Potential Lunar In-Situ Resource Utilization Experiments and Mission Scenarios

G. Sanders[a,*]

[a] Lunar Surface System Office, NASA Johnson Space Center, Houston, TX., USA

Abstract

The extraction and use of resources on the Moon, known as In-Situ Resource Utilization (ISRU), can potentially reduce the cost and risk of human lunar exploration while also increasing science achieved. By not having to bring all of the shielding and mission consumables from Earth and being able to make products on the Moon, missions may require less mass to accomplish the same objectives, carry more science equipment, go to more sites of exploration, and/or provide options to recover from failures not possible with delivery of spares and consumables from Earth alone. While lunar ISRU has significant potential for mass, cost, and risk reduction for human lunar missions, it has never been demonstrated before in space. To demonstrate that ISRU can meet mission needs and to increase confidence in incorporating ISRU capabilities into mission architectures, terrestrial laboratory and analog field testing along with robotic precursor missions are required. A stepwise approach with international collaboration is recommended. This paper will outline the role of ISRU in future lunar missions, and define the approach and possible experiments to increase confidence in ISRU applications for future human lunar exploration.

Keywords: In-Situ Resource Utilization, ISRU, Lunar Flight Experiments

1. Introduction

The concept of lunar In-Situ Resource Utilization (ISRU) has been considered and studied for decades, and scientists and engineers were theorizing and even testing concepts for how to extract oxygen from lunar soil even before the Apollo 11 mission to the Moon. There are four main areas where ISRU can significantly impact how human missions to the Moon will be performed: mission consumable production, civil engineering and construction, energy production, storage, and transfer, and manufacturing and repair. The area that has the greatest impact on mission mass, hardware design and selection, and mission architecture is mission consumable production, in particular, the ability to make propellants, life support consumables, and fuel cell reagents. Mission consumable production allows for refueling and reuse of spacecraft, increasing power production and storage, and increased capabilities and failure tolerance for crew life support. The other three areas allow for decreased mission risk due to radiation and plume damage, alternative power systems, and failure recover capabilities while also enabling

* G. Sanders, Phone +281 483 9066, E-mail: gerald.b.sanders@nasa.gov

infrastructure growth over Earth delivered assets.

While lunar ISRU has significant potential for mass, cost, and risk reduction for human lunar missions, it has never been demonstrated before in space. Because of this, mission planners are hesitant to incorporate ISRU capabilities and systems into mission critical roles early in human lunar architecture plans. However, if ISRU is not incorporated early into mission plans, transportation and surface systems may be designed not to take advantage of ISRU products, and the benefits of utilizing ISRU capabilities will be lost. An approach is required that increases confidence in ISRU capabilities early such that human exploration systems can take advantage of the benefits with the minimum risk to mission architecture success. That approach is to demonstrate that ISRU can meet mission needs through terrestrial laboratory and analog field testing along with robotic precursor missions in a stepwise approach with international collaboration.

2. Risks Associated With ISRU Incorporation

While incorporation of ISRU into missions and architectures can provide tremendous mass and cost reductions, there are risks associated with ISRU that must be addressed to ensure mission success. There are five major risks associated with ISRU.

i. The resource required is not at the site of exploration
ii. The resource is present at the site of exploration but not in the form or location expected
iii. The ISRU system does not operate due to environmental conditions, such as vacuum, reduced gravity, thermal extremes, etc.
iv. The ISRU system does not operate due to sustained exposure to lunar regolith
v. The ISRU system and products are not compatible with the end-users

The first two risks associated with resource uncertainties are the most difficult to overcome through terrestrial-based laboratory and analog field testing. Lunar simulants have been created that now contain reasonably good mineral and size distributions of particles compared to Apollo mare and highland samples and include glass and agglutinate fractions [1]. However, developing a lunar simulant that incorporates all aspects of actual lunar material is impossible, and use of actual Apollo samples in development and testing will be extremely limited. The 3rd, 4th, and 5th risks listed also apply to most surface exploration hardware, especially mobility systems and Extra-Vehicular Activity (EVA) suits which incorporate joints, mechanisms, and/or wheels that will repeatedly come in contact with the abrasive, fine-grain lunar regolith.

To overcome these risks, three risk mitigation efforts are required. Terrestrial laboratory and environmental chamber tests (C), Analog field testing (A), and Robotic precursor flight experiments (D). Table 1 depicts the risks associated with incorporation of ISRU into mission plans, the potential impacts to the mission, and how each of the three risk mitigation efforts can be applied to reduce or eliminate the risks.

Table 1. Risks and Mission Implications of ISRU Incorporation

			Risk	Potential Impact
A D	1		Potential resource is not available at site of exploration	Mission failure if resource processing and product is critical to mission success
	2		Resource is present BUT	
		a	Form is different than expected (concentration, state, composition, etc)	Processing failure or reduced production rate
D		b	Location is different than expected (depth, distribution, terrain)	Resource not obtainable or reduced production rate
		c	Unexpected impurities	Processing failure, degraded performance, and/or product contamination
C D	3		ISRU system does not operate properly in lunar environment (vacuum, temperature, temperature swings, 1/6 g)	Processing failure or degraded performance/increased energy required
C D	4		ISRU system does not operate properly after sustained exposure to lunar regolith	Processing failure, degraded performance, and/or loss of product
A	5		ISRU systems and products not are compatible with end-user (interfaces, contaminants)	Mission failure if resource processing and product is critical to mission success

3. Stepwise Approach to ISRU Incorporation into Human Mission Plans

With respect to ISRU incorporation into the lunar architecture, there are three driving factors to consider: Potential resources need to be fully understood and characterized before they can be used; ISRU capabilities need to be adequately demonstrated before they are utilized in a mission critical role; and not all ISRU capabilities are needed at once, but are linked to growth and evolution of other surface system elements and architecture goals. The approach for incorporation of ISRU advocated is a four phased approach:

i. *Characterize resource availability* – verify resource type, amount, and distribution along with the energy required to acquire the resource
ii. *Demonstrate the feasibility of the ISRU function or application* – perform subscale proof-of-concept demonstrations of critical subsystems/systems
iii. *Deploy Pilot operations to provide benefits* - provide products and services to enhance or extend mission capabilities and/or reduce mission risk above Earth-delivered assets and logistics, while at the same time verifying production rates, reliability, and long-term operations before full implementation begins.
iv. *Institute full implementation of ISRU functions or applications when verified* – incorporate ISRU in mission critical roles and include industry to allow for an on-ramp of commercial products and services.

Figure 1 provides a graphical representation of how each ISRU implementation phase may affect Earth supplied logistics and mission criticality, and at what point in lunar mission plans each phase occurs. The first two phases can be combined under appropriate conditions.

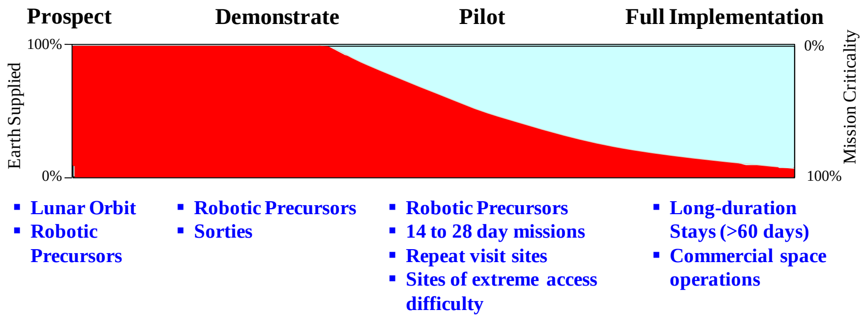

Figure 1. ISRU Architecture Incorporation Approach

The first step is to understand the resources available through orbital and surface exploration missions. Lunar resources of particular interest are hydrogen, hydroxyl, water, and other polar volatile resources recently measured by Chandrayaan, Lunar Reconnaissance Orbiter (LRO), and the Lunar Crater Observation and Sensing Satellite (LCROSS). Pyroclastic glasses and areas of high iron-oxide/ilmenite concentrations are also of interest for solar wind volatile and oxygen extraction from regolith. The second step is to demonstrate critical aspects of ISRU systems to prove ISRU is feasible under lunar environmental and resource conditions (ex. subscale oxygen extraction from regolith). The third step is to perform integrated missions with ISRU and other connected systems, such as power, consumable storage, surface mobility, and life support at a relevant mission scale to demonstrate ISRU capabilities as well as the critical interfaces with other exploration systems. If possible, the mission should demonstrate the use of ISRU products (ex. in a rocket engine or fuel cell). This ‘dress rehearsal’ mission would be the final step before full implementation of ISRU into human missions, and may be performed during human lunar exploration activities. This stepwise approach is the most conservative approach, and may only be possible with international cooperation due to the limited number of robotic missions each nation/space agency can perform within their budget.

4. Purpose of Lunar Robotic Precursor Missions

Before initiating and selecting experiments and systems for potential robotic precursor missions, an assessment must be made to justify the cost of performing the mission with respect to the benefit provided. There are five main reasons to select and perform robotic precursor missions.

i. Demonstrate long-term operations & environmental impacts on lunar surface system hardware
ii. Reduce risk for high pay-off (“Game Changing”) technologies, systems, and concept of operations
iii. Evaluate potential exploration sites
iv. Obtain early design and flight experience before human mission design and certification

v. 'Mars Forward' experience and applicability

For the first and forth reasons, we must remember that Apollo hardware and operations only occurred for a maximum of 3 days on the lunar surface, with limited traverse distances, and only during the sunlit 'morning' phase of the lunar solar cycle in the equatorial region. For human exploration missions, hardware will need to operate for orders of magnitude longer then the experience provided by Apollo. Early precursors could provide the engineering and hardware life experience not possible to obtain from terrestrial-based testing facilities before final designs for the human missions are set. We also need to remember that Apollo occurred 40 years ago and a new generation of engineers and mission managers need to be trained. Also, Apollo was solely performed by the USA. Future human lunar missions will require significant international involvement and cooperation in mission critical roles.

For the second reason, it must be recognized that mission planers and hardware developers for human space exploration are extremely risk adverse, and incorporate only technologies that have been adequately demonstrated or flight tested. Therefore, it is difficult to incorporate advanced technologies that can impact multiple subsystems, such as ISRU, cryogenic fluid management systems, advanced power and fuel cell systems, and new materials. Robotic precursor missions can provide the fight testing required to adequately demonstrate these game changing technologies.

For the third reason, even though the Lunar Reconnaissance Orbiter (LRO) can provide sub-meter resolution images, it will be important to scout potential sites of human exploration, to minimize the risk of crewed missions, to justify sending humans to that site for exploration, and to help identify locations and resources for possible long-duration or permanent surface stays.

Lastly, for the fifth reason, while the Moon is vastly different from Mars in many ways, technologies used for lunar exploration as well as operations and procedures for how these technologies and systems are used can be highly applicable to Mars exploration. Because of the relative nearness of the Moon (minimum time delays) and large number of launch windows compared to Mars missions, performing lunar precursor missions to prepare for Mars may be important. For example, lunar regolith excavation and processing to extract oxygen utilizes similar technologies and operations that would be associated with extracting water from Mars surface soils.

5. Potential Lunar ISRU Precursor Experiments and Missions

While ISRU-related experiments in general meet all five main reasons for performing robotic precursor missions, initial focus should be placed on technologies, experiments, and systems that correlated to one or both of the first two reasons; demonstrate operations to reduce risk, and demonstrate high-payoff technologies. For each of these areas of interest, payloads that are actually selected will most likely be a function of mission payload mass and power capabilities, funding, and the number of robotic precursor missions available before human exploration begins. Table 2 depicts a sample set of potential lunar ISRU experiments in relationship to the mission focus, mission payload capability, and level of ISRU incorporation into the architecture. The sample set is not meant to be all inclusive, but does represent items applicable to past and recent human lunar architecture scenarios. Three experiments of potentially great interest to early human lunar exploration plans deal with characterizing lunar polar volatiles (#3), performing proof-of-concept evaluation of oxygen extraction from regolith techniques (#4), and performing a larger scale 'dress rehearsal' of ISRU and other important surface system elements before human missions begin or as a pre-deployment 6 months to a year before the crew arrives (#5).

Table 2. Sample Set of Potential Lunar ISRU Experiments

Demonstrate Operations/Risk Reduction Payloads	**Experiment/Mission Focus**
Concept/Subsystem Evaluation: ~15 kg Class	
1. Size Sorting & Mineral Beneficiation Demo	Concept validation & Environmental compatibility
2. Physical/Mineral Characterization Instrument Suite	Mineral resource availability
Proof-of-Concept Demos: ~50 kg Class	
3. Lunar Polar Volatile/Ice Characterization Payload	Resource availability & Environmental compatibility
4. Subscale Oxygen Extraction from Regolith	Concept validation & Environmental compatibility
Pilot Demonstration: ~300 kg Class	
5. Integrated ISRU Pilot-scale O_2 Production and Surface System Demo	System Integration; Mission enhancement and/or extension
Game Changing or Infrastructure Growth ISRU Payloads	**Experiment/Mission Focus**
Concept/Subsystem Evaluation: ~15 kg Class	
6. Surface Preparation/Sintering Demonstration	Concept Validation
Proof-of-Concept Demos: ~50 kg Class	
7. Thermal "Wadi" Nighttime Survival Demo	Concept validation & Environmental compatibility
Pilot Demonstration: ~300 kg Class	
8. Solar array production	Concept Validation

Characterizing lunar polar volatiles is of potentially great importance to both Science and Exploration objectives for exploring the Moon. With respect to Science, understanding and characterizing lunar polar volatiles provides scientific data for understanding the solar system and Earth-Moon formation and history. It can also provide 'ground truth' data for Lunar Prospector, Clementine, Lunar Reconnaissance Orbiter, and Lunar Crater Observation and Sensing Satellite (LCROSS) information before cargo and human lander missions begin to contaminate polar sites. With respect to Exploration objectives, characterizing lunar polar volatiles, especially water/ice, could be 'game changing' in the ability to make significant amounts of propellants for lunar transportation systems while also providing water for life support systems and radiation shielding significantly reducing the risk of long-term human exploration and settlement. To characterize lunar polar volatiles, NASA initiated development of an experiment package called RESOLVE, for Regolith and Environment Science & Oxygen and Lunar Volatile Extraction in 2005 [2]. RESOLVE was originally designed to meet the following objectives; (1) obtain "Ground Truth" data for resources at lunar pole; (2) obtain bulk and fine-grained regolith characteristic and environment data; (3) extract and collect volatiles from lunar regolith outside and inside permanently shadowed regions; (4) extract oxygen from regolith; and (5) perform a hydrogen/water resource processing demonstration after it has been evolved and collected (must deal with uncertainty in form of hydrogen found). Since initiation of the project, RESOLVE has developed two generations of hardware and performed two analog field tests in Hawaii mounted on mobility platforms to simulate mission operations [3]. A third generation of RESOLVE is now in work, in partnership with the Canadian Space Agency (CSA). to reduce the total payload mass to below 60 kg and power below 200 Watts average.

The lunar regolith is made up of greater than 40% oxygen. Unlike lunar polar volatiles, this oxygen can be extracted from lunar regolith anywhere on the Moon. Over twenty different methods for extracting oxygen from regolith have been proposed and many examined in the laboratory since the early 1960s. In 2006, NASA initiated development of three oxygen extraction systems that bound the risk and performance ranges of all of these methods; hydrogen reduction, carbothermal reduction, and molten electrolysis. Even though each of these methods are different and extract oxygen from different minerals in the lunar regolith, they do all share common aspects such as regolith excavation, handling, and sorting, as well as oxygen and reactant cleaning/contaminant removal, recycling, and storage. Figure 2 depicts the critical functions associated with oxygen extraction from regolith.

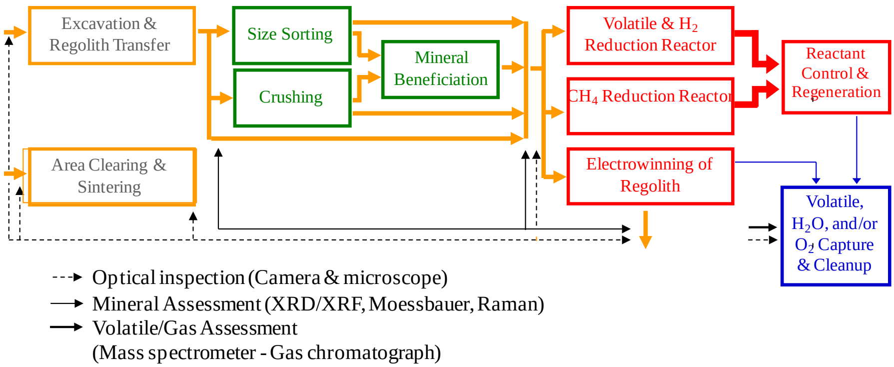

Figure 2. Critical Functions Associated with Oxygen Extraction from Regolith

As was mentioned previously, while Earth-based testing and lunar simulants can be used to increase the confidence and reduce the risk of deploying these systems and functions on the Moon, there are aspects of the first two risks discussed previously that can't be fully addressed without performing tests in the lunar environment and with actual lunar regolith. It is proposed that a subscale demonstration be flown that demonstrates each of the critical functions depicted in Figure 2, at a scale sufficient to provide the engineering and life data necessary to design the larger scale systems needed to support crewed operations. It is also proposed to include science instruments, such as Raman and Mossbauer spectroscopy, gas chromatography/mass spectroscopy, and microscopic imaging to examine the regolith and volatiles present (including trace gases and contaminants) as it proceeds through each step in the process such that performance can be assessed as a function of the feedstock utilized.

Lastly, should sufficient payload mass be available, a larger scale mission that includes full-scale or near-full scale hardware associated with ‘game changing’ technologies for multiple surface systems be considered as a final risk reduction method before human missions begin. By incorporating ISRU, mobility, fuel cell and solar array power, and cryogenic fluid management subsystems into an integrated package and operated on the lunar surface for 6 months to a year, confidence in the ability of the hardware to meet the orders of magnitude increase in life over Apollo hardware could be achieved. Because of the expense of performing long-term environmental chamber tests on Earth, performing this ‘dress rehearsal’ mission may actually be cost effective compared to traditional flight certification testing approaches for spacecraft. Figure 3. depicts both a concept picture of this mission payload as well as a 1st generation hardware system that was field tested in November 2008 in Hawaii. If the mission is successful, a cache of oxygen, water , or fuel cell reactants could be available for crew use in subsequent missions, freeing up payload mass for other science or exploration hardware.

Figure 3. Integrated Pilot Scale ISRU and Surface System Demonstration

5. Summary

While In-Situ Resource Utilization (ISRU) can provide mass, cost, and risk reduction benefits to future human lunar exploration missions, it requires further development and demonstration to convince mission planners to incorporate ISRU capabilities into early missions. A stepwise approach utilizing laboratory, environmental chamber, analog field testing, and robotic precursor flight experiments with international participation is recommended. Three robotic precursor flight experiments are proposed that may provide the greatest impact and risk reduction aspects for early incorporation of ISRU into lunar architecture plans: (1) characterizing and mapping lunar polar volatiles and water/ice, (2) performing subscale demonstrations of critical oxygen extraction from regolith tasks, and (3) performing a near full-scale system demonstration of ISRU, mobility, power, and cryogenic fluid management technologies.

REFERENCES

[1] Butcher, Alan R., Pieter WSK, Botha, Pieter, & Power, Matthew R, "Experimental Analysis of Lunar Simulants: NU-LHT-1M; OB-1; JSC; JSC-1; JSC-1A; FJS-1; MLS-1", Lunar Simulant Workshop, MSFC, 22th February 2008,
[2] Sanders, Gerald, Moore, Landon, McKay, David S., et. al., "Regolith & Environment Science, and Oxygen & Lunar Volatile Extraction (RESOLVE) for Robotic Lunar Polar Lander Mission", International Lunar Conference, Toronto, Canada, Sept., 2005
[3] G. B. Sanders, T. M. Simon1, B. J. Rosenbaum, W. E. Larson, J. W. Quinn, J. E. Captain, D. S. Boucher, "Overcoming the Hurdles of Incorporating In-Situ Resource Utilization (ISRU) into Human Lunar Exploration", ASCE Earth & Space Conference 2010, Hawaii, March, 2010