**LUNAR POLAR IN SITU RESOURCE UTILIZATION (ISRU) AS A STEPPING STONE FOR HUMAN EXPLORATION.** Gerald B. Sanders, NASA-Johnson Space Center, 2101 NASA Parkway, Houston, TX,

**Introduction:** A major emphasis of NASA is to extend and expand human exploration across the solar system. While specific destinations are still being discussed as to what comes first, it is imperative that NASA create new technologies and approaches that make space exploration affordable and sustainable. Critical to achieving affordable and sustainable exploration beyond low Earth orbit (LEO) are the development of technologies and approaches for advanced robotics, power, propulsion, habitats, life support, and especially, space resource utilization systems. Space resources and how to use them, often called In-Situ Resource Utilization (ISRU), can have a tremendous beneficial impact on robotic and human exploration of the Moon, Mars, Phobos, and Near Earth Objects (NEOs), while at the same time helping to solve terrestrial challenges and enabling commercial space activities. The search for lunar resources, demonstration of extraterrestrial mining, and the utilization of resource derived products, especially from polar volatiles, can be a stepping stone for subsequent human exploration missions to other destinations of interest due to the nearness of the Moon, complimentary environments and resources, and the demonstration of critical technologies, processes, and operations.

**ISRU and the Moon:** There are four main areas of development interest with respect to finding, obtaining, extracting, and using space resources: Prospecting for resources, Production of mission critical consumables like propellants and life support gases, Civil engineering and construction, and Energy production, storage, and transfer. The search for potential resources and the production of mission critical consumables are the primary focus of current NASA technology and system development activities since they provide the greatest initial reduction in mission mass, cost, and risk. Because of the location of the Moon, understanding lunar resources and developing, demonstrating, and implementing lunar ISRU provides a near and early opportunity to perform the following that are applicable to other human exploration mission destinations:

- Identify and characterize resources, how they are distributed, and the material, location and environment in which they are found;
- Demonstrate concepts, technologies, and hardware that can reduce the cost and risk of human exploration beyond Earth orbit;
- Use the Moon for operation experience and mission validation for much longer missions farther from Earth
- Develop and evolve ISRU to support sustained, economical human presence beyond Earth's orbit, including promoting space commercialization

As Table 1 depicts, the Moon provides environments and resources applicable to Mars and NEOs. Two lunar ISRU resource and product pathways that have significant synergism with NEO, Phobos/Demos, and Mars ISRU are oxygen/metal extraction from regolith, and water/volatile extraction from lunar polar materials. To minimize the risk of developing and incorporating ISRU into human missions, a phased implementation plan is recommended that starts with prospecting and demonstrating critical technologies on robotic and human missions, then performing pilot scale operations (in non-mission critical roles) to enhance exploration mission capabilities, leading to full utilization of space resources in mission critical roles. Which lunar ISRU pathway is followed will depend on the results of early resource prospecting/proof-of-concept mission(s), and long-term human exploration plans.

Table 1. Human Destination Characteristics

| | Moon | Mars | NEOs |
|---|---|---|---|
| Gravity | 1/6 g | 3/8 g | Micro-g |
| Temperature (Max)<br>(Min.)<br>(Min. Shade) | 110 °C/230 °F<br>-170 °C/-274 °F<br>-233 °C/-387.4 °F | 20 °C/68 °F<br>-140 °C/-220 °F | 110 °C/230 °F<br>-170 °C/-274 °F<br>-233 °C/-387.4 °F |
| Solar Flux | 1352 $W/m^2$ | 590 $W/m^2$ | Varied based on distance from Sun |
| Day/Night Cycle | 28+ Days - Equator<br>Near Continuous Light or Dark - Poles | 24.66 hrs | Varied - hrs |
| Surface Pressure | $1x10^{-12}$ torr | 7.5 torr | $1x10^{-12}$ torr |
| Atmosphere | No | Yes<br>$CO_2$, $N_2$, Ar, $O_2$ | No |
| Soil | Granular | Granular & clay; low hydration to ice | Varied based on NEO type |
| Resources | <br>Regolith (metals, $O_2$)<br><br>$H_2O$/Volatile Icy Soils | Atmosphere ($CO_2$)<br><br>Hydrated Soils | <br>Regolith (metals, $O_2$)<br>Hydrated Soils<br>$H_2O$/Volatile Icy Soils |

**Why the Lunar Poles and Resources?:** The poles of the Moon provides an optimal location for sustained surface operations with areas of near permanent sunlight for power and habitats, and permanent shadow for power, science instruments, and resources. The shadowed areas at the lunar poles may contain significant quantities of hydrogen and water as well as other volatiles that may be extremely helpful such as carbon monoxide, ammonia, and light hydrocarbons. With these resources, a wide range of consumables can be produced for propulsion, life support, and power. As with other locations on the Moon, oxygen and metals can also be extracted from the lunar regolith. From these resources, sustained and reusable transportation is possible for lunar surface-to-surface exploration, surface-to-orbit, and even cis-lunar space, as well as increased crew safety for life support and radiation shielding. Ultimately, ISRU propellants, consumables, and metals can enable the commercialization of cis-lunar space.

**Determining Whether Operationally Useful Resources Exist at the Poles:** While the Lunar Crater Observation and Sensing Satellite showed that hydrogen, water, and other volatiles exist in at least one shadowed crater at the lunar poles, and the Lunar Reconnaissance Orbiter and other scientific spacecraft show that these volatile resources may exist elsewhere, it is still necessary to determine whether the volatile resources at the poles are 'operationally useful'. Whether a resource is operationally useful is a function of its location and how economical it is to extract and use.

With respect to the location, the resource must be assessable, it must be within a reasonable distance of the mining infrastructure (including power, logistics, processing, etc.), and it must be within reasonable distance of transportation capabilities to ensure the product can reach the necessary 'markets'. For lunar polar volatiles, there are five main site selection criteria: 1) presence of surface/subsurface volatiles (neutron spectrometer, radar, optical), 2) traversable terrain, 3) limited solar illumination/subsurface temperature <100 K, traversable terrain, 4) direct to Earth communication, and 5) hospitable environment nearby for outposts and infrastructure.

For the resource extraction and processing to be economical, the concentration and distribution of the resource and associated processing technique must allow for a return on investment (ROI) for mass, cost, time, and/or mission and crew safety. This is highly dependent on what product is needed, how much is needed, how often it is needed, and what is required to extract the resource. During NASA's Constellation Program, a production need of 1000 kg of oxygen per year was desired to eliminate life support consumable delivery needs from Earth for a crew of 4 to 6. Performing simple first-order rocket equation propellant needs for a reusable lunar lander from the lunar surface to an Earth-Moon $L_1/L_2$ Lagrange point, somewhere between 3000 kg of oxygen to 30,000 kg of oxygen and hydrogen are required per mission depending on whether a depot at $L_1/L_2$ containing propellants from Earth are used for some of the mission phases. Laboratory tests to date have shown that infrastructure for oxygen extraction from regolith can provide mass and cost ROI for these production needs in less than 3 years.

To determine whether polar volatile resources are operationally useful, a three phase approach of Exploratory Assessment, Focused Assessment, and Mining Feasibility is recommended. The Exploratory Assessment is potentially a short duration mission to evaluate the physical and mineral characteristics of polar regolith, determine the distribution of polar volatiles down to 1 to 2 meters and spatial distribution to 1 to 3 km, validate site selection methods, and validate the design and operation of the hardware. NASA's Resource Prospector Mission (RPM) and Russia's Luna 27 mission which are both tentatively scheduled for 2017/2018 will perform this type of resource assessment. If the site looks promising, a Focused Assessment, possibly nuclear powered to allow for sustained operations in the shadowed region, should be pursued to fully assess the distribution of polar resources as well as determine the economics of extracting them. Finally, a mining feasibility mission (either demonstration or pilot scale) should be flown to validate mining and resource extraction and collection techniques for a sustained period of time.

**Lunar Polar ISRU as a Stepping Stone for Human Exploration:** Using NASA's Resource Prospector and Asteroid Retrieval concept missions as potential starting points, a notional evolutionary mission sequence can be constructed to guide in the selection and development of common technologies and systems that will minimize the cost and risk for development and utilization of space resources for multiple human exploration destinations. The International Space Station can also be utilized to begin the examination of micro-gravity effects on regolith collection, transport, and processing. Should NASA and other space agencies proceed from the initial lunar polar volatile Exploratory Assessment phase with RPM and Luna 27 to more Focused Assessments and Mining Feasibility, the ISRU and mission capabilities evolved and developed for these missions can serve as the basis for enabling other missions to NEA's, Phobos, and Mars.

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