offsetting any residual impacts [18].

To perform and enable responsible lunar ISRU, it is important for Lunar ISRU developers and mission planners to utilize the lessons-learned from terrestrial mining and the information presented earlier in this paper to better inform and influence on-going and future resource extraction and processing hardware and system designs and operations. It is also important for the whole sustained human lunar presence and space commercialization community to consider a sustainable ISRU-based circular economy as discussed in Section V. Design and operational considerations for lunar ISRU systems and processes need to begin to address the Moon to Mars Objectives listed in Section III and Figure 3 for Responsible ISRU and provide a starting point for future dialog. There are five major drivers for the following Lunar ISRU design and operation considerations:

i. Minimize the near and long-term impact to the local terrain and environment
ii. Minimize the impact on science and/or provide benefits to science objectives
iii. Minimize the impact to surface hardware and infrastructure
iv. Minimize waste streams and promote circular economy
v. Reduce/eliminate crew safety hazards

Lunar ISRU Design and Operation Considerations

1. Overarching Lunar ISRU Design and Operation Considerations
    a. Design elements with maintainability and end-of-life in mind from the start. This will include:
        - Maximize use of common elements: motors, controllers, sensors, connectors and interfaces, latches/attachment points
        - Maximize use of modular/swappable elements/units
        - Promote in situ manufacturing of replacement parts and recycling of high-wear elements
    b. Due to factors such as teleoperation time delays, high levels of autonomy, and planned or inadvertent mobility of assets, some level of 'self-awareness' of all ISRU mining and processing operations and surroundings is required to prevent or inhibit operations if unsafe conditions arise (i.e. conditions where damage to itself or other assets/people could occur)
    c. Environmental impact should be considered in the design and operation of ISRU system to avoid harmful contamination, forward contamination, and heritage protection. This will include the following:
        - Minimize release/exposure of corrosive/hazardous reagents and fluids to crew/space suits and environment
        - Mitigate environment impacts on hardware/operations and vice versa
        - Distributed environmental monitoring on a continuous basis
        - Remediate sites at completion of operations
    d. Foster circular economy throughout the Mining-Processing system; reduce, reuse, and recycle. Incentive the transformation of waste into useful feedstocks and products
    e. Mission and Crew safety are paramount. System designs need to minimize time critical safety operations, and on-site human/crew involvement in hazardous/high-risk operations needs to be minimized with appropriate safety inhibits when crew are present
2. Resource Exploration
    a. Experience and lessons learned from early demonstrations and end-to-end Pilot plant validation of technologies, production, and product operations will be used to refine subsequent agreements, guidelines, and eventually requirements
    b. Resources mapped, site locations defined, and excavation and processing plan established before operations begin.
3. Resource Excavation
    a. Excavation site locations will be coordinated with human exploration and science as part of the site master plan
    b. Excavation sites in permanently shadowed regions associated with full-scale commercial operations will be identified and initiated after the combined resource assessment/science assessment of the location to determine the reserve potential has been completed.
    c. Disturbance and lofting of regolith during excavation and transfer will be minimized to the maximum extent possible for performance and environmental considerations. Amounts will be defined through early ground and flight demonstrations and measured on a regular/periodic basis.
    d. At the completion of mining operations, the mining site will be remediated to the previously agreed upon state at the start of operations.
4. Traversing
    a. Mobile asset traverses due to delivering excavated materials, captured resources, process tailings, and ISRU products should be performed with the minimum of lofted regolith and surface area disturbance to the maximum extent possible for performance and environmental considerations. It is anticipated that

roads/pathways will be utilized as early as possible in established/commercial operations to minimize further impact on the lunar surface and environment, and subsequently reduce wear and maintenance of the mobile assets. These ISRU transportation systems may evolve into more permanent infrastructure such as rail/pipe-based delivery systems.

   b. Excavated/pre-processed regolith should be covered/contained during traverse operations to minimize regolith release into the ‘atmosphere’

5. <u>Regolith Transfer and Preparation</u>
   a. Regolith and material preparation (crushing, size sorting, mineral separation) and transfer operations should be designed to minimize evolution/release of regolith dust into the processing and adjacent hardware
   b. Regolith transfer devices and operations should be contained/covered to the maximum extent possible to minimize regolith release

6. <u>Regolith Decomposition Processing for Production of Oxygen, Metals</u>
   a. Maximize regeneration of reactants used in processing. Continually assess options for improvement.
   b. Reactant venting during processing and regeneration should be minimized to the maximum extent possible for performance and environmental considerations. Amounts will be measured and defined through early ground testing and measurements are recommended during flight demonstrations. Venting during Pilot and subsequent production operations should be measured on a regular/periodic basis.
   c. Analyses of venting amounts/rates on local and global lunar environments should be performed to understand and establish ‘acceptable’ release amounts and constituents
   d. As production rates increase with time and exceed allowable limits, alternative approaches to capturing gas reactants and products verses venting should be considered for implementation

7. <u>Regolith Processing for Water/Volatile Extraction</u>
   a. Water and other volatiles not captured during processing should be measured and defined through early ground testing and measurements are recommended during flight demonstrations. Venting during Pilot and subsequent production operations will be measured on a regular/periodic basis.
   b. Analyses of venting amounts/rates on local and global lunar environments should be performed to understand and establish ‘acceptable’ release amounts and constituents

8. <u>Gas/Liquid Product Storage & Transfer</u>
   a. Gas/liquid venting during storage should be minimized to the maximum extent possible for performance and environmental considerations. This may require active cooling for cryogenic liquids to prevent boiloff, and/or vent capture and recycling. Amounts should be defined through early ground testing and measurements are recommended during flight demonstrations, and on a regular/periodic basis during full scale operations
   b. Gas/liquid venting during transfer should be minimized to the maximum extent possible for performance and environmental considerations. This may require no-vent liquid/cryogenic fluid transfer techniques. Venting of gases and products during connector leak checking, purging, and spill volumes after disconnection need to be minimized. Amounts should be defined through early ground and flight demonstrations, and on a regular/periodic basis during full scale operations.
   c.

9. <u>ISRU Waste Management</u>
   a. Processed regolith waste (after size sorting, beneficiation, and/or processing) should be removed and separately stored at pre-designated tailing sites
   b. Material properties for each tailing site should be characterized and publicly documented to encourage usage for further processing/refining of ISRU-derived products
   c. Tailing site location should be coordinated with human exploration and science as part of the site master plan

10. <u>Surface Waste Management/Recycling/Reuse</u>
   a. Wastes associated with sustaining crews on the lunar surface (food, life support, and packaging and crew wastes) should be identified and emphasis should be placed on materials and processes that reuse, recycling, and conversion into useful products. All trash should be processed to the maximum extent possible into other useful forms before discarding on the lunar surface.

11. <u>Disposal/Reclamation</u>
   a. At the completion of mining operations, the mining site should be remediated to the state previously agreed upon at the start of operations. Hardware and equipment used in the extraction and processing of resources and for storage and transfer of products from resources should be recycled and/or removed. Note that the

salvage of hardware and equipment at the conclusion of ISRU operations can only occur with permission of the owners (or the liable nation).

b. Owners should have reclamation plans (with liable nation) before start of the commercial production phase. The liable nation will be responsible if abandonment occurs. Note, reclamation does not require modifications back to the original state, only to an agreed upon desired end state.

Lunar Science and Lunar Mining & Processing

The Moon to Mars Objectives establish the guidelines for NASA to perform space exploration, and especially lunar ISRU, in an ethical and in an environmentally responsible manner. In particular, **SE-7** states “Preserve and protect representative features of special interest, including lunar permanently shadowed regions and the radio quiet far side as well as Martian recurring slope lineae, to enable future high-priority science investigations”. It should be noted that implementation of resource exploration for lunar ISRU can provide opportunities to increase lunar science.

Before full scale commercial mining operations will occur, a significant amount of knowledge on the geotechnical, mineral, and volatile materials and resources needs to be obtained to determine the ‘reserve potential’ of the resource. To ensure the availability of resources, especially water ice, for scientific use, the capability to map and understand these resources is critical. The information collected will be significantly greater than that obtained by a typical science mission.

Excavation of lunar resource will provide significantly greater access to subsurface areas of the Moon for possible science evaluation. To maximize this potential, it is recommended that periodic ‘pauses’ in excavation operations be performed to allow for scientific evaluations (in line with Zone of Permission rules).

To understand the potential impact of lunar mining and processing operations on the lunar environment, it is recommended that environmental monitoring instruments and measurement capabilities be added to early ISRU demonstrations and Pilot Plant operations in coordination with NASA’s Science Mission Directorate (SMD) and the science community. It is also recommended that environmental monitoring capabilities/measurements be added to all Zones of Operation/Permission.

Large amounts of regolith processing via heating will release significant amounts of volatiles present in regolith (solar wind volatiles, endo/exogenic water, etc.) For ISRU operations, measurement of released gases is primarily aimed at understanding/characterizing operation performance and the potential buildup of contaminants. It is recommended that extra measurements by SMD and the science community should be added for more detailed understanding (ex. isotopic concentrations/ratios).

Finally, it is recommended that the following finding from the Science Decadal Survey be implemented, “A strategic plan is needed to identify measurements most critical to informing ISRU architecture options, ensuring sustainable exploration, and the connection to addressing decadal-level science questions.” [19].

Zones of Permission/Non-Interference

Interpretation and official positions on issues associated with the Outer Space Treaty fall outside the scope of this paper and these authors. However, just as access around active mining operations on Earth can raise significant safety and operation issues, unhindered/unscheduled access in and around ISRU operations on the lunar surface could cause significant environmental, hardware, and crew safety issues. It should be noted that while the Outer Space Treaty promotes free access and does not allow for ‘ownership’ (national appropriation) of lunar sites, it does require nations and organizations/industry under the jurisdiction of nation(s) to perform exploration in a ‘safe’ manner through rules on responsibility, liability, and due regard. Separate from the legal question of resource ownership and zones of exclusion based on this principle, it should be noted that safe exploration operations will require some level of agreed upon access control. For example, locations of ISRU operation can be hazardous to assets and personnel due to autonomous/teleoperated mechanical operations, venting of reactants, transfer of molten materials, etc. Therefore, zones of hazardous operations will need to be established for all operations, irrespective of interpretation of the Outer Space Treaty. Visual/electronic warning and perimeter markings and devices should be utilized to denote the location and boundaries of hazardous operations. Any asset/personnel not previously cataloged and associated with the hazardous operation zone should need to seek permission before entering the zone. The time between seeking permission and gaining access approval must allow for reasonable request processing and evaluation time. Also, the size of the zone of operation for permission cannot be ‘excessive’ in that it would prevent or significantly hinder other non-ISRU related surface operations. Both the process of establishing Zones of Permission and the rules/guidelines for procedures for allowing limited duration access to these zones requires further work beyond this paper.

VIII. Conclusion

The paper is meant to provide top-level understanding of the issues/challenges facing both terrestrial and space/lunar resource exploration, extraction, and processing systems and operations, and to begin the dialog on design and operational considerations for implementing and achieving Responsible ISRU and commercial operations on the Moon. The next steps will be to continue to engage with the terrestrial industry to dive deeper into the areas of commonalty discussed in the paper and determine if there are opportunities for spin-in/spin-off and joint development and testing activities. At the same time, consider what the 'Mine of the Future' looks like for both terrestrial and space applications and work toward how to utilize lunar ISRU systems and the infrastructure required to enable lunar surface operations as a means to understand and demonstrate the benefits/implications of simultaneously advancing and employing all of the areas of commonality discussed in Section VI.

Acknowledgement

The authors would like to acknowledge Michelle Keegan and members from the Australian Remote Operations for Space and Earth (AROSE) organization, Jonathon Ralston, Chad Hargrave, and colleagues from Commonwealth Scientific and Industrial Research Organization (CSIRO), Serkan Saydam, Andrew Dempster, Jeff Coulton, and Nicholas Bennett from the University of New South Wales (UNSW), Shanker Gopalan, and Trent Smith from Theiss, and Eric Reiner and Simon Zillman from Caterpillar for the conversations, knowledge, papers, and references they shared on terrestrial mining and ties to lunar ISRU.

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] P. Murphy, J. Falker, K.D. Earle, W.M. Cirillo, and D. Reeves, "STMD's New Strategic Framework Update", Dec. 5, 2017, https://www.nasa.gov/sites/default/files/atoms/files/336429-508-to5_nac_dec_2017_strategicplanningintegration_tagged.pdf
[3] NASA ISRU Envisioned Future Priorities update, https://techport.nasa.gov/framework
[4] Gerald. B. Sanders, Dr. Julie E. Kleinhenz, "NASA Envisioned Future Priorities for In Situ Resource Utilization", IAC-22-D3-2A-x67971, 73rd International Astronautical Congress, Paris, France, 18-22 Sept. 2022.
[5] *NASA's Moon to Mars Strategy and Objectives Development* document, April, 2023, https://www.nasa.gov/sites/default/files/atoms/files/m2m_strategy_and_objectives_development.pdf
[6] The Canadian Minerals and Metals Plan, PDF: M4-175/2019E-PDF, MinesCanda.ca, March 2019,
[7] Michelle Keegan, Gavin Gillet, and Clytie Danger, "Solving our largest on earth challenges through the benefit of technology transfer between space and mining"
[8] Notes from Keynote speeches/presentations at the World Mining Congress, Brisbane, Australia, 26-29 June, 2023
[9] The 17 UN Sustainability Goals, https://sdgs.un.org/goals
[10] UN Net Zero Commitments by 2050, https://www.un.org/en/climatechange/net-zero-coalition
[11] US Space Policy Directive 1. https://2017-2021.state.gov/space-policy-directive-1-reinvigorating-americas-human-space-exploration-program/
[12] James Reuter, Keynote Presentation, Lunar Surface Innovation Consortium Meeting Spring 2023, Laurel, MD, April 24-25, 2023, https://lsic.jhuapl.edu/uploadedDocs/presentations/1919-1.03_Reuter_042423%20-%20LSIC%20-%20Reuter.pdf
[13] Lunar Surface Innovation Consortium (LSIC) Supply and Demand Workshop, Sept. 2020, https://lsic.jhuapl.edu/Events/103.php
[14] Sommariva, A. et al, "The Economics of Moon Mining', International Academy of Astronautics, Torino, Italy, June 17-19, 2019
[15] Circular Economy definition provided by Oxford Languages
[16] Afreen Siddiqi, Ph.D., "From Sustainable Development to Exploration: Concepts from Living on Earth for Forging Futures on Moon and Mars", Artemis and Ethics Workshop, NASA HQ, Washington D.C., April 12-14, 2023
[17] "What is Edge Computing? Everything you Need to Know", https://www.techtarget.com/searchdatacenter/definition/edge-computing
[18] J.A. Dallas, S. Raval, S. Saydam, and A.G. Dempster, "An Environmental Impact Assessment Framework for Space Resource Extraction", Space Policy 57 (2021) 101441, May, 2021

[19] "Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032", Section 19 Human Exploration, The National Academies Press, 2022, http://nap.edu/26522