NASA ISRU – Closer to Reality. G. B. Sanders[1] and Dr J. E. Kleinhenz[2], [1]NASA Johnson Space Center, Houston, TX, 77058, USA, [2]NASA Glenn Research Center, Cleveland, OH 44135, USA

Introduction: 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. While much of NASA's plans for the Artemis program currently focus on the Human Lunar Return (HLR) and the initial Foundational Exploration (FE) segments that will allow astronauts to explore the lunar surface for limited durations (days/weeks) each year, 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 lunar exploration program, known as the Sustained Lunar Evolution (SLE) segment, is to better understand and characterize the resources on the Moon and learn how to extract and use these resources.

Commonly known as In Situ Resource Utilization (ISRU), the search for, acquisition, and processing of resources on the Moon and Mars has the potential to greatly reduce the cost and risk of human exploration, Incorporation and use of ISRU can achieve this by reducing what needs to be delivered from Earth, reducing the dependency of supplies and logistics delivered from Earth, lowering costs through commercial operations, and expanding infrastructure for safer and more capable exploration and surface operations. Large scale ISRU will provide propellants for surface hopping, lunar ascent/descent, and cis-lunar transportation systems, reactants for fuel cells, consumables for crew, and feedstocks for manufacturing, production of energy generation, storage, and transfer systems, and surface construction of landing/ascent pads, roads, shelters, and habitats.

In 2023, four significant activities/events occurred with respect to human lunar exploration, surface infrastructure, and ISRU. One was the release of the Artemis Architecture Definition Document ESDMD-001 Revision 1 [Ref 1] that included ISRU as a sub-architecture in the FE segment. The second was technology advancement through on-going and new projects through several NASA internal projects, solicitations, and challenges. The third was the release of a Request for Information (RFI) for the Lunar Infrastructure Foundational Technology-1 (LIFT-1) mission with the primary objective of extracting oxygen from lunar regolith. The fourth was the Defense Advanced Research Projects Agency (DARPA) release and selection of participants in the LunA-10 lunar architecture study aimed at achieving a thriving lunar economy in 10 years (2035). This paper will provide an overview and status of on-going technology and system development activities and the LIFT-1 mission, an update on the insertion of ISRU into the Artemis Moon to Mars campaign, and progress on establishing a sustainable cis-lunar economy with ISRU.

ISRU Strategy, Plans, and Priorities Are Established: To guide development of ISRU technologies and systems on the ground and demonstration of these capabilities on the Moon and Mars as defined in the Artemis Programs Moon to Mars Objectives, NASA created and released the ISRU Envisioned Future Priorities (EFP) strategic plan in 2021 and updated it in 2022 [Ref 2] after significant interaction with industry, academia, and international agencies. While lunar ISRU technology development was initiated before the release of the ISRU EFPs, these publicly released strategic plans have been used to guide and prioritize technology development, assess the progress in achieving the vision, and identify the gaps that still need to be addressed.

ISRU Insertion into Artemis Campaign: There are two critical documents that provide guidance and direction for NASA efforts and activities associated with the Artemis Campaign. The first is NASA's Moon to Mars Strategy and Objectives document [Ref 3] which establishes Why we explore space and the long-term goals and objectives the US exploration program needs to encompass. The second document is the Artemis Moon to Mars Architecture Definition Document (ADD) [Ref 1] which as stated in the document "establishes the process, framework, and decomposition of objectives to empower the executing systems', programs', and projects' success in achieving human exploration of the cosmos." This second document was initially released in 2022 with planned updates each year after a significant number of trade studies and architecture evaluation tasks are completed, reviewed, and agreed upon.

The ADD revision 1 released in 2023 identified ISRU as a sub-architecture and began to define ISRU objectives and activities that would occur in the Foundational Exploration segment of the Artemis Campaign. ISRU in this segment would involve capabilities dealing with estimating resource reserves and harvesting these resources to generate products on other planetary bodies with the goal of reducing the reliance on Earth-based resources and make space missions more sustainable and cost-effective.

To decompose the NASA Moon to Mars objectives in Ref. 3 into eventual hardware elements and operations, the ADD has established processes and frameworks, such as Figure 1, that provide guidance on how to start with the objectives to define Characteristics & Needs, which are further decomposed into critical Functions and Use Cases. These Functions and Use Cases can then lead to defining Reference Missions and Elements.

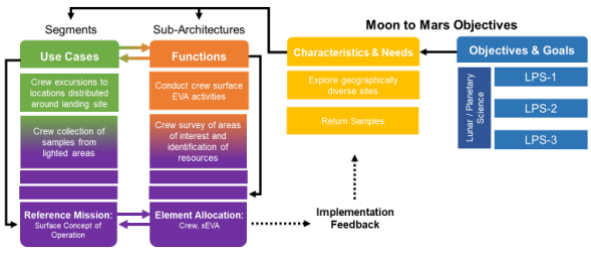

Figure 1. Notional Example of Mapping Objectives to Use Cases [ref 2].

For the current NASA Strategic Analysis Cycle (SAC24), which will lead to changes to the next ADD released, the NASA ISRU team is involved in a significant number of activities to better define how ISRU will be incorporated into the Artemis Lunar FE Segment and initial human Mars mission campaign. Besides further decomposing and defining the Capabilities & Needs, Functions, and Use Cases, there

are a significant number of Lunar and Mars studies and tasks with direct (4) or indirect ISRU (11) involvement, as well as an effort to better understand what is needed to assess lunar resources for ISRU. Results of these efforts are expected to be documented in the next ADD revision.

NASA ISRU Technology Advancement: Since NASA ISRU technology development pivoted from Mars to the Moon in 2017 with the ending of the Evolvable Mars Campaign, a significant amount of research and development has been performed on lunar ISRU resource assessment, acquisition, preparation, and processing technologies. With the initiation the Strategic Technology Architecture Roundtable (STAR) in 2020, the NASA Space Technology Mission Directorate (STMD) Strategic Framework in 2021, and the development and release of the ISRU Envisioned Future Priorities strategic plan in 2022, the ISRU technology development efforts have become more focused and prioritized. In 2023 there were over 50 NASA funded ISRU-related active technology projects across the Technology Readiness Level (TRL) spectrum and ISRU value chain from 'prospect to product'. With respect to oxygen/metal extraction from regolith both Sierra Space (Carbothermal Reduction) and Lunar Resources (Molten Regolith Electrolysis-MRE), made significant advances, and Blue Origin was awarded a Tipping Point on MRE to solar array production. Also, extended lunar-g testing of technologies is planned with upcoming flights on the Blue Origin New Shepard capsule dealing with lunar regolith characterization (5), and oxygen transport through viscous material (1). An ISRU System Modeling and Analysis project was restarted to provide more detailed analyses of technologies and systems for trade studies, technology benefit evaluation, and mission concept definition. On a less positive note, the technology development for lunar water extraction has not adequately progressed due to budget cuts and limited success, and Mars ISRU development efforts have not been reinitiated.

ISRU Mission Advancement: Since around 2020, it has been a major objective of the ISRU program in STMD to break the 'chicken-and-egg problem' of inserting ISRU into human architectures by funding ISRU technology demonstrations to the Moon and demonstrating end-to-end resource extraction to product storage in a Pilot Plant to eliminate the risk for human exploration and space commercialization. Because of several years of budget cuts, there have been delays in the overall timeline, but the plan continues and has made significant strides toward this goal. Progress in ISRU resource assessment and flight demonstration missions have made very good progress in 2023 going into 2024. The ISRU hardware for both the PRIME-1 and VIPER missions are being integrated onto their respective lander and rover for their upcoming missions. In October, 2023 NASA released a Request for Information (RFI) for the first in a series of STMD Lunar Infrastructure and Fundamental Technology (LIFT) demonstrations missions with LIFT-1 aimed at ISRU extraction of oxygen from lunar regolith. A Request for Proposals (RFP) is expected in 2024 after evaluation of the RFI responses.

A critical need for ISRU that still hasn't been fully addressed is the need for increased resource exploration missions to be able to analyze the potential reserves and economic feasibility of extracting resources such as water and other LCROSS identified volatiles [Ref 4] in permanently shadowed regions of the lunar poles, especially the South Pole. Several missions are now planned by the US and other countries to begin the 'ground-truth' assessment of these potential resources. While the data that will be obtained from these missions will be extremely beneficial for better understanding of these polar resources and the technologies that will be needed for extraction, they are insufficient to estimate their reserve potential. Also, with the failures of all the lunar resource focused CubeSats and the failures and partial successes of the recent lunar lander missions, it should be recognized that a robust and coordinated effort is needed between government agencies and industry to ensure the necessary data is obtained within a reasonable timeframe. Several studies and workshops have been held on how this might be achieved, with the latest effort defined in "The Moon Needs an International Lunar Resource Prospecting Campaign" by Neal, et. al, [Ref 5]

Advancing the Cis-Lunar Ecosystem: For space resources and ISRU to be successful, there needs to be a market for the products, infrastructure to support the activities, and a cis-lunar economy not fully dependent on government agencies for funding and support. In the past few years, significant NASA and private investments have been made in ISRU and support infrastructure such as transportation, power, mobility, robotics & automation, space manufacturing, and surface construction. The Lunar Surface Innovation Consortium (LSIC) is promoting the establishment of the lunar ecosystem through their focus groups and workshop activities. Several consortiums have been created in the US and elsewhere to promote the development of standards and interfaces and areas of particular commercial interest. Lastly, with the DARPA LunA-10 study to evaluate how to create a sustainable cis-lunar ecosystem in 10 years, all these activities are contributing to advancing the possibility of a commercial cis-lunar ecosystem. It will be extremely important that while government agencies will want to collaborate as much as possible to meet their strategic needs and priorities, it is also important to establish a framework that allows for competition to advance performance, cost effectiveness, and commercial interests. Making sure ISRU and support infrastructure technologies and operations benefit Earth needs and advance terrestrial mining and processing efforts will be very important as well to achieving the long-term vision of sustained human lunar surface activities.

References:

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