The purpose of In Situ Resource Utilization (ISRU), or "living off the land", is to harness and utilize space resources to create products and services which can enable and significantly reduce the mass, cost, and risk of near-term and long-term space exploration. By producing propellants, life support and fuel cell power consumables, and other items from in situ resources and eliminating the need to launch everything from the Earth, long-term launch and mission costs can be reduced, while potentially increasing science and exploration capabilities and mission safety. In Dec. 2006, NASA unveiled a draft lunar architecture that involves the deployment and buildup of an Outpost at a single location on the Moon that could take advantage of the sunlight and potential water resources at the lunar poles. The architecture also proposed the deployment of an ISRU system to make oxygen and water for life support and Extra-Vehicular Activity (EVA) by 2023 and potentially for propulsion applications by 2027. Besides consumable production, the ability to excavate and manipulate lunar soil (or regolith) and modify surface features and terrain for crew radiation protection, landing plume mitigation and shielding, habitat and nuclear reactor deployment, and minimizing dust generation during surface activities were also considered as potentially important capabilities for Outpost deployment and operations. The purpose of the following subtopics is to demonstrate and/or develop critical technologies and capabilities to meet Outpost architecture and surface manipulation objectives for near and long term human exploration of the Moon.

**Subtopics**

**X5.01 Oxygen Production from Lunar Regolith**

*Lead Center: JSC*

*Participating Center(s): GRC, KSC, MSFC*

Oxygen production from lunar regolith processing consists of receiving regolith from the excavation subsystem into a hopper, transferring that regolith into a reactor where it is reduced using chemical or an electrochemical process, potentially intermediate reactions to reach oxygen, purification of the oxygen, and transfer of the oxygen to the liquefaction and storage subsystem. After oxygen has been extracted from the regolith, the spent regolith must be removed from the reactor and returned to the excavation subsystem for disposal. Depending on the process used, the reactor may contain reduced metals that can be extracted in their pure form for use as a manufacturing feedstock.
To maximize the benefits of In Situ Resource Utilization (ISRU) for the Lunar Exploration Architecture, oxygen production systems must minimize the mass and power consumption of ISRU systems. ISRU systems must be able to produce many times their own mass in oxygen and other products to provide a benefit to the architecture. ISRU systems must be able to autonomously operate in a harsh environment that has wide temperature swings, high radiation and abrasive dust. Depending on the outpost location, the systems must be able to sustain many startup and shutdown sequences when solar power is not available. Some of these shutdown periods may exceed several hundred hours.

The next phase of ISRU research and development will focus on the design and testing of a regolith reduction system that can produce roughly 1000 kilograms of oxygen in a year. The operation assumption is that the production plant will operate off of solar power which is estimated to be available about 70% of the time and will operate at a lunar pole with highlands soils. The current oxygen production approaches being developed into prototypes are: Hydrogen Reduction, Carbothermal and Molten Oxide Electrolysis. The basic description of these approaches can be found in the NASA funded report by Eagle Engineering, entitled "Conceptual Design of a Lunar Oxygen Pilot Plant (1988)". The report can be found on the web at http://www.isruinfo.com/index.php.

NASA is seeking subsystem component technologies rather than full system proposals. We would like to encourage the development of subsystem components that could be inserted into our Exploration Technology Development Program funded oxygen production systems to improve the mass, power and efficiency of the system. Technology areas of particular interest are:

- Heat exchangers to recover energy from heated regolith;
- Low/No maintenance system filtration technologies for removing dust from gas lines;
- Water condensers that would use the cooling potential of the space environment to water condensation with minimal energy usage;
- Solar Concentrators that are lightweight and able to deliver concentrated solar thermal energy to reactors generating regolith temperatures from 900°C up to 1600°C;
- Gas Separators that provide low pressure drop separation of the system and product gas streams from impurities (e.g., $\text{H}_2\text{S}$, $\text{SO}_2$);
- Microchannel methanation reactors that convert a mixture of carbon monoxide, carbon dioxide, and hydrogen to methane and water vapor with carbon monoxide and carbon dioxide consumed to the maximum extent possible;
- $\text{O}_2$ Purification technologies that perform the removal (and reclamation) of all contaminants prior to liquefaction of the oxygen;
- Feed systems to introduce regolith to the reactors and remove the regolith, slag or molten products from the reactor post processing. The systems must minimize the possibility of dust contaminating the reactor seals;
• Reactor Seals: The sealing of reactors includes sealing gas interfaces from the reactor to the remainder of the system and also the regolith feed/exit to the reactor. Valves proposed for use for gas interfaces must be capable of 1000s of operations and able to operate when lunar dust is present in the gas stream. Reactor regolith feed/exit seals proposed for use must either be kept clean, can be automatically cleaned, or seal even with a coating of lunar dust. Interested companies should keep in mind that each reactor system operates at significantly different temperatures so the gas and regolith sealing methods could see a wide range of thermal conditions.

X5.02 Lunar Regolith Excavation and Material Handling

Lead Center: JSC
Participating Center(s): GRC, JPL, KSC

The lunar regolith excavation, handling, and material transportation subtopic is intended to include all aspects of lunar regolith handling for oxygen and other resource collection and site preparation and construction including tasks such as buildup of berms (approximately 3m above grade) and burying of reactors or habitats for radiation protection (approximately 3m below grade). Excavation capability may be limited to collection of unconsolidated surface regolith for oxygen production (approximately 0.2m) or extended to extraction of more consolidated material at greater depths (approximately 3m) if the power and mass requirements for transportation of surface regolith exceed those of deeper digging. Excavation, handling and transportation systems must be operable over broad temperature ranges (generally 110K to 400K) and in the presence of abrasive lunar regolith and partial-gravity environments. Excavation and material handling systems must process 100’s to 1000’s of times their own mass of extracted regolith in their useful lifetimes. Expectations for maintenance by human supervision, crew operation, and crew training for these systems must be minimal and affordable. Figures of merit for lunar regolith excavation, handling and material transportation technologies and systems include: excavation and material delivery rate (kg/hr), excavation and delivery energy efficiency (power required/excavation rate), and excavation depth and berm height. To insert hardware developed as part of the SBIR program, excavation for oxygen production should support a minimum of 20 kg/hr (worst case hydrogen reduction at poles for 1 MT oxygen per year) with maximum of 200kg/hr of the top 0.2m. Excavation requirements for surface construction, habitat emplacement, reactor burial, etc. are extremely preliminary at this time are 500 to 1000kg/hr with excavation down to 3m below the surface and berm building up to 3m above the surface. Specific areas of interest include:

• Excavation technology or systems for collecting unconsolidated surface regolith with low power consumption and hardware mass. Defining interfaces requirements with surface mobility platforms (mass, power, physical attachment, traction, storage and dump apparatus, etc.) is critical. Proposals can include some aspects and demonstration of surface mobility platform efforts but should not be a significant portion of the proposed work.

• Technologies and systems for collecting regolith and its delivery to oxygen production plants that address the engineering trade offs between total system mass, power and energy consumption that arise in co-varying excavation depth and transportation distance.

• Specific technologies for stabilizing a contoured lunar surface area, including but not limited to methods to induce regolith sintering, for the purpose of providing lunar outpost site preparation capabilities.

• Specific technologies for flow of regolith in the lunar environment related to excavation, handling and transportation.
Modeling of granular material physics in partial gravity related to regolith excavation, handling and transportation.

X5.03 Lunar Volatile Resource Prospecting and Collection

Lead Center: JSC
Participating Center(s): GRC, JPL, KSC

Lunar volatile extraction, separation, and collection consists of all aspects of locating and characterizing lunar volatile resources (especially polar hydrogen/water); excavating regolith in the permanently shadowed craters (-233°C and down to 2 meters); mechanical, thermal, chemical, and/or electrical processing of this regolith to release volatiles; identifying/quantifying all volatiles; and separating and collecting volatiles of interest. Metrics of interest include: excavation rate (kg/hr); excavation efficiency (power required/excavation rate); resource extraction efficiency (Watts per mass of volatiles produced per hour); collection efficiency (mass collected vs. total evolved); and collection purity (mass collected of desired product vs. total collected). Specific areas of interest include:

- Excavation techniques for soil-like to rock-like regolith (70MPa), depending on water content, and very cold (40K to 100K) regolith and local environment conditions;
- Excavation technology or systems for collecting regolith while preserving the loosely held volatile species that may be present;
- Regolith handling, processing, and heating techniques that minimize the amount of time and energy required to evolve volatiles (either solar wind implanted or in permanently shadowed craters);
- Gas separation and collection techniques for a product stream containing various concentrations of hydrogen, carbon dioxide, nitrogen, helium, water, ammonia, and methane;
- Demonstration of sealing technology for repetitive (less than 50 times) use at a wide range of temperatures (40K - 500K nominal and up to 1500K maximum) in abrasive, electrostatic, high vacuum environment; and
- Specific technologies or recipes for implanting volatile species in terrestrial samples of lunar regolith simulant to support volatile species collection and extraction technology development.