ISRU at a Lunar Outpost: Implementation and Opportunities for Partnerships and Commercial Development

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Abstract. The NASA Lunar Architecture Team (LAT), which was commissioned to help answer the question 'how' will humans return to the Moon, and the Synthesis Team and the recently released Global Exploration Strategy, which was commissioned to help answer the question 'why' will humans return to the Moon and go on to Mars have identified the ability to extract and use in-situ resources as important to extending human frontiers, reduce dependence on Earth, and further economic and commercial expansion into space. The extraction and processing of space resources into useful products, known as In-Situ Resource Utilization (ISRU), can have a substantial impact on mission and architecture concepts. In particular, the ability to make propellants, life support consumables, and fuel cell reagents can significantly reduce the cost, mass, and risk of sustained human activities beyond Earth. Potential lunar resources include solar wind implanted volatiles, vast quantities of metal and mineral oxides, possible water/ice at the poles, abundant solar energy, regions of permanent light and darkness, the vacuum of space itself, and even scavenging leftover descent propellants and/or trash and waste from human crew activities. Suitable processing can transform these raw resources into useful materials and products.

The establishment of a human lunar Outpost, as proposed by NASA at the 2nd Space Exploration Conference in Houston in December 2006, opens up the possibility for the first time of breaking our reliance on Earth supplied consumables and learn to "live off the land". The ISRU phasing and capability incorporation strategy developed during LAT Phase I & II is based on the premise that while ISRU is a critical capability and key to successful implementation of the US Vision for Space Exploration, it is also an unproven capability for human lunar exploration and can not be put in the critical path of architecture success until it has been proven. Therefore, ISRU needs to take incremental steps toward the desired end state. However, at the same time, the lunar architecture needs to be open enough to take advantage of ISRU when proven available. From this, the following ISRU capabilities and phasing was determined to be most beneficial for establishing an Outpost for sustained human presence while incrementally proving and building confidence in ISRU fulfilling critical mission needs:

<u>Pre-Outpost</u>
- Determine type, amount, and location of possible resources of interest (i.e. iron oxides, water, etc.) – link to Science objectives if possible
- Perform proof-of-concept and risk reduction demonstrations to certify ISRU and surface element capabilities for use at the Outpost - link to commercialization of space if possible
- Perform site characterization of surface topography, subsurface, and lighting conditions

<u>Initial ISRU Capabilities to be pursued during early Outpost</u> (first 5 years)
- Excavation & site preparation (i.e. radiation shielding for habitats, landing plume berms, landing area clearance, hole or trench for habitat or nuclear reactor, etc.)
- Pilot-scale oxygen production, storage, & transfer capability (replenish consumables)
- Pilot-scale water production, storage, & transfer capability – assuming hydrogen source/water is accessible
- Scavenge descent propellants (oxygen, hydrogen, and fuel cell water)
- Fuel cell reactant production, storage, & transfer capability
- Demonstration of In-situ fabrication and repair demonstration

<u>Mid-Term ISRU Capabilities - Exploration growth</u> ("Hub & Spoke")
- Propellant production for lunar ascent vehicle, robotic sample return, or propulsive hopper from Outpost
- Life support and power consumables for long-range pressurized rover
- Construction and fabrication demonstrations

<u>Possible Long-Term Lunar Capabilities</u> (Settlement)
- In-situ manufacturing and assembly of complex parts and equipment

- Habitat and infrastructure construction (surface & subsurface)
- In-situ life support – bio support (soil, fertilizers, etc.)
- Propellant depot in lunar orbit for descent to the outpost and/or cis-lunar transportation
- Power generation for Moon and beyond: beaming, helium-3 isotope (^3He) mining, etc.

With this approach, ISRU can be integrated into Outpost habitat and lunar surface system functions and needs without being in the 'critical path' since early mission consumables could still be brought from Earth if ISRU is shown to be not technically feasible or not beneficial from a mass or cost perspective. ISRU oxygen and water production would be complementary to life support by providing a functional backup and providing makeup for consumables that were not completely regenerated. ISRU would also provide consumables for open systems, like Extra Vehicular Activity (EVA) suits, and could potentially utilize trash as an in-situ feedstock. If properly coordinated early, ISRU could utilize similar functions, technologies, and modules with life support, fuel cell power, and EVA systems to provide a robust surface architecture, and minimize development and deployment mass and cost. With the ability to produce mission consumables, ISRU could also off-set uncertainties in development and deployment of other lunar architecture transportation and surface elements. For example, the impact of life support system development not meeting the water and air recycling loop closure requirements could be mitigated with ISRU. Once demonstrated in terrestrial field tests and possibly robotic precursors, and demonstrated early in the Outpost, ISRU production and use can be expanded with increased confidence in both ISRU and lunar transportation elements, such that in-situ propellant for lunar ascent might be possible.

To ensure ISRU capabilities are available for pre-Outpost and Outpost deployment by 2020, and mission and architecture planners are confident that ISRU can meet initial and long term mission requirements, NASA has initiated an ISRU technology and system development project in four development stages: Phase I - Demonstrate feasibility; Phase II - Evolve system w/ improved technologies; Phase III - Develop one or more systems to TRL 6 before start of flight development; Phase IV - Flight development for Outpost. To minimize cost and ensure that ISRU technologies, systems, and functions are integrated properly into the Outpost, technology development efforts are being coordinated with other technical development areas such as Surface Mobility, Surface Power, Life Support, EVA, and Propulsion. Also, efforts are being made to coordinate these development activities with outside government agencies (DOD, DOE, DARPA, etc.), industry, academia, and International Partners to the maximum extent possible to leverage funding and increase commonality of hardware at the Outpost. Lastly, laboratory and field system-level tests and demonstrations will be performed a minimum of one time per Phase and subsystem tests will be performed as often as possible during each Phase of development to demonstrate improvements in: Capabilities (ex. digging deeper); Performance (ex. lower power); and Duration (ex. more autonomy or more robustness). Yearly demonstrations will be based around important capabilities or "Themes" to define and distinguish goals and characteristics associated with different surface operations that may be required for pre-Outpost and Outpost surface operations. Themes currently in work for laboratory and field demonstrations in 2007 and 2008 as part of Phase I - Demonstrate Feasibility are: Prospecting/Site Surveying/Science; end-to-end Oxygen Extraction from Regolith; and Surface Manipulation for Outpost Emplacement and Safety.

To successfully implement the ISRU capabilities defined above will require multiple elements working together. As long as interfaces and operations are planned properly, each element or even major technologies or functions in each element could be provided by different participating space agencies where it best meets their technology and strategic interests. The system integration and demonstration field demonstrations proposed could be utilized to build international partnership relationships, procedures, technical data exchange, and operation coordination in a non-flight environment while still demonstrating important capabilities and surface operations that may be required for an international lunar Outpost. This paper will provide the status of work performed to date within the NASA ISRU project with respect to technology and system development and field demonstration activities as a starting point for future discussions with International Partners, industry, and academia.

PRINCIPAL AUTHOR'S BIO

Gerald Sanders currently serves as the Project Manager for ISRU in NASA ETDP program, the Principal Investigator (PI) for the RESOLVE project and past co-PI on the Mars in-situ propellant production Precursor (MIP), and is the NASA ISRU lead for the Lunar Architecture Team and architecture planning activities.