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NASA Envisioned Future Priorities for In Situ Resource Utilization

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Abstract

A major objective of the United States National Aeronautics and Space Administration's Artemis program is to create a sustainable human lunar exploration program through the establishment of lunar infrastructure and commercial space operations. A key aspect in achieving this objective is characterizing the resources that exist on the Moon and Mars, and learning how to utilize them to create products for crew, power, transportation, and infrastructure growth. Commonly known as In Situ Resource Utilization (ISRU), the ability to make products from local materials instead of bringing everything from Earth has the potential to significantly reduce mission costs, mass, risks, and dependency on Earth. To achieve this vision, NASA's Space Technology Mission Directorate (STMD) established a strategic framework, called the Strategic Technology Architecture Roundtable (STAR) process, to coordinate development of critical capabilities around four major Thrusts (Go, Land, Live, and Explore). To guide and drive the development of critical mission capabilities, the STAR process involves establishing a 'grand vision' known as an Envisioned Future for each of these capabilities. For ISRU, the Envisioned Future is "Scalable ISRU production/utilization capabilities including sustainable commodities on the lunar and Mars Surface". This paper will discuss the STAR process, and the strategic plan and near-term priorities for achieving the ISRU Envisioned Future.

Keywords: In Situ Resources Utilization, Lunar Resources, NASA, ISRU Strategic Plan

Acronyms/Abbreviations

AECO – Autonomous Excavation, Construction and Outfitting
CH_3OH - Molecular formula for methanol
CLPS - Commercial Lunar Payload Services
CO - Molecular formula for carbon monoxide
CO_2 - Molecular formula for carbon dioxide
ESDMD – Exploration Systems Development Mission Directorate
EVA - Extra-Vehicular Activity
H_2 - Molecular formula for hydrogen
H_2O - Molecular formula for water
H_2S - Molecular formula for hydrogen sulfide
ISECG – Int'l Space Exploration Coordination Group
ISM – In Space Manufacturing
ISRU - In Situ Resource Utilization
LCROSS - Lunar Crater Observation and Sensing Satellite
LSIC - Lunar Surface Innovation Consortium
NASA - National Aeronautics and Space Administration
NH_3 - Molecular formula for ammonia
O_2 - Molecular formula for oxygen
PSR - Permanently Shadowed Region
SOA – State of the Art
SMD - Science Mission Directorate
STAR - Strategic Technology Architecture Roundtable
STMD - Space Technology Mission Directorate
US – United States of America

1. Introduction

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 [1]. A major objective of this program is to characterize the resources that exist on the Moon and Mars, and to 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 delivered from Earth, thereby reducing mission costs, risks, and dependency on Earth.

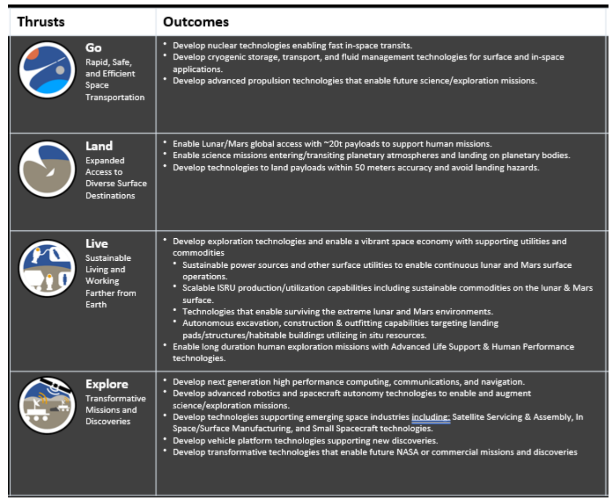
2. ISRU is Enabling

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 space, lunar lander, and surface transportation systems required for human exploration; expanding and enhancing HOW humans get to, explore, and return from the lunar surface. 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. Because of this, ISRU supports and enables commercial involvement, beyond NASA and governmental agency plans by both lowering the cost of sustained transportation to/from/on the Moon as well as supporting the customers and 'markets' required for needing these transportation systems.

There are many benefits for making products from in situ resources at the site of exploration versus bringing everything from Earth. The most significant benefit ISRU has on missions and architectures is the ability to reduce launch mass thereby reducing either, or both, the size and number of the launch vehicles needed or allowing extra science and exploration hardware to be flown on the same launch vehicle. Since propellants make up a significant mass fraction of space transportation and lander/ascent vehicles, making propellants or even oxygen alone can provide significant mission savings, and lead to more sustainable and reusable space transportation systems. Another benefit for incorporating ISRU into mission architectures is the ability to grow and expand infrastructure and exploration capabilities beyond what has been or can be delivered from Earth, such as expanding power generation, transmission, and storage, radiation shielding, consumable storage vessels, and unpressurized/pressurized structure construction. Doing these things leads to a third benefit, which is the ability to rely less on Earth provided hardware and commodities, especially in cases of emergency. To achieve the greatest benefits of ISRU incorporation into mission architectures, other systems need to be designed around the availability and use of ISRU-derived products. Therefore, **ISRU is a disruptive capability** and requires an architecture-level integrated system design approach from the start. To minimize infrastructure mass and 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.

3. Strategic Framework

To achieve this vision, NASA's Space Technology Mission Directorate (STMD) ensures the coordinated development of ISRU and other critical space and surface infrastructure elements such as propulsion, power, manufacturing, construction, and robotics through the Strategic Technology Architecture Roundtable (STAR) process [2]. Through STAR, an integrated framework and process has been created allowing for capabilities and technologies to be linked and assessed, gaps to be identified, specifications and metrics to be established, and a means to prioritize and implement technology development and missions. A critical part of the STAR process has been the establishment of the Strategic Framework that organizes all work under four major Thrusts (Go, Land, Live, and Explore), and identifies the driving Outcomes for each of these Thrusts [3]. From the Thrusts and Outcomes, all work can be categorized and linked between Capability Areas, and Technology Gaps can be identified and addressed (Figure 1.)



Thrusts	Outcomes
Go Rapid, Safe, and Efficient Space Transportation	• Develop nuclear technologies enabling fast in-space transits. • Develop cryogenic storage, transport, and fluid management technologies for surface and in-space applications. • Develop advanced propulsion technologies that enable future science/exploration missions.
Land Expanded Access to Diverse Surface Destinations	• Enable Lunar/Mars global access with ~20t payloads to support human missions. • Enable science missions entering/transiting planetary atmospheres and landing on planetary bodies. • Develop technologies to land payloads within 50 meters accuracy and avoid landing hazards.

Live Sustainable Living and Working Farther from Earth	• Develop exploration technologies and enable a vibrant space economy with supporting utilities and commodities
	  • Sustainable power sources and other surface utilities to enable continuous lunar and Mars surface operations.
	  • Scalable ISRU production/utilization capabilities including sustainable commodities on the lunar & Mars surface.
	  • Technologies that enable surviving the extreme lunar and Mars environments.
	  • Autonomous excavation, construction & outfitting capabilities targeting landing pads/structures/habitable buildings utilizing in situ resources.
	• Enable long duration human exploration missions with Advanced Life Support & Human Performance technologies.

Explore Transformative Missions and Discoveries	• Develop next generation high performance computing, communications, and navigation. • Develop advanced robotics and spacecraft autonomy technologies to enable and augment science/exploration missions. • Develop technologies supporting emerging space industries including: Satellite Servicing & Assembly, In Space/Surface Manufacturing, and Small Spacecraft technologies. • Develop vehicle platform technologies supporting new discoveries. • Develop transformative technologies that enable future NASA or commercial missions and discoveries

Figure 1. Strategic Framework and STAR Framework

4. ISRU Envisioned Future

To drive the development of technologies and capabilities, the STAR process involves establishing a 'grand vision' of where each Outcome and Capability is aiming to be considered complete. For ISRU, the Envisioned Future is "Scalable ISRU production/ utilization capabilities including sustainable commodities on the lunar and Mars Surface". This involves starting with 10's of metric tons of products per year and evolves into 100's to 1000's of metric tons per year of products such as water, oxygen, and propellant commodities, construction and manufacturing feedstock, and commodities for habitat and food production and operations (Figure 5). The term 'commodities' is us used to denote items and consumables that can be eventually sold.

5. Scope of ISRU Capability

5.1 What is ISRU?

ISRU involves any hardware or operation that harnesses and utilizes 'in-situ' resources (natural, waste, and discarded hardware) to create commodities for robotic and human exploration and space commercialization. The overarching scope of ISRU is the 'Prospect to Product' philosophy that starts with Destination Reconnaissance & Resource Assessment, followed by Resource Acquisition, Isolation, and Preparation, leading into Resource Processing, which is further subdivided into mission consumables and feedstocks for construction and manufacturing (Figure 2) .

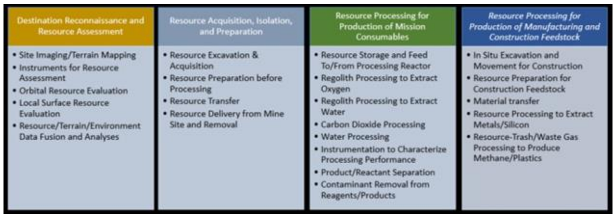


Figure 2. ISRU Functional Breakdown Structure

Destination Reconnaissance and Resource Assessment involves the characterization and mapping of physical, mineral, chemical, and water/volatile resources, terrain, geology, and environmental conditions. Resource assessment is performed from orbit and on the surface, and surface missions will most likely progress from initial short duration missions with limited instrument/assessment capabilities to longer-duration missions with suites of instruments to thoroughly assess the resources available for site selection and mine operation planning. Destination Reconnaissance and Resource Assessment overlaps with and has significant commonalities with other mission activities such as science in general, mission site selection, and landing site and outpost planning; and therefore, needs to be coordinated with the Science Mission Directorate (SMD) and Exploration Systems Development Mission Directorate (ESDMD) to ensure all objectives are met in a timely manner. Just as with terrestrial mining, Destination Reconnaissance and Resource Assessment uses different techniques and instruments in a continuous process, from initial site evaluation to detailed resource exploration, to locate resource rich areas, assess the economic and technical feasibility of extracting the resources into products, and planning the mining infrastructure layout and operations.

Resource Acquisition, Isolation, and Preparation involves functions associated with acquiring, separating, and preparing resources from their natural state or location. This functional area includes activities such as i) excavation and drilling for acquisition; ii) adsorption, membranes, cryogenic distillation, and mineral beneficiation for isolation of gases and volatiles; and iii) crushing, grinding, and size sorting. For trash and discarded equipment, this also includes disassembly, shredding, and sorting. Besides acquiring, separating, and preparing resources, this functional area also involves delivering and transferring extracted and prepared resources to subsequent resource processing units.

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 Autonomous Excavation, Construction, and Outfitting (AECO) and In Space Manufacturing (ISM). 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.

5.2 Dual Lunar Resource/Product Paths

The ISRU Envisioned Future considers what resources are available, and attempts to address what, how, and when these resources will be evaluated and harnessed. The plan also considers which products/ commodities can be obtained for early use, and which ones require more time and/or users of refined products. ISRU starts with the easiest resources to mine, that require the minimum of infrastructure to operate, and can provide immediate usage for local assets. The initial focus is on two primary resources found at the lunar South Pole: 1) highland-type regolith, and 2) water and other volatiles that may exist in the permanently shadowed regions (PSRs) at the Moon's poles. The latter resource has been detected from orbit and particularly in the plume from the impact of the Lunar Crater Observation and Sensing Satellite (LCROSS)[4,5]. Initial products from highland regolith could include bulk and refined regolith (sieved for desired size fractions and/or beneficiated to increase certain minerals), oxygen, and raw aluminum and ferro-silicate metals that may be obtained after extracting oxygen. Besides water, there may be other hydrogen-bearing (H_2, H_2S, NH_3) and carbon-bearing (CO, CO_2, CH_3OH) volatiles in PSRs that are useful in making fuels, plastics, and plant/food nutrients.

Because of the differences in regolith-based and polar water/volatile-based resources, their extraction and processing technologies, and their products, NASA is pursuing a parallel, dual-path Oxygen/Metal from Regolith and Lunar Polar Water/Volatile development and flight demonstration strategy. Both paths have benefits and risks for developing and incorporating ISRU systems into human lunar and commercial mission architectures. Water is an amazing resource with products that can significantly influence mission element mass, efficiency, complexity, and reusability ('game changing'). However, there is significant uncertainty in the location, form, and distribution of these resources, and operations in PSRs will be extremely challenging. Oxygen and metals on their own can provide significant mission element benefits and processing can be performed in relatively benign and sunlit locations. However, a fuel from Earth is still needed, and significant work is required for operating under lunar conditions for months/years with abrasive lunar regolith.

6. It Takes an Architecture

ISRU does not exist on its own. By definition, it requires customers/users to use the products/ commodities produced by ISRU systems. Also, for an ISRU capability to exist, it must obtain products and services from other systems and local infrastructure. An important aspect of the STAR process and the ISRU Envisioned Futures Priorities strategy is to identify and link all of these systems and capabilities to achieve the desired end state (Figure 3).

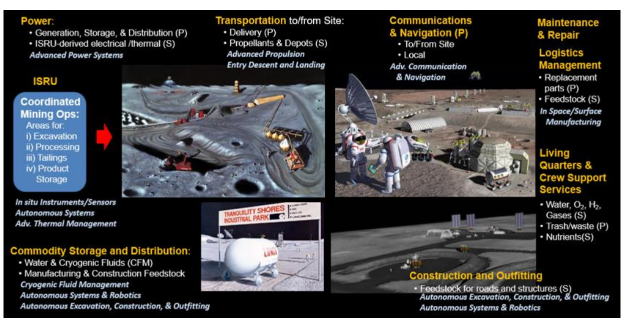


Figure 3. ISRU as Part of a Larger Architecture
(P) = Provided to ISRU; (S) = Supplied by ISRU

7. ISRU Capability Drivers

The guiding principles for NASA's Space Technology Development for Artemis are to develop critical technologies and capabilities that enable (i) a sustainable Lunar surface presence, (ii) the future goal of sending humans to Mars, and (iii) promoting critical technologies to enable future science and commercial missions. It is a major goal of the Artemis campaign to establish basic assets and infrastructure (or 'base camp') for crew and robotic operations at the lunar South Pole by approximately the end of the decade.

As well as identifying important capability linkages, Figure 3 also highlights the important infrastructure elements required to evolve the initial base camp for short duration lunar robotic and human surfaces missions into sustainable human and commercial surface operations. Besides ISRU, these elements include large scale power generation and distribution (from multiple sites), landing pad, road/pathway, and unpressurized/pressurized structure construction, payload and hardware offloading and deployment, gas, liquid, and cryogenic fluid and propellant depots, human and robotic maintenance and repair, and lander/surface vehicle servicing and fueling. It is the goal of NASA that these services by commercialized.

The ISRU Envisioned Futures Priorities and lunar dual resource/product path strategy is aligned with the Artemis campaign to develop and demonstrate ISRU capabilities in this timeframe that could lead to sustained human and robotic surface operations, infrastructure growth, and commercial operations in the next decade (Figure 4).

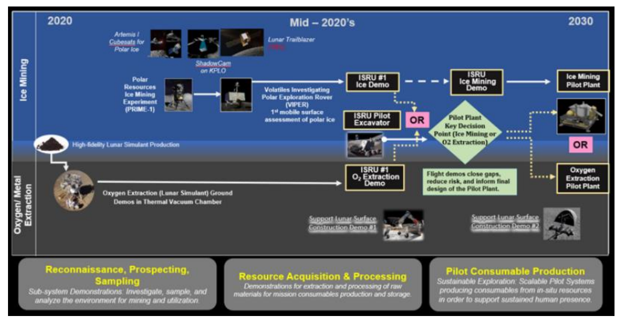


Figure 4. ISRU Dual Path to Full Implementation and Commercialization

7. ISRU Development and Flight Strategy

The use of space resources to create mission critical products to support human spaceflight has been discussed and proposed in numerous NASA strategic plans and mission architectures for decades. While significant advances were made during NASA's Constellation program on both lunar ISRU technology and system level demonstrations [6,7], the effort was primarily focused on mare regolith processing and was cancelled before advancement to testing under lunar surface environmental conditions was achieved. 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 demonstrated its performance in the actual flight environment. To achieve the ISRU Envisioned Future of using ISRU products for mission critical applications and infrastructure growth, NASA has defined a conservative ground and flight development strategy for ISRU. This strategy incorporates a five-step approach:

I. Know customer needs (type, quantity, and need dates) and develop suppliers,
II. Extensive ground testing at mission relevant scale under mission environmental simulation and analog operation conditions,

III. Reduce risk of ISRU through direct measurement of resources and demonstration of critical technologies in flight on the lunar surface,
IV. 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), and
V. Utilize ISRU systems and products in a mission critical role (replace Earth supplied products).

Step I is critical for ISRU development and deployment since knowing what products are needed, when they are needed, and how much is needed, is essential for both defining the technologies and capabilities needed, as well as defining the timeline for development and deployment of these capabilities. This Step continues throughout the development of ISRU capabilities, but starts with discussions with Artemis mission elements, the Moon/Mars surface architecture teams, and with industry and international partners as to how ISRU products can influence designs, plans, missions, and overall architectures. In particular, discussions and coordination are required with product users inside and outside of NASA, such as life support systems and plant/food production, transportation systems, and manufacturing, and construction systems. A successful example of this approach was the Supply and Demand Workshop hosted by the Lunar Surface Innovation Consortium (LSIC) where 6 potential propellant suppliers and 6 transportation companies presented information leading to better understanding of the possible ISRU-derived propellant 'market' [8].

Besides initial product delivery, coordination is also needed for any wastes produced throughout exploration element operations, since these may be 'resources' for another processes. It is vitally important that throughout this Step, terrestrial/space industry, academia, international partners, and potential commercial operators are included in the discussions to ensure development and investments are properly aligned.

In Step II, NASA is developing and advancing technologies, subsystems, and systems that will acquire and process lunar simulants into mission products at mission relevant scales. The development will involve testing under ambient laboratory and analog field, lunar environmental, and/or lunar gravity conditions. Concepts and hardware applicable for use in Mars ISRU systems is also a consideration in technology selection in this Step. The development efforts in this Step involves a combination of competitive in-house NASA development, external competitive solicitations, and public-private partnerships to lay the foundation for long-term lunar human exploration and economic development.

In Step III, NASA and/or industry will utilize orbital and Commercial Lunar Payload Services (CLPS) lander missions to better understand the resources on the Moon, especially for lunar polar water and volatile resources, that are needed to support technology development and eventual site selection for long-term human surface operations. At the same time, early CLPS missions will be aimed at obtaining critical data on lunar regolith and environmental properties that were not obtained from the previous Apollo and Lunar Surveyor missions. Step III will also perform industry developed proof-of-concept and risk reduction demonstrations of critical ISRU technologies and concepts that are most dependent on interacting with lunar regolith and/or need to interact with large amounts of lunar regolith under lunar surface conditions to validate longevity and robustness.

In Step IV, NASA and/or industry will integrate technologies, many of which were demonstrated in Step III, into an end-to-end system that will produce products at a mission relevant scale and mission duration with respect to future robotic/human lunar missions and commercial operations. Based on the Oxygen/Metal from Regolith and Lunar Polar Water/Volatile dual-path strategy, NASA is studying and modelling full-scale system and mission concepts for both resource processing approaches [9]. Using the LSIC Supply and Demand Workshop results as well as using the Rocket Equation and mission assumptions, it can be estimated that ISRU systems will need to produce anywhere from 5 to 10 metric tons of oxygen for ascent from the lunar surface back to the Gateway orbit, all the way to 40 to 50 metric tons of oxygen/hydrogen for a single-stage ascent/descent reusable lander per mission (Figure 5). It should be noted that possible in-situ produced propellant needs for the SpaceX Starship are currently unknown but are expected to be significantly greater than these estimates. From these studies and models, NASA is in the process of examining what mission relevant scales are for different technical approaches as well as identifying mission enhancing applications that could utilize the ISRU-derived oxygen, water, and/or hydrogen products. No firm plans have been made, but concepts under consideration include utilizing oxygen for surface Extra-Vehicular Activity (EVA) and pressurized rover use, using water for crew radiation shielding and drinking, and using oxygen and/or oxygen/fuel for a robotic hopper mission.

Based on results from Step IV, in Step V, it is NASA's goal that industry will deploy ISRU production systems and all the infrastructure required to implement and utilize ISRU products in mission critical roles. This could include fueling crew ascent vehicles and surface hoppers and/or building landing pads and structures for crew and infrastructure protection. Satisfactory demonstration of the ISRU capability operations, life, and product quality/quantity, in Steps III and IV will lead to Step V, utilization of ISRU in a mission critical role/application.

8. State of the Art and Gaps

To achieve the ISRU Envisioned Future, an extensive effort was performed to understand the State of the Art (SOA) for ISRU going back decades, and to assess the SOA against the near and long-term goals and objectives of the ISRU Strategic Outcome objectives. Individual SOA analyses were made for Resource Assessment, Oxygen and Oxygen/Metal Extraction from Regolith, Polar Water Mining, Construction/ Manufacturing Feedstock, and Cross Cutting/System Level Resources. Once completed, the SOA was compared to ISRU goals and metrics for initial ISRU capabilities for mission usage to understand and define the gaps that remain that need to be addressed and closed. Several of the gaps identified were assigned to other surface elements and disciplines to ensure ISRU capability development was properly coordinated with the other linked areas identified in Figure 3.

While the released ISRU Envisioned Futures Priorities only includes a top-level definition of both the SOA and Gaps, further information on these for ISRU can be found in the ISRU Gap Assessment Study performed for the International Space Exploration Coordination Group (ISECG) [10]. To provide further guidance to industry and academia, a top-level assessment was performed that rates six critical ISRU capability and technology areas into one of three assessment levels: Significant Funding, Partially Covered/More Required, and Limited/No Funded Activities. The six critical ISRU capability and technology areas of emphasis in the ISRU Envisioned Future plan were: Lunar Oxygen Extraction, Lunar Polar Resource Assessment and Water Mining, Manufacturing and Construction Feedstocks, Integrated ISRU Systems, Flight Demonstrations, and Engagement with Industry and Academia for Space Commercialization. While all areas require continued emphasis on funding and development, Lunar Polar Resource Assessment and Water Mining, and Manufacturing and Construction Feedstocks require enhanced emphasis in the near-term. Note, results of this assessment can be found in the presentation for this paper.

9. Envisioned Future Priorities: Next Steps for ISRU

A significant amount of work covering a broad range of technology areas has been performed over the last several years on lunar ISRU [11]. However, to reach the Envisioned Future for ISRU, a lot more work is required at the technology level that will lead to integrated system testing in analog field and lunar environmental simulation facilities, as well as technology flight demonstrations in the near future.

To guide investments in NASA, industry, and academia, 5 specific areas of near-term high priority focus areas were identified. These are:

1. Complete development of the Water and Oxygen Mining Paths and close technology gaps, with emphasis on oxygen extraction from Highland regolith and polar water extraction techniques.
2. Expand development of metal extraction, refinement, and feedstock production for manufacturing and construction applications, with emphasis on aluminium and easy to obtain/make construction feedstocks leading to more refined metals and other regolith-derived products. Also, evaluate biologically inspired/derived technologies in bio-mining, bio-plastic, and other feedstock commodity production.
3. Ensure the resource assessment needed for future ISRU commercial operations, especially water and volatiles that may exist in lunar polar PSRs, is coordinated with near and long-term science objectives, Artemis mission and base camp locations of interest, international partners, and industry.
4. Initiate NASA and industry-led system-level analyses, integration, and testing activities for ISRU capabilities. While significant work has been performed at the technology and subsystem level, it is now important to understand how these technology investments can be leveraged and utilized in actual systems and applications.
5. Initiate industry led/NASA supported lunar ISRU technology flight demonstrations leading to initial ‘Pilot Plant’ end-to-end production capability demonstrations.

Acknowledgements

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10 to 30 mT Range for Initial Full-Scale Production

	Demo Scale	Pilot Plant	Crewed Ascent Vehicle[1]	Full Descent Stage[1]	Lockheed Martin[6]		Dynetics[6] Single Stage/ Drop Tanks	Single Stage to NRHO[2]	Human Mars Transportation[3]	Commercial Cis-Lunar Transportation[4]
			3 Stage Arch to NRHO		2 Stage	Single Stage				
Timeframe	days to months	6 mo - 1 year	1 mission/yr	1 mission/yr	per mission	per mission	per mission	1 mission/yr	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	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	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_2O in PSR	100's W	~2 KW		~25 KW				14 to 23 KW		150 to 800 KW
Power for H_2O 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

[1] Estimates from rocket equation and mission assumptions

[2] Estimates from J. Elliott, "ISRU in Support of an Architecture for a Self-Sustained Lunar Base"

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[4] Estimate from "Commercial Lunar Propellant Architecture" study

[5] Electrical power generation and product storage mass not included

[6] APL Lunar Surface Innovation Consortium Suppy-Demand Workshop, 9/17/2020

- Table uses best available studies and commercial considerations to guide development requirements/FOMs
- Table provides rough guide to developers and other surface elements/Strategic Technology Plans for interfacing with ISRU
- Table created before selection of SpaceX Starship for HLS. More rapid evolution to larger scale production may be warranted

Figure 5. In Situ Propellant & Consumable Production Phases of Evolution and Use