

Using ISRU and Surface Construction to Define Long-Term Lunar Infrastructure Needs

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While much of NASA's plans for the Artemis program currently focus on the Human Lunar Return and initial Foundational Exploration segments, the longer-term vision for the Artemis program is to enable sustained human exploration and commercial operations beyond Earth's orbit into cis-lunar space and the lunar surface. The Human Lunar Return segment involves the Space Launch System, Orion spacecraft, new Extra Vehicular Activity (EVA) suits, Human Landing Systems (SpaceX and Blue Origin), initial elements of the Gateway, and initial communication, and positioning, navigation, and timing (PNT) capabilities. The Foundational Exploration segment will add greater lunar surface exploration durations and distances through the addition of lunar terrain vehicles (LTVs) and a pressurized rover. A surface habitat for extended surface operations is also planned for deployment near the transition between the Foundational Exploration and Sustained Lunar Evolution segments. The currently planned infrastructure for the lunar surface to support these activities (power, communication, and PNT capabilities) as well as the level of autonomy and avionics/computational capabilities and maintenance, repair, and logistics needed are aimed primarily at supporting a crew of 4 astronauts on the lunar surface for up to 28 days per year with a limited number of surface assets. To support and enable sustained and evolving lunar surface operations (larger numbers of people for longer periods of time) as well as evolving commercial operations on the lunar surface and cis-lunar space, the initial infrastructure will need to significantly grow to support these operations. To ensure early infrastructure decisions allow for scalable and potentially exponential growth, an 'envisioned future' surface operation and infrastructure state needs to be considered. A significant driver for lunar infrastructure will be large-scale In Situ Resource Utilization (ISRU) and surface construction activities. Large scale ISRU will provide propellants for surface hopping, lunar ascent/descent, and cis-lunar transportation systems, reactants for fuel cells, consumables for crew, feedstocks for manufacturing of hardware and power systems and feedstocks for construction. Large scale construction will initially provide landing/ascent pads and meteoroid/radiation/thermal protection, but will grow to construction of towers, expanding roads/rails, surface habitation, and lunar space ports. Just like terrestrial mining and construction sites of the future, large scale lunar ISRU and construction will require support services and infrastructure including: transportation to/from the operating sites, local navigational aids, communications to/from and within the operational site, crew support, logistics management, maintenance, and repair capabilities, power generation, transmission, and management, and communications systems to enable large amounts of data collection and analysis for tele and autonomous operations and performance assessment. The AIAA ASCEND 2023 paper, "Lunar Mining and Processing: Considerations for Responsible Space Mining & Connections to Terrestrial" Mining" by Sanders et al, discussed the commonalities that exist between NASA lunar ISRU envisioned future and the 'terrestrial mine of the future' and how these commonalities can be used in future collaborations and development strategies. This paper will begin to address and define the lunar long-term infrastructure needs for large scale ISRU and surface construction. A future paper will address the interactions, interconnectivity, and influences/dependencies of the disciplines and major factors associated with large scale lunar ISRU and surface construction activities.

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I. Introduction

In the 80's and early 90's, numerous workshops and conferences were held on human exploration of the Moon, space resources, and large scale In Situ Resource Utilization (ISRU) mining and processing operations [ex. Ref 1]. While workshops described and analyzed big visions for space resources and their usage, very little hardware development had actually occurred. When lunar ISRU began a reemergence in the early 2000's and actual hardware development activities were initiated for the Constellation program, the vision for lunar ISRU and its usage was very modest in scope; provide oxygen to support a continuous crew of 4 on the lunar surface, and possibly utilize lunar-derived oxygen for the crewed ascent vehicle propulsion system [Ref 2]. While the scope of ISRU usage for human lunar exploration was modest, the development and testing of ISRU hardware and systems for consumable production and surface civil engineering and construction (first in the laboratory and then at analog field test sites) showed that even modest operations require a significant amount of development and operation coordination across multiple technical disciplines, hardware providers, and international partners [Ref 3].

Last year, the AIAA ASCEND 2023 paper, "Lunar Mining and Processing: Considerations for Responsible Space Mining & Connections to Terrestrial Mining" by Sanders et al [Ref 4], provided an introduction to NASA's envisioned future for Lunar ISRU and the commonalities that now exist between terrestrial mining and potentially large-scale mining on the lunar surface. As is the case with terrestrial mining and processing, for lunar ISRU 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 (Figure 1).

In 2017, The National Aeronautics and Space Administration (NASA) of the United States of America (US) initiated what has become the Artemis program to send astronauts back to the lunar surface, create a sustainable human lunar exploration program, and lead the first human exploration mission to the Mars surface. As depicted in Figure 2, the Artemis program consists of four segments: Human Lunar Return (HLR), Foundational Exploration (FE), Sustained Lunar Evolution (SLE), and Humans to Mars [Ref 5]. Once NASA has successfully demonstrated returning humans to the Moon, the program will proceed to the Foundational Exploration segment that will allow astronauts to explore the lunar surface for limited durations (days/weeks) each year. While much of NASA's plans for the Artemis program currently focus on the HLR and the initial FE segments, the longer-term vision for the Artemis program is to enable sustained human exploration and commercial operations beyond Earth's orbit into cis-lunar space and the lunar surface. An important aspect of achieving the longer-term vision of the Artemis program is to better understand and characterize the resources on the Moon and learn how to extract and use these resources starting in the FE segment and becoming fully operational in the SLE segment.

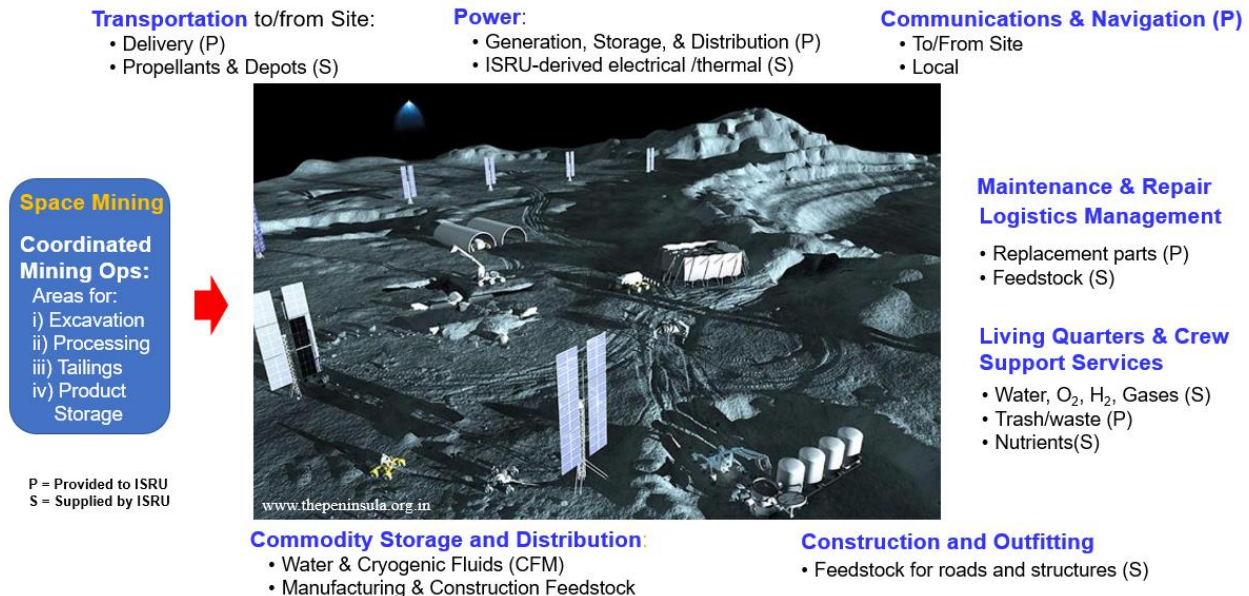


Figure 1. ISRU as Part of a Larger Architecture

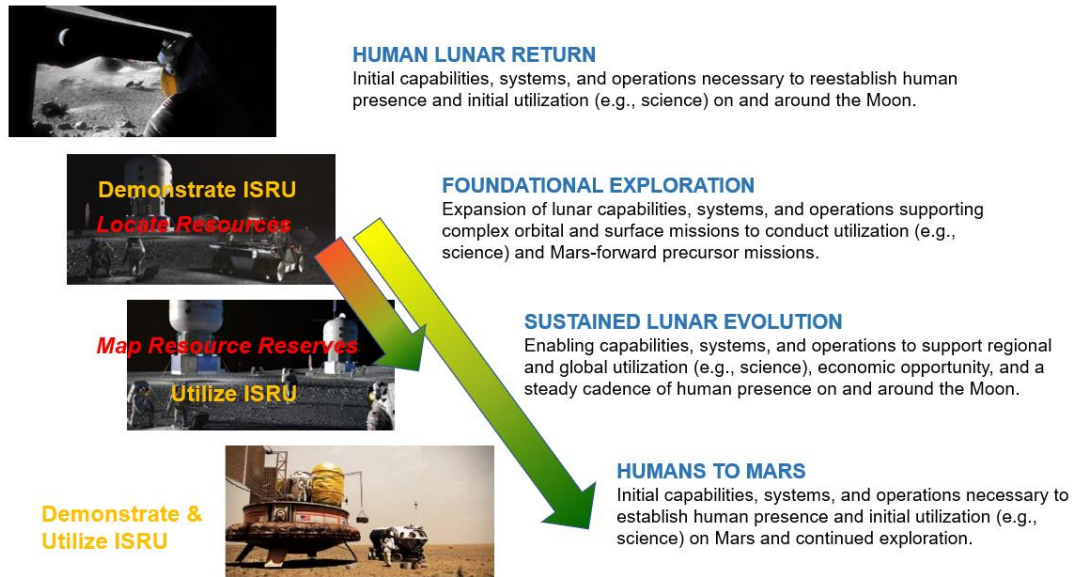


Figure 2. Artemis Architecture Segments and ISRU Insertion

II. Coordination Across Technical Disciplines to Achieve Large-Scale ISRU and Surface Construction Operations

The lunar surface capabilities and infrastructure needed to support a crew of four on the lunar surface for weeks per year during the FE segment, is significantly less than what is needed for the SLE segment, especially to support large-scale ISRU and surface construction activities. Therefore, while NASA is developing mobility, offloading, maintenance, autonomy, software/avionics, power, communication, and precision navigation and timing (PNT) capabilities for the FE segment, it is important to recognize the future needs for these capabilities in the SLE segment to ensure technologies and concepts of operation selected for the FE segment can properly evolve and expand to the needs of the SLE segment. Based on experience from the International ISRU Analog Field tests in Hawaii [Ref 3] during the Constellation program, it is important to formulate and advertise capability needs, requirements, and interfaces as early as possible to ensure that all the technologies and capabilities needed to support large-scale ISRU operations and supporting infrastructure are developed in a coordinated and timely manner. Figures 1 and 3 depict ISRU system and supporting infrastructure architectures and highlights the different NASA discipline areas that are needed for the overall capability to successfully operate. It should be noted that while Figure 3 shows all the disciplines and functions required for a complete ISRU System at the Capability Level (dashed purple box), only the green shaded items in Figure 4 are developed under the ISRU discipline area.

A major revelation from discussions and interactions with representatives from the terrestrial resource exploration and extraction community in 2023 (and subsequently documented in Ref 4), is that these terrestrial activities need to completely change their technologies and operations to meet Net Zero and United Nations Sustainability Goals by 2050, and that these technologies and operations have significant alignment with the NASA large-scale ISRU envisioned future on the Moon and Mars. Also, besides identifying fifteen (15) areas of commonality between terrestrial mining and space ISRU, this paper [Ref 4] also examined the interactions, interconnectivity, and influences/dependencies each of these areas have on each other and the overall architecture, as well as identified questions on interconnectivity that need to be addressed to proceed forward (Figure 4).

The main objectives of this paper are to provide initial thoughts on the near and long-term ISRU and infrastructure needs, capabilities, and concepts of operation to:

1. Align and focus discipline development and integration inside and outside of NASA.
2. Align development and cooperation between terrestrial resource exploration, extraction, and processing and space ISRU.

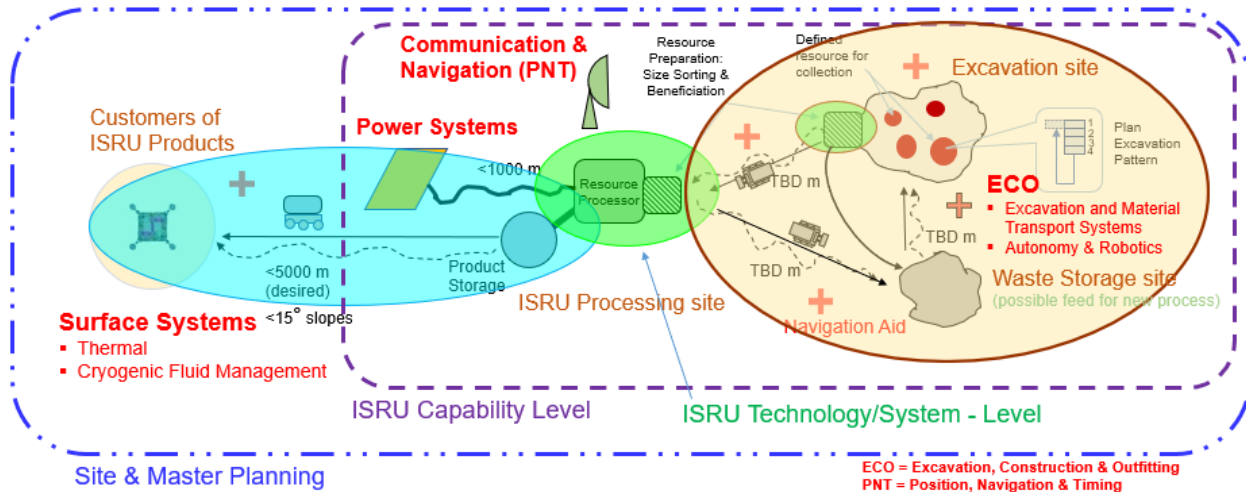


Figure 3. Collaboration & Coordination Between NASA Disciplines Required for ISRU Capability

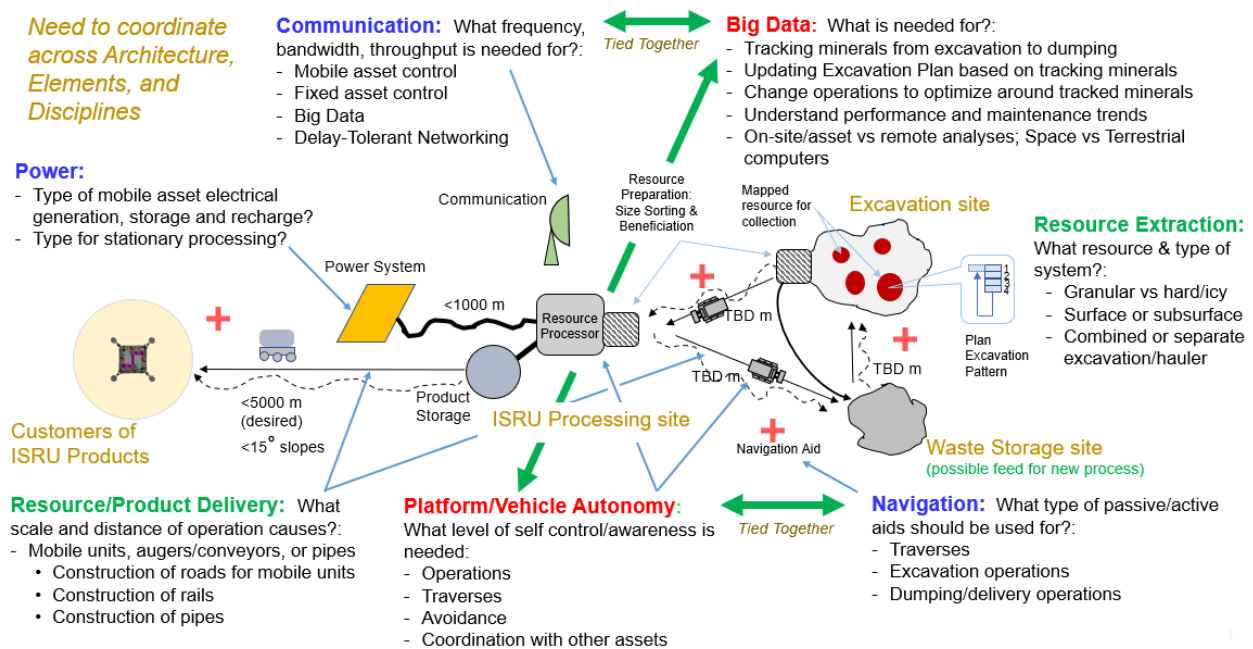


Figure 4. Interconnectivity Associated with Implementing Commonalities for the Large Scale ISRU

III. Concept of Large-Scale ISRU Operations

To begin to focus and coordinate the development and integration of all the disciplines and major factors associated with implementing large-scale lunar ISRU and surface construction, it is important to first provide an overarching vision for the operations, infrastructure, and products. Figure 5, depicts a notional large-scale ISRU operation at a lunar regional scale where several different ISRU mining and processing operations are going on simultaneously. Some of these operations have resource processing sites directly tied to resource extraction sites, resource processing sites fed by multiple sites, and multiple processing sites may be fed from a centralized resource extraction site. Each of these operations may also be performed by different commercial entities and/or international partners.

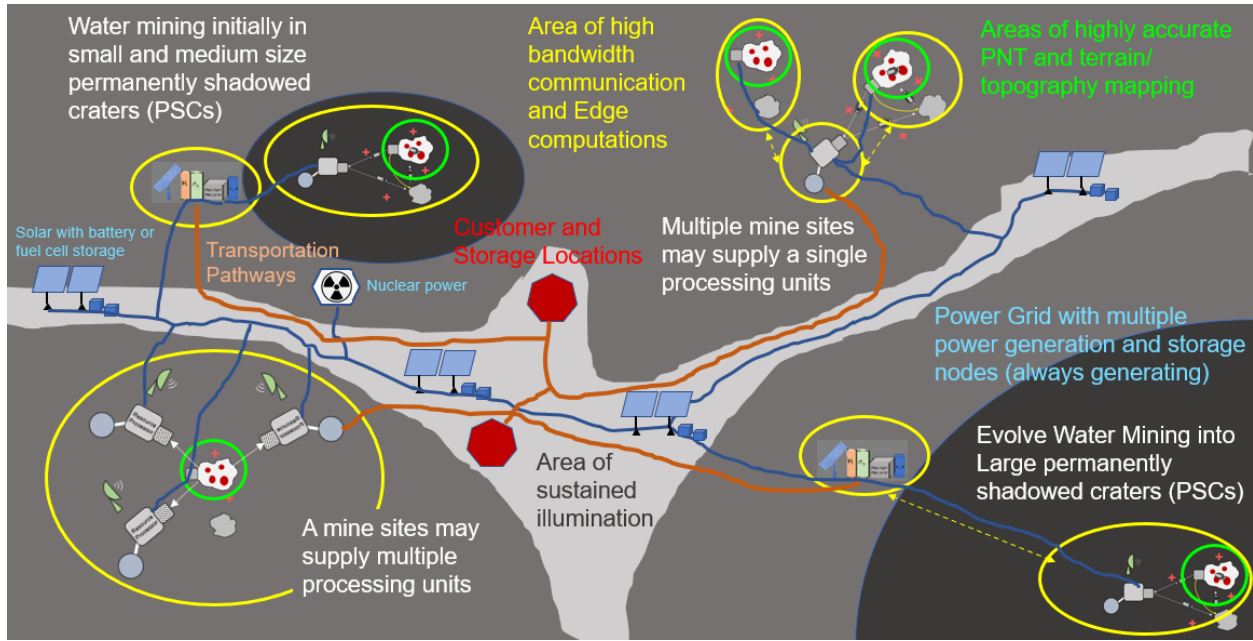


Figure 5. Notional Large-Scale Lunar ISRU and Infrastructure

Figure 5 also depicts ISRU operations occurring in both large and small permanently shadowed regions (PSR) for water and other volatiles that have been previously mapped. At this time, it is assumed that water and volatile extraction operations occur within the PSR, and these resources are transported out of the PSR for further processing/refining in mostly sunlit areas (see Figure 11). A transportation network between ISRU sites and customers is also established to increase productivity and minimize maintenance. The large-scale ISRU architecture also depicts areas where high levels of communication, and precision navigation and timing (PNT) are needed to support intense robotic and autonomous operations, and data collection and analyses.

The large-scale ISRU architecture also depicts a regional power grid, with multiple power generation and storage capabilities to allow for continuous power generation throughout the region. While the architecture assumes solar power generation will predominate the production of electrical energy (at least initially), it is expected that nuclear power will be included as well as potentially lunar-thermal energy storage and conversion. At a regional scale, it is assumed that at least some portion of the power generation grid will be in sunlight throughout the year so that continuous power generation (with or without nuclear power) is possible at some capability.

IV. ISRU System Architecture, Concept of Operation, and Evolution

With an overarching regional level vision for large-scale ISRU operations established, the next step is to dive down into a generic concept of operations and identify the major steps and functions associated with finding, mapping, extracting, transporting, and processing lunar resources, delivering ISRU-derived products to customers, and defining the infrastructure needed to support these operations. Figure 6 depicts the full ISRU system cycle (green pentagons) with required infrastructure (blue hexagons), and overarching aspects (red diamonds) to ensure successful long-term operations. Primary ISRU operations occur at four distinct sites: Excavation, Processing, Product Storage, and Waste Storage sites. To support lunar ISRU operations, which will be performed primarily through remote and autonomous operations, an extensive communication and navigation system will be required, as well as an extensive power generation, storage, and distribution architecture. Because lunar ISRU operations will occur around the clock in an extremely harsh environment (vacuum, temperature and sunlight extremes, abrasive regolith), a comprehensive maintenance and repair capability is required.

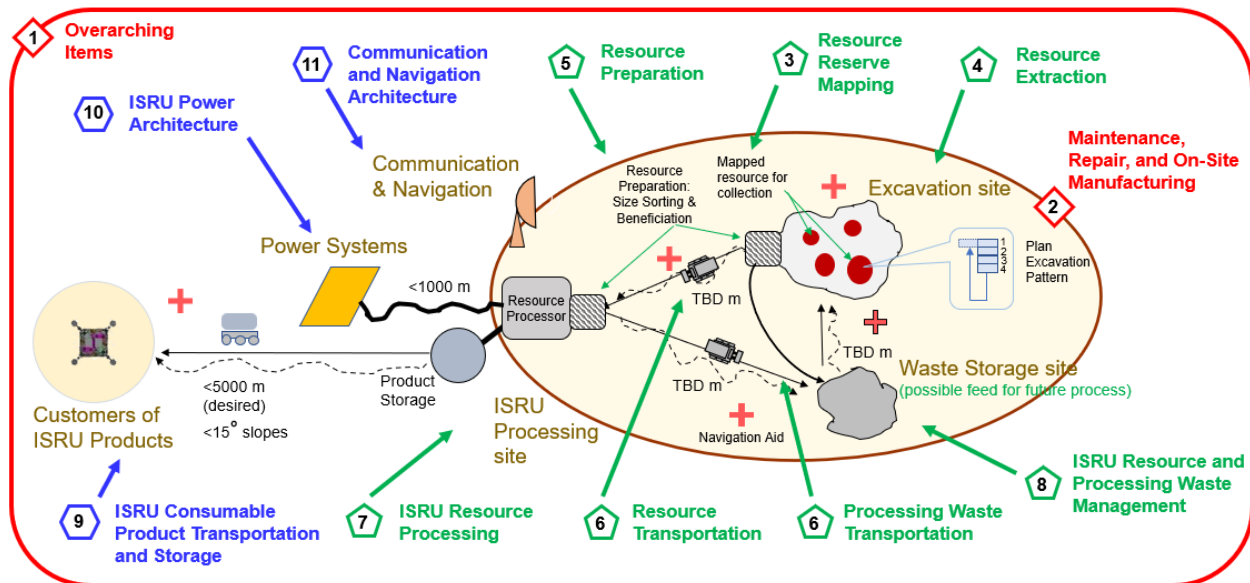


Figure 6. Lunar ISRU System and Concept of Operations

1. Overarching Items: Before examining each of the major ISRU steps and functions depicted in Figure 6, it is important to assess the overarching guidelines and principles that will drive and shape the capabilities and evolution required to achieve large-scale lunar ISRU operations. Besides establishing a maintenance and repair strategy (which is covered in #2), there five overarching items large-scale ISRU and surface construction architectures need to adhere to.

i. Design Elements with Maintainability and End-of-Life in Mind from the Start.

To design for maintainability, minimize life cycle costs, and design for end of life (recycle/repurpose), all hardware and assets should maximize the use of common elements (motors, controllers, sensors, connectors and interfaces, latches/attachment points). Designs should also consider maximizing the use of modular/swappable elements/units. It is recognized that large-scale ISRU will require hardware and assets from multiple entities (countries and companies) that will need to work effectively with each other. It is also recognized that designing for maintainability, modularity, and common hardware can lead to increases in mass and volume and potentially non-optimum performance. Therefore, incentives will be required to encourage these design approaches and commonality of hardware between different companies/vendors/countries. As part of this overarching design factor, it is important to promote the usage of in situ/on-site manufacturing of replacement and recycling of parts, especially high-wear elements (see 2. Maintenance, Repair, and On-Site Manufacturing)

ii. Control: Software & Autonomy

For large scale resource exploration, extraction, and processing to be successful on the Moon, high levels of autonomy and a data rich environment with near real-time measurements will be required along with rugged on-board processing and Edge computing. A large number of assets and processes will need to be controlled, coordinated, and optimized. To do so will require the development of intelligent and integrated control hierarchies that allow operations to be more efficient and reactive to changes identified or new information. These control hierarchies will need to consider dynamic daily and ‘seasonal’ optimization. Because not all systems will be operating at the same pace and operations will be tuned to different customer demands, buffers are needed for material flow and power management. Large scale autonomous and remotely supervised operations will require the transmitting, collecting, managing, and analyzing large amounts of data. Shared responsibilities will be needed between individual assets/processes and centralized control. Also, some level of ‘self-awareness’ of all ISRU mining and processing operations and physical 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).

iii. Mission and Crew Safety are Paramount.

In all aspects of human spaceflight, mission and crew safety are of paramount importance. 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. While it is important to minimize the

disturbance of operations when crew are present, it may be necessary to shutdown and safe (depressurize/deenergize) hardware before direct crew interaction with visible inhibits.

iv. Sustainability and Responsible Operations should be a Focus from the Start

As mentioned in Ref 4, 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. The importance of sustainability and responsible use of space are emphasized in NASA's *Moon to Mars Strategy and Objectives Development*, objectives SE-7, OP-13, and RT-6 [Ref 6].

To meet NASA's sustainability and responsible use goals and objectives, design and operational considerations for lunar ISRU systems and processes need to consider the following major drivers from the start:

- Mitigate and minimize environment impacts from ISRU hardware/operations. This includes:
 - Minimizing release/exposure of corrosive/hazardous reagents and fluids to crew/space suits, human exploration hardware, and environment
 - Minimizing the near and long-term impact to the local terrain and environment
 - Minimizing the impact on science and/or provide benefits to science objectives.
 - Remediate sites to a pre-agreed upon state at completion of operations.
- Continuously monitor ISRU operations and potential environmental impacts. Utilize a distributed environmental monitoring system on a continuous basis.
- Promote and enable a Circular Economy; reuse and minimize waste streams, recycle hardware.

v. Technologies and systems need to be scalable and evolvable from Initial Commercial Operations.

To date, ISRU hardware and systems have only been developed and demonstrated at small extraction and processing rates. These are orders of magnitude less than what the envisioned end states will require. To provide some guidance for ISRU technology and system developers as well as infrastructure providers, Table 1 was created to provide production estimates for different phases and usage of ISRU-derived mission consumables/propellants from early demonstrations to potential commercial end-states. The table does not provide exact amounts and rates but uses the best available studies and commercial considerations to guide development requirements and design Figures Of Merit (FOMs). The table also provides a rough guide to developers of other surface elements for interfacing with ISRU designs and plans.

To achieve the longer-term production rates in Table 1, developers will need to recognize that initial designs and hardware will need to evolve. It is anticipated that the use of modularity in initial designs will allow for some level of scale-up before newer/larger-scale processing units need to be developed. Commercial operations should consider 'generations' of hardware based on lessons-learned from initial hardware in life, maintainability, and performance capabilities. It is anticipated that the 1st generation of hardware (at a minimum) will be designed around minimizing mass and power with very limited repair and maintenance capabilities. Once process performance and operation are better understood, subsequent generations of hardware will need to focus on sustainability and maintainability.

Table 1. ISRU Consumable Production Phases and Usage

	Commercial Propellant Production											
	Initial Commercial						End-State Commercial					
	Demo Scale	Pilot Plant	Crewed Ascent Vehicle ¹	Full Descent Stage ¹	Lockheed Martin ³		Dynetics ⁵	Single Stage to NRHO ²	Human Landing System - Starship ²	Human Mars Transportation ²	Commercial Cis-Lunar Transportation ²	
			3 Stage Arch to NRHO		2 Stage	Single Stage	Single Stage/ Drop Tanks					
Timeframe	days to months	6 mo - 1 year	1 mission/yr	1 mission/yr	per mission	per mission	per mission	per mission	per mission	per year	per year	
Demo/System Mass ⁵	10's kg to low 100's kg	1 mt O ₂ Pilot 1.3 – 2.5 mt Ice Mining	1400 to 2200 kg	2400 to 3700 kg				Not Defined		Not Defined	29,000 to 41,000 kg	
Amount O ₂	10's kg	1000 kg	4,000 to 6,000 kg	8,000 to 10,000 kg	10,000 kg	33,000 kg	32,000 kg	30,000 to 50,000 kg	120,000 (NRHO) 440,000 (Earth)	185,000 to 267,000 kg	400,000 to 2,175,000 kg	
Amount H ₂	10's gms to kilograms	125 kg		1,400 to 1,900 kg	2,000 kg	7,000 kg	Methane Fuel	5,500 to 9,100 kg	Methane Fuel	23,000 to 33,000 kg	50,000 to 275,000 kg	
Power for O ₂ in NPS	100's W	5 to 6 KW	20 to 32 KW	40 to 55 KW				N/A		N/A	N/A	
Power for H ₂ O in PSR	100's W	~2 KW		~25 KW				14 to 23 KW			150 to 800 KW	
Power for H ₂ O to O ₂ /H ₂ in NPS		~6 KW		~48 KWe				55 to 100 KWe			370 to 2,000 KWe	

NPS = Near Permanent Sunlight
PSR = Permanently Shadowed Region

¹Estimates from rocket equation and mission assumptions
²Estimates from J. Elliott, "ISRU in Support of an Architecture for a Self-Sustained Lunar Base"
³Estimate from C. Jones, "Cis-Lunar Reusable In-Space Transportation Architecture for the Evolvable Mars Campaign"
⁴Estimate from "Commercial Lunar Propellant Architecture" study

⁵Electrical power generation and product storage mass not included
⁶APL Lunar Surface Innovation Consortium Supply-Demand Workshop, 9/17/2020
⁷Calculations/Assumptions from Publicly Available Data

2. Maintenance, Repair, and On-Site Manufacturing: For large-scale ISRU operations to be successful, hardware and processes need to operate continuously in extremely harsh and remote environments. 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. To reduce logistics issues and needs, there are two major factors that must be considered: 1. how to reduce the number/mass of items needing to be shipped, and 2. how to optimize/plan logistics shipments. Since logistics needs are largely based on the level of maintenance and repair needed, it is important to: i) reduce the time and effort associated with maintenance and repair, and ii) focus on preventive maintenance versus repair after failure. The section 1. *Overarching Item i. Design elements with Maintainability and End-of-Life in Mind from the Start* introduced the need for: a. Common elements, b. Modular/swapable units, and c. On-site manufacturing as important design and operational items for implementation. Three more important design and operational items needed are: d. Utilizing a two-step maintenance approach, e. Understanding high wear/failure components, tied to predictive and prescriptive maintenance philosophies, and f. Implementing automated supply chains.

Utilizing a two-step maintenance and repair approach is key to implementing the other design and operational items. This approach, depicted in Figure 7 starts with Step 1 performing quick robotic repair and maintenance during battery charging for mobile assets or processing systems when shutdown/deenergized. The quick repair focuses on removing and replacing high wear parts and removing and replacing modular Line Replaceable Units (LRUs) that have failed components. Step 2. is to repair the failed components in the removed LRUs off-line by robots or humans in a controlled environment facility. The repairs and logistics associated with Step 2 are minimized through the use of common parts/interfaces, and fasteners/tools, the use of On-site manufacturing, to replace failed parts, especially high wear components, and the use of health monitoring data/digital twins for predictive modeling of failures and failure rates that is tied to automated supply chain logistics to ensure parts are available before needed.

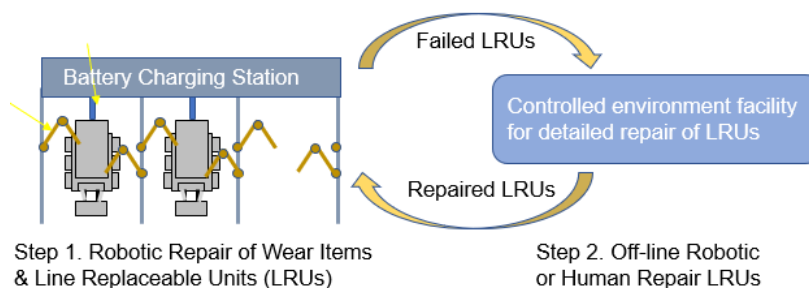


Figure 7. Two Step Maintenance & Repair Approach

The two-step maintenance approach allows for reduced down-time of hardware/assets leading to increased operation productivity. A driving requirement for this effort as well as minimizing human/crew involvement will be the ability to perform remote robotic maintenance, especially for hazardous and extreme environments such as lunar permanently shadowed regions (PSRs). For lunar operations, the capability of on-site manufacturing of failed parts 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.

An important aspect of the 2. *Maintenance, Repair, and On-Site Manufacturing* approach is the large-scale collection and monitoring of asset operation and performance data, and the large-scale data analysis of this health monitoring and operations data through digital twins. A major benefit of the digital twin/model simulation, through collection of large amounts of data and Edge Computing, 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.

3. **Resource Reserve Mapping:** The first step in terrestrial and space mining is to locate, characterize, and map the resources of interest and the location and environment in which these resources can be found. This effort involves the characterization and mapping of physical, mineral, chemical, and water/volatile resources, local geology and terrain, and environmental conditions (sunlight, temperatures, pressures, electrostatics, etc.). The effort also involves overlaying hardware and infrastructure restrictions, limitations, and site selection criteria and factors. In 2020, NASA performed the Lunar Polar Water ISRU Measurement Study (LWIMS) to better understand the resource mapping process, and specifically aimed at understanding the types of missions, instrumentation, and measurements needed to determine the reserve potential of water resources in permanently shadowed regions at the lunar poles [Ref. 7]. The study outlined that resource assessment typically starts with orbital missions/measurements, leading to three Types of

surface missions to provide higher and higher confidence in the resource reserve potential (Figure 8). All of the measurements are tied to providing greater confidence in predictive models to help identify locations not yet directly examined.

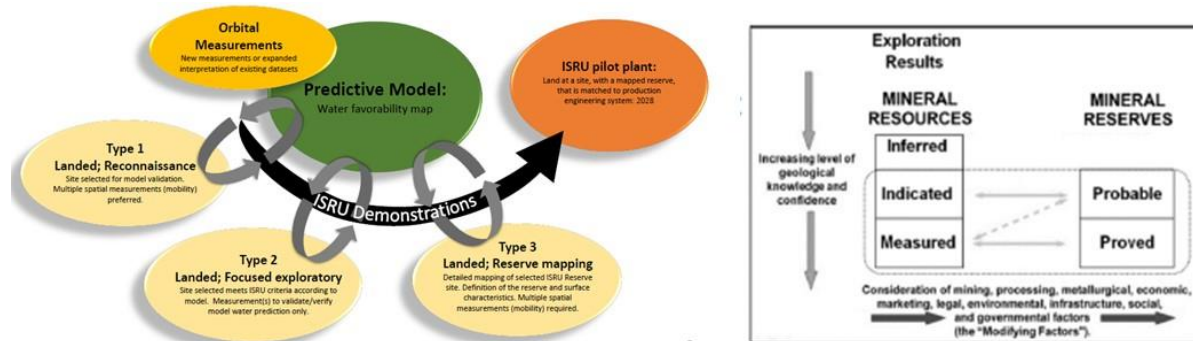


Figure 8. Resource Exploration Measurement and Resource Reserve Estimation Plans

Type 1. Resource Reconnaissance and Type 2. Focused Resource Exploration missions are primarily aimed at obtaining information on particular locations that will increase confidence in the Predictive Model results and its ability to properly select sites for potential mining. These missions may be limited in the types of instruments used, the duration of the mission, and the infrastructure needed for mission operations to be successful. It should be noted that both NASA's Polar Resources Ice Mining Experiment 1 (PRIME-1) and Volatiles Investigating Polar Exploration Rover (VIPER) missions are considered Type 1 missions.

Type 3 Reserve Mapping missions are of the greatest interest with respect to the type and extent of infrastructure needed to successfully map resource reserves and plan for subsequent resource extraction. Type 3 Resource Mapping will require a broader set of measurements and may require more than one mobile asset and/or mission to successfully determine the reserve potential of the resource of interest. These mobile assets and missions will require coordination of instrument and measurement types and will include a significant number/density of surface and subsurface measurements (downhole instruments and subsurface sample analysis). To perform resource mapping properly, the data should be fused and interpreted as close to real-time as possible to allow for adaptive mission measurements and operations. Because a significant amount of data needs to be collected and analyzed over potentially several lunar days, local power generation and storage capabilities will most likely be needed to survive lunar eclipse periods and support sustained operations in PSRs of interest (Figure 9). Significant navigation capabilities with high levels of PNT are needed to support around the clock operations and to ensure data collected is properly localized. Lastly, high bandwidth communication capabilities are needed with the possible need for Edge computing to simultaneously control multiple mobile assets and collect and analyze data in near-real time to allow for adaptive and optimized operations.

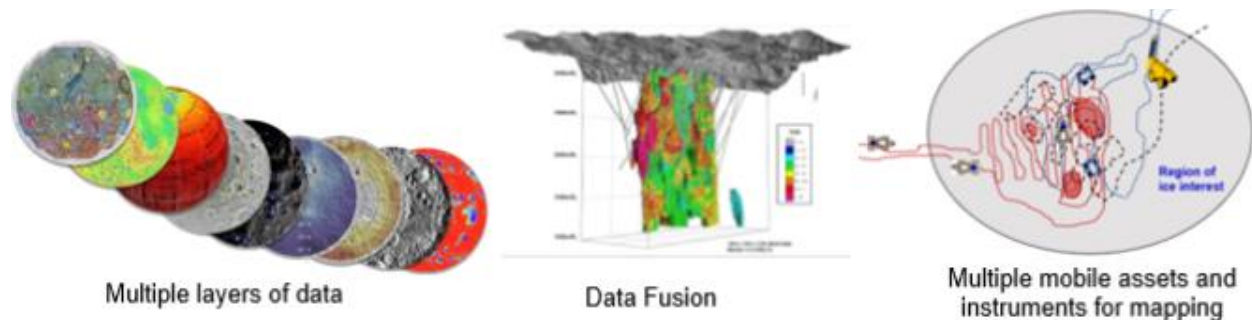


Figure 9. Elements of Resource Reserve Mapping

4. Resource Extraction Planning and Operations:

i. **Planning for Resource Extraction.**

Once the resource has been mapped and determined to be economically viable/practical to extract, the next step in the logistics train of ISRU is to extract the resource for subsequent preparation and processing. Before extraction begins, a plan for the operations, locations, and time phasing of the resource is required. The plan utilizes the knowledge of the resource and terrain in the predictive model to determine which resource concentration will be

extracted and in what order/sequence. The plan will develop and utilize high fidelity models of the resource, movement and stockpiling as well as the equipment to be used. An overall objective of this plan will be to minimize the footprint of the extraction operations. For lunar regolith and water/volatile resources, the most likely extraction process to be used will be surface ‘open pit’ mining, and initially these processes will most likely not be very deep. However, before resource extraction operations begin, it is important to consider the long-term production and product demand. The desired footprint of the extraction site, along with mineral distribution, will factor into the open pit mining plan.

ii. Initial and Continuous Monitoring of Resources

To control operations and continuously optimize the extraction plan, the mineral and/or volatile content of the resource at each stage of the extraction and transfer operations from ‘mine face’ to extracted resource delivery needs to be measured and tracked. This will require the utilization of rapid measurement instruments and sample measurements to provide real-time data to update predictive models and inform upstream processing of the ‘quality’ and properties of the extracted resource. The measurements will also allow for better understanding of the underlying geology, thus how material is sourced and distributed. While operations are occurring, it will also be important to monitor changes to terrain (at cm level), slopes and slope stability, as well as monitor environmental impacts: dust and emissions.

iii. Overview of Extraction Operations and Evolution

The surface extraction approach utilized for lunar ISRU will most likely be performed by multiple – modular assets (instead of one big unit) requiring coordination. To perform the extraction process, the extraction tasks most likely will be performed in series and aligned with previous extraction/excavation operations and locations. Technologies and extraction approaches should be aimed to minimize the extraction footprint and the environmental impact of the extraction process (i.e. limit dust lofting and do not utilize explosives/blasting). During the extraction operation, the performance of each asset used will be tracked to manage and optimize the extraction and delivery operations, as well as support hazard mitigation and maintenance. To achieve this for larger operations will require high bandwidth communication for multi-asset control and Edge computations. Tracking includes power consumption/usage to align with the recharge/maintenance approach outlined in #2 *Maintenance, Repair, and On-site Manufacturing*.

Initial Operations:

Initially, it is expected that operations will be limited until production rates exceed 50 to 100 metric tons per year. The planning, operations, and tracking will be limited to a small number of vehicles with limited communication, navigation, and maintenance/repair capabilities. Excavation/extraction units may also serve as regolith delivery vehicle (ex. ISRU Pilot Excavator - IPEx). Autonomy may be limited with on-board hazard avoidance of surface features and other assets.

End State Operations:

Excavation/extraction units will be tailored specifically to regolith/resource physical characteristics and maintenance repair strategy. Significant resource extraction may require vibratory, percussive, and/or ripper type operations to break through highly dense and consolidated materials. Operations will involve a significant number of mobile assets which will require highly accurate PNT (#11) and terrain/topography mapping for centimeter-level control of excavation operations for autonomous mining/extraction and excavation plan. Centimeter-level topography measurements of the excavation/extraction site also allow for continuous extraction planning optimization. Regolith delivery to bins/hoppers for #5. *Resource Preparation* and #6. *Resource Processing* will also require centimeter-level control with active and/or passive sensors. Operations are expected to utilize supervised autonomy to the maximum extent possible with on-board hazard avoidance of surface features and assets.

5. Resource Preparation:

i. Overview of Resource Preparation Operations and Evolution

The function of the resource preparation step is to modify the resource extracted in #4 *Resource Extraction* to the desired feed properties for #7 *Resource Processing*. Resource preparation functions including Crushing, Size Sorting, Mineral Beneficiation, and Blending.

Size Sorting involves concentrating one or more size ranges of interest based on processing performance and inlet/outlet feed limitations of 7. *Resource Processing*. It is expected that as a minimum, size sorting to eliminate particles greater than a certain size will be required for most oxygen and metal extraction processing techniques and reactors. During size sorting, it may be advantageous to eliminate the very fine particles which could cause internal wear and filter blockage. Larger size fractions could be of interest for construction and blending.

Crushing: If possible, crushing should be avoided due to energy expenditure and wear. Since lunar regolith in the top several meters are already highly pulverized, it is not expected that initial resource preparation will require

crushing operations. Exceptions are 1. Preparing post-processed regolith waste for other operations, 2. Mars hydrated minerals, and 3. Potentially consolidated icy regolith.

Mineral Beneficiation involves concentrating ores/minerals of interest. By concentrating ores/minerals of interest, energy for resource processing can be reduced as a function of KW-kg product/kg feedstock. Discards from mineral beneficiation should be evaluated and advertised for subsequent use. Mineral beneficiation will require power to support material transfer and magnetic, electrostatic, and turbocharging separation techniques. This energy will need to be compared to the performance and energy required to process non-beneficiated regolith to determine the usage value.

Blending involves mixing different mineral/material concentrations after crushing, size sorting, and mineral beneficiation to obtain a specific range of mineral/material properties required for efficient resource processing (#7). Blending of mineral and size fractions may be required for specific construction techniques.

Initial Operations:

Size sorting as a minimum is expected in early ISRU processing systems to due to valve regolith flow limitations and wear. Mineral beneficiation will be added once separation techniques have justified the mass/energy and life of operations in comparison to Resource Processing performance enhancements. Lunar polar highland regolith is primarily anorthosite so processes aimed at this mineral-type may not require mineral beneficiation to begin with. It is expected that resources involving iron, titanium, and KREEP (Potassium, Rare Earth Elements and Phosphorous) material will utilize mineral beneficiation. Initially, these operations are expected to be performed near 7. *Resource Processing* due to limitations in hardware deployment and power generation and distribution infrastructure.

End State Operations:

For large scale ISRU operations, it is expected that resource preparation will be performed near 4. *Resource Extraction* sites to minimize the energy of mass transfer of material for 7. *Resource Processing*. This will require more extensive power distribution to extraction sites. Non-utilized (tailing waste) material will be transferred to designated storage area for subsequent use. Resource blending may be required at this location or at the processing site if 7. *Resource Processing* requires a specific range of material sizes/minerals. Blending at construction sites may also be preferred for construction operations. Because lunar regolith is extremely abrasive, it is expected that Resource Preparation operations will require significant maintenance and repair. The real-time measurement and tracking of all the material streams and locations will require extensive instrumentation and communication capabilities. Due to the significant amount of material manipulation performed, extensive environmental monitoring is also required.

ii. Initial and Continuous Monitoring of Resources

Starting with resource information measured and tracked in #4 *Resource Extraction*, the material flow streams through all stages of Resource Preparation needs to be measured and tracked in near real-time. Figure 10. Depicts all the steps associated with Resource Preparation and the need to track the location and content of each product and waste stream for subsequent usage.

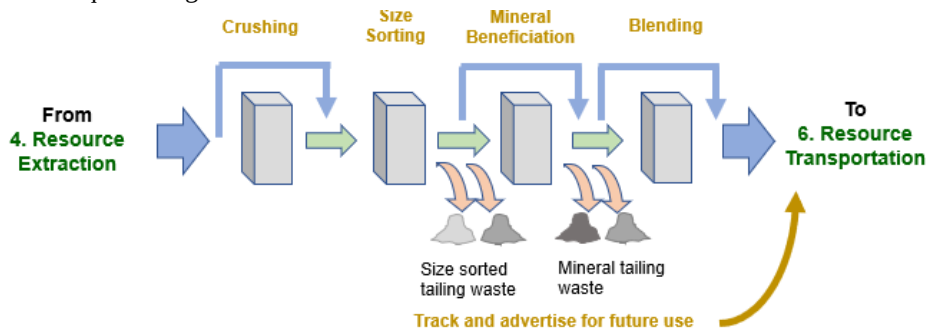


Figure 10. Resource Preparation Process and Material Flow.

6. Resource & Waste Transportation

i. Overview of Resource & Waste Transportation Operations and Evolution

The function of the resource transportation will evolve as a function of scale of operation and resource/waste being transferred. Figure 11 depicts the two major resources to be transferred on the lunar surface: regolith-based resources and water/volatiles extracted from lunar regolith.

Initial:

Initial resource transportation operations will be performed by mobile assets. For mineral resources, the resource delivery transportation asset may be the same as that used for extraction/excavation operation. For water and volatiles,

mobile tankers are currently baselined. Since wastes from #7 *Resource Processing* may be in different forms (from granular to melted solid chunks of material), granular excavation platforms will most likely not be applicable for hauling processed waste. Dedicated haul/dump mobile assets will most likely be required. Initial regolith, waste, and water transportation capabilities are discussed in two NASA mission studies; one for carbothermal reduction of regolith and the other for water mining in a permanently shadowed region [Ref 8 & 9]

The distances travelled will be less than a kilometer, most likely in the 10's to low 100's of meters. Initial traverses will be over unprepared surfaces. PNT capabilities for traverses/transportation will most likely be minimal and tied to the delivery destination (ex. payload lander). Preplanned traverse paths will turn to roads. Waypoint navigation should evolve into navigation aids for autonomous operation.

Intermediate

Once lunar ISRU extraction and processing operations and production have become firmly established, it is expected that dedicated mobile assets for loading and hauling will be used, and that leveled paths/dedicated roads will be established to reduce transportation energy and wear/maintenance. This may also evolve into utilizing short distance rail or conveyors for material movement. Larger scale water mining may require a transition from tankers driving in/out of the PSR to a more dedicated conveyor or cable car-like transfer method. Tracking of material movement and content will require ever increasing communication and timing capabilities. Centimeter level positioning capabilities will be needed for loading and unloading of mineral resources being transferred using active and/or passive sensors.

End States

Large scale ISRU operations will most likely evolve to include dedicated rails/conveyors for solid material transportation over large distances from the resource extraction to resource preparation sites, resource preparation to resource processing sites, and resource processing to waste sites, with dedicated assets for loading and unloading. Large scale water and oxygen/fuel products may also utilize pipes for transportation, though thermal management of water pipes may be difficult in lunar PSR conditions.

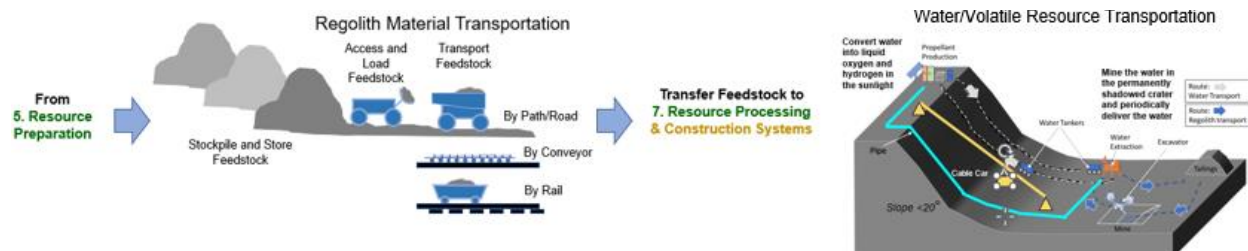


Figure 11. Regolith and Water/Volatile Resource Transportation

7. Resource Processing

i. Overview of Resource Processing

Resource Processing involves the extraction of specific materials or elements of interest through physical, chemical, thermal, and/or electrical processes. Resource processing is performed in stages and should be designed to incorporate modules that allow for easy upgrades or increase in production with parallel operations. Figure 12 depicts top-level functional block diagrams (modules) for lunar polar water/volatile processing and for lunar regolith oxygen and metal processing systems.

The Resource Processing operation begins with resources delivered directly from mine site #4 *Resource Extraction* or after #5 *Resource Preparation* and ends with the generation of one or more products for subsequent delivery and usage. The material for processing is delivered to an inlet hopper that provides a buffer of material to ensure continuous processing if there are issues with #6 *Resource Transportation*. As discussed in #5 *Resource Preparation*, material being fed into the processor may be pre-blended or blended at the Resource processor (i.e. multiple hoppers feeding material) if the Resource processor must operate within a specific band of material/mineral properties.

Lunar Resource Processing systems fall into two broad categories: Resource Processing for Production of Mission Consumables and Resource Processing for the Production of Manufacturing and Construction Feedstocks. Resource Processing for Production of Mission Consumables involves the extraction and processing of resources from prepared and delivered resources into products that can be used for critical mission consumables such as rocket propellants, fuel cell reactants, and life support commodities such as water, oxygen, and nitrogen. Resource Processing for Production of Manufacturing and Construction Feedstocks involves synergistic functions and technologies utilized in the production of mission consumables to produce feedstock that can be subsequently utilized for manufacturing and construction capabilities found in NASA's Autonomous Excavation, Construction, and

Outfitting (AECO) and In Space Manufacturing (ISM) disciplines. For example, some processes utilized for extracting oxygen from regolith also concentrate or separate metals in the regolith as well, which can be further refined and separated as needed. While similar, the functions are still separate since they will be tailored to use specific resources, create specific end products, and operate at different processing rates.

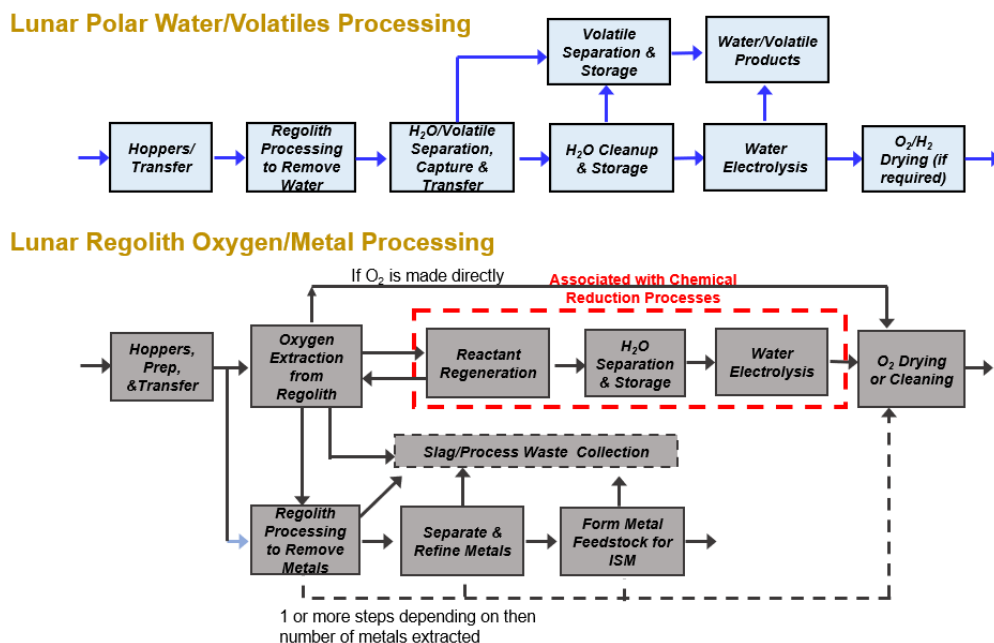


Figure 12. Lunar ISRU System Functional Block (Modular) Diagrams

ii. Initial and Continuous Monitoring of Resources

Resource fed into the processor must be continuously measured to support processing operations and optimization. Outlet product and waste material should be analyzed on a continuous basis to both characterize reactor performance and understand waste streams for possible subsequent use or further processing. All material input, product, and recycle streams need to be monitored in real-time and compared to predictive/digital twin models. Also, all external releases from processing systems need to be monitored for content and mass for environmental monitoring impacts.

iii. Resource Processing Operation and Infrastructure Evolution

Resource Processing is the main driver for all ISRU systems and concepts of operation depicted in Figure 6. As such, as resource processing capabilities and rates grow and evolve, so to will the infrastructure required to support these operations.

Initial:

Initial Resource Processing systems will be limited in scale and number of products produced; most likely one major product per processing system/unit. Processors will most likely be relatively close to the mine site to minimize transportation and infrastructure needed. The systems will be pre-integrated before delivery from Earth, with no or minimum assembly required. Processors may also remain on the delivery lander to minimize offloading needs.

For support infrastructure, Power Generation, Storage & Delivery (#10) will most likely be dedicated to the ISRU regolith processing system. For initial small-scale water/volatile mining in PSRs, a long power cable (<5 km) from a predominantly sunlit region to the operations in the PSR will most likely be utilized, Communications (#11) will be primarily Direct-to-Earth and direct line-of-site for all stationary and mobile assets, with possible relay satellites for part time communication for more remote locations. Autonomy and software (#1) will include on-board monitoring, but critical decisions will be made on Earth.

Intermediate:

As ISRU systems mature and grow/evolve, the distance from the resource processing units to the extraction and/or preprocessing site may be primarily based on power generation/storage location and availability, as well as access to multiple resource acquisition sites. ISRU processing systems should be modular with standardized interfaces between the modules. ISRU modular systems will need to be offloaded from delivery landers and robotically assembled. These systems will be based around a primary product stream with secondary streams for other customers/processing units to minimize waste and increase productivity.

Support infrastructure capabilities will grow and evolve with ISRU Processing evolution. Power Generation, Storage & Delivery (#11) for regolith processing will include a local micro-grid that can support multiple processing operations simultaneously with survive-the-night capability as a minimum and continuous processing for critical processing operations. The micro-grid will include both solar power and nuclear power generation capabilities. Larger scale water mining operations in PSRs may include power beaming and nuclear power beyond the initial cable power transmission into the PSR. The communication architecture will allow for around the clock communication with Earth, as well as surface relays and relay satellites for asset-to-asset communication on the lunar surface. The communication architecture will also allow for significant data transmission and Edge Computing/local data analysis for real-time process control and optimization. Autonomy and software (#1) will support on-board monitoring and control with supervised oversight, but time-critical decisions made by the asset itself.

End State

The end state for Resource Processing is a continued evolution and grow of the *Intermediate* capabilities which could include a combination of integrated excavation/processing and main processing sites associated with multiple mine extraction and Pre-Processing site feeds. Coordinated operations should be based on the distribution of resource of interest, the demand for resources and products, and the infrastructure capabilities. Resource processing systems and/or coordinated processing systems should include multi-product streams with minimal waste, with multiple processing units/customers tied together in a local ecosystem.

8. ISRU Resource and Processing Waste Management

Waste management is essential for establishing a lunar Circular Economy and performing sustainable and responsible lunar surface operations. Most of the important aspects of waste management has already been discussed in #5. *Resource Preparation*, #6. *Resource and Waste Transportation*, and #7. *Resource Processing*. Figure 13 depicts the waste sources/streams from #5 *Preparation* and #7 *Processing*. The important factors to reiterate are:

- Track location, content, and form of all streams; dedicated tailing piles for future usage. The alternative to dedicated tailing piles is to use for site remediation on a continuous or incremental basis.
- Recycle reactants/reagents to the maximum extent possible to minimize losses.
- Minimize emissions/releases during processing operations.
- Track the amount and content of reactant and product losses and releases. Also, track the performance of Processing assets and the impact on waste generated.

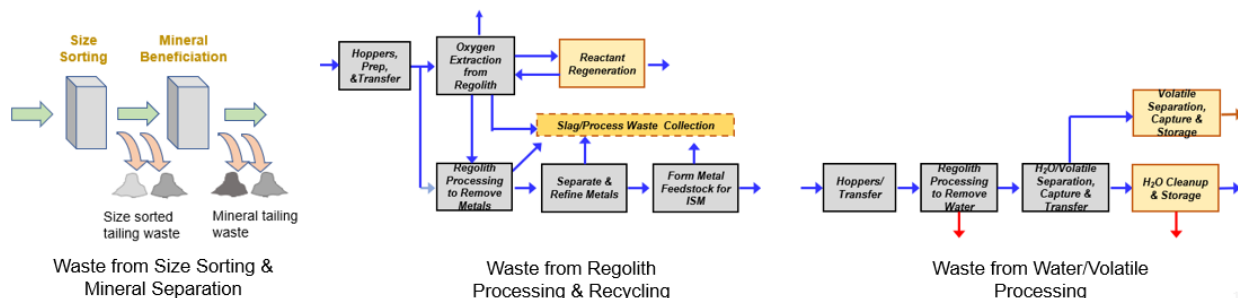


Figure 13. Lunar ISRU Waste Streams

9. ISRU Mission Consumable Product Storage and Transportation

One of the largest benefits of incorporating ISRU into mission architectures is the production and use of mission consumables such as rocket propellants and fuel cell reactants. Table 1 depicts the evolution of these mission consumables starting at 10's to low 1000's kilograms of product for demonstrations and pilot scale operations, to an initial production capacity of 10 to 50 metric tons, with end state production values of 100's to 1000's of metric tons per year. Mass, power, and volume efficient liquefaction and storage of oxygen, hydrogen, and methane are critical for large scale ISRU mission consumable production to be successful and economic.

i. Operation and Infrastructure Evolution

Initial:

Mission Consumable product storage hardware and operations will occur next to #7 *Resource Processing*. Oxygen and Hydrogen products for propulsion applications will be liquefied and stored as a cryogenic liquid. Smaller quantities of these products will be stored as high-pressure gases. Mission Consumables will be transferred to the customer via mobile tanker. Initial operations should be based on using standard mobile platforms (ex. Lunar Terrain Vehicle or LTV) with tank pallet(s) that can be loaded/unloaded easily. Designs and operations will need to minimize

cryogenic fluid transfer losses through active/passive cooling, preconditioning, and ullage transfer. Tanks used for product storage are delivered from Earth, ISRU system payload delivery lander tanks may be used (if possible) after landing as storage vessels.

End State:

For large-scale mission consumable production, product tank farms will need to be established near Resource Processing and/or Customers (depicted in Figure 14). Besides mobile tankers, pipelines may be established for transfer from Processing to Storage to Customers (lunar regolith is highly insulating). Large-scale mission consumable production (100s to 1000s metric tons/year) will require significant storage capabilities. To meet these storage needs, tank scavenging, inflatable tanks, and in-situ manufactured tanks and pipes will need to be considered. The liquefaction, storage, and transfer of large amounts of mission consumables will require extensive power and thermal management capabilities that should include sunshades constructed at lunar polar locations.

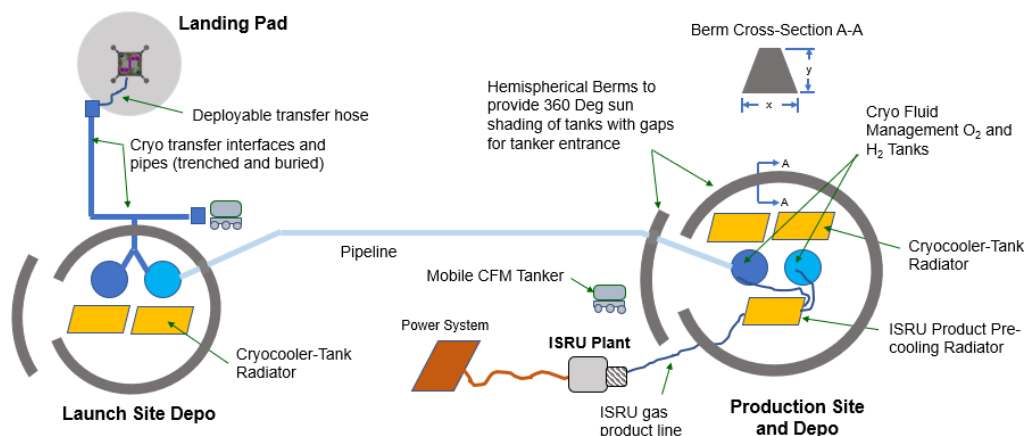


Figure 14. Notional End State for ISRU Mission Consumable Storage and Transfer

10. ISRU Power Architecture

Large scale ISRU requires significant amounts of energy, so the power system architecture utilized will be a significant factor in the economic viability of commercial lunar ISRU operations. While the next largest customer for power will be for supporting human operations, habitats, and life support systems, the power demand for these applications will be significantly less than ISRU until large scale human surface operations occur. Since the authors of this paper are not experts in power system technologies and architectures, the following initial thoughts will be updated in future papers/articles with the appropriate experts involved.

i. Operation and Infrastructure Evolution

Initial:

Initial lunar ISRU systems and operations will utilize solar power generation with electrical storage (batteries or regenerative fuel cells) to provide keep alive power for surface assets and cryogenic liquid boiloff control. These power generation and electrical storage capabilities will be directly tied to mission/lander deployed hardware. Mobile mining assets will utilize battery power recharged with dust-insensitive chargers and centralized power generation. This will eliminate dust issues on solar panels on mobile assets dealing with regolith excavation and transportation operations. For ISRU operations in PSRs for water/volatile extraction, power delivery will be performed via cable (<5 km). All power generation, storage, and transfer assets will be delivered from Earth.

Intermediate:

Power generation will still be provided primarily solar energy, with potentially multiple power generation units and power storage units connected via a micro-grid. This micro-grid will provide electrical energy for multiple surface assets deployed from multiple lander missions. ISRU operations will be primarily performed during sunlight periods. The micro-grid with multiple power generation units distributed in a region may reduce but not eliminate shutdown during eclipse periods if all the power generation units are not eclipsed. It is expected that one or more nuclear fission reactor may be included to provide a continuous base load for some around the clock operations. The NASA Fission Surface Power (FSP) reactor concept is also required to be mobile to allow for relocation to new areas starting up ISRU operations until greater power generation is available. For larger scale lunar water mining, it is expected that power beaming and/or nuclear power in PSRs will also be available to increase production rates and possible power delivery distances. ISRU-derived electrical generation and electrical/thermal storage capabilities will be demonstrated

and utilized to provide increased capability to Earth-delivered systems. Tower assembly/usage for solar arrays is also expected to be utilized to decrease power eclipse periods.

End State:

As depicted in Figure 5, it is expected that regional-scale ISRU will include a large-scale power grid with power generation capabilities during all lunar phases (nuclear and power generation somewhere in sunlight). This large-scale power grid will integrate multiple surface operation regions and customers. Solar arrays produced by ISRU will be available to highly expand power generation capabilities. Extensive power conditioning and conversion capabilities distributed throughout the power grid will also be required for power transmission and on-site operations. Fuel cell reactants and/or ISRU derived electrical storage will be used extensively. Also, thermal energy storage and thermal energy conversion (hot to cold regions) will also be used to increase in situ capabilities beyond Earth supplied capabilities.

ii. Challenges

Energy for ISRU operations at a particular site can come from multiple energy generation and storage devices for stationary-continuous (solar/battery or fission) and mobile-periodic power recharging assets (fuel cells, batteries, power beaming, combination). One challenge will be adapting mining and energy network operations to deal with fluctuating supply and power demand. Control systems may need to adapt mining operations and energy network to cope with fluctuating supply and demand, through a combination of efficiency improvements, storage, and changing operational modes to adapt to (cyclic and event-based) energy constraints, and increased demand for ISRU products.

11. ISRU Communication and Navigation Architecture

As mentioned throughout the paper, large-scale ISRU operations will require significant amounts of data to be transmitted and analyzed to autonomously control and optimize stationary and mobile assets near real-time. Also, these mobile asset operations will require highly accurate navigation, positioning, and timing (PNT) information to function properly and safely. Since the authors of this paper are not experts in communication and PNT technologies and architectures, the following initial thoughts will be updated in future papers/articles with the appropriate experts involved.

i. Remote/Autonomous Operations requires preparation.

Since terrestrial mines typically require prepared roads and ramps in and out of the excavation site, it is expected that lunar ISRU operations will need accurate terrain maps to TBD slope and height accuracy. Site-level terrain/subsurface measurements ('aerial' photography, lidar, or radar scanning) with TBD slope and height accuracy are needed at semi-regular intervals for assessing changes and for position and navigation. Start and end locations need to be established before operations began including electric 'keep out' fence/barrier surrounding operations.

ii. Communications and Position, Navigation, and Timing (PNT) are drivers for remote operations.

The amount and type of data (video and operation data) transmitted from semi-autonomous and autonomous mobile assets are expected to drive communication requirements. Communication and PNT architectures for ISRU will need to consider all the remote asset types and numbers that need to be operated and tracked, which is expected to be significantly more than current Artemis campaign is considering, as ISRU capabilities evolve. Local PNT capabilities are critical for remote operation and meeting cost and performance objectives. It should be noted that both on-board and local/situational awareness cameras should be included for remote controllers/operators and hazard avoidance. All of these activities will require real-time on-board PNT measurements with TBD accuracy.

iii. On-board and Remote Operations are strongly influenced by Communication and Avionics capabilities.

The increased time delay for lunar operations will drive the need for increased autonomy/reduced remote operator 'real-time' control. As was mentioned previously, to support real-time adaptive operations and optimization through data analyses and predictive models/digital twins will require large amounts of information/data ('Big Data') to be transmitted and continuously analyzed. This is required for refining the knowledge of the resource of interest and all the product and waste streams generated throughout the ISRU operations depicted in Figure 6. Lunar ISRU Systems and Operations. On-board Machine Learning (ML) and processing/data manipulation capabilities (drives on-board avionics and software) needs to be balanced with data transmission requirements and capabilities.

V. Surface Construction

Due to time limitations, the authors were not able to delve as deeply into large-scale lunar surface civil engineering and construction activities as initially desired for this paper. However, it is important to stress at this time, that many of the design attributes, tasks, operations, and infrastructure needed for surface construction are similar to those discussed in #4. *Resource Extraction*, #5. *Resource Preparation*, #6. *Resource Transportation*, and even #7. *Resource Processing*. Figure 15 depicts notional surface civil engineering and horizontal construction activities that align with ISRU operations discussed in previous sections of this paper. Important factors to highlight for all remotely operated/autonomous construction operations are the need for:

- Highly accuracy information on terrain topography on continuous bases
- Highly accuracy position, navigation, and timing for mobile units and regolith/construction operations
- Advanced space computers, avionics, and software for remote/autonomous operations
- High bandwidth communications on-site and to/from Earth
- Dust insensitive power storage; fast recharging
- Long-life and maintainable mobile units and implements.

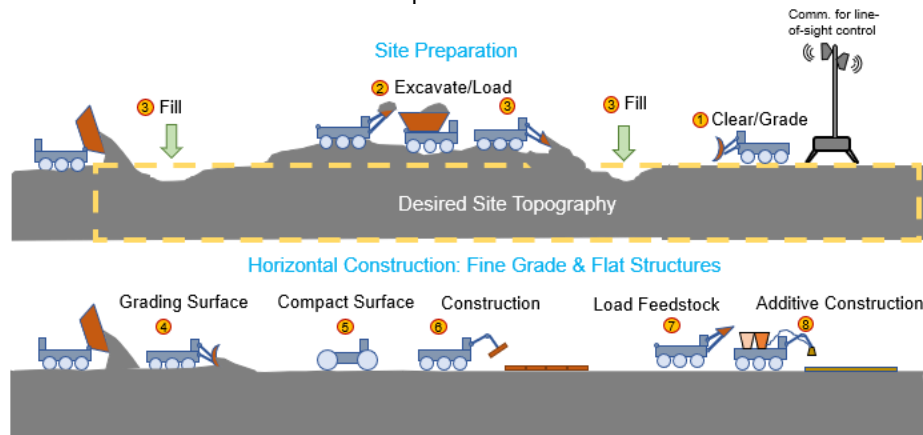


Figure 15. Notional Surface Civil Engineering and Horizontal Construction Operation

VI. Next Steps

As was mentioned at the end of Section II, the main objectives of this paper are to provide initial thoughts on the near and long-term ISRU and infrastructure needs, capabilities, and concepts of operation to:

1. Align and focus discipline development inside and outside of NASA.
2. Align development and cooperation between terrestrial resource exploration, extraction, and processing and space ISRU.

In the coming months, the authors of the paper will expand upon the concepts of operation and infrastructure needed for large-scale surface construction, and work with NASA discipline experts as well as experts in terrestrial and space mining to examine and refine the 11 areas depicted in Figure 6. *Lunar ISRU System and Concept of Operations*, as well as dive deeper into the questions and interactions highlighted in Figure 4. *Interconnectivity Associated with Implementing Commonalities for the Large Scale ISRU*. All of this work will be published and presented at a future conference; possibly AIAA ASCEND 2025.

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