Instead of bringing everything from Earth, a key to fulfilling the goal of sustained and affordable human and robotic exploration will be the ability to use resources that are available at the site of exploration to "live off the land", known as In Situ Resource Utilization (ISRU). Past studies have shown making propellants and other mission critical consumables (life support and power) in situ can significantly reduce mission mass and cost, and also enable new mission concepts (e.g. surface hoppers). The ability to excavate and manipulate regolith can also have significant mass and risk reduction benefits. The primary objectives for the following ISRU subtopics are to develop technologies and systems that meet Lunar Precursor and Robotic Program (LPRP) and human lunar exploration mission objectives in the following areas: (1) Lunar regolith excavation, handling, and material transportation; (2) Oxygen production from lunar regolith processing; and (3) Lunar volatile resource extraction, separation, and storage, especially in the permanently shadowed craters at the lunar poles. To support future LPRP and human missions, the technologies and systems developed must meet the following:

- LPRP payload mass and power requirements are unknown at this time, however notional payloads should be designed to
- Technology and systems for lunar human Sortie mission demonstrations should be notionally 1/5th scale of early Outpost mission needs and no smaller than 1/10th scale. Payloads should be nominally 100 to 200 kg and no greater than 500 kg in mass.
- The current estimate for lunar human Outpost needs are 2 MT of oxygen per year for life support and EVA usage, and 7 MT of oxygen per year for propulsion to support two ascent missions per year.

**Subtopics**

**X4.01 Lunar Regolith Excavation and Material Handling**

Lead Center: JSC

Participating Center(s): GRC, KSC, MSFC

Lunar regolith excavation, handling, and material transportation deal with all aspects of lunar regolith handling for site preparation, resource collection, and construction activities. Excavation and transport technologies and systems are required to support regolith excavation and transport to support oxygen production from regolith.
(notionally down to 0.5 m), and regolith excavation and transport to support site construction and reactor placement (notional depth down to 3 meters and berms up to 3 meters). To maximize the benefits of incorporating in situ resource utilization (ISRU) capabilities into missions, ISRU excavation and material handling systems must require the minimum amount of mass and power to accomplish the tasks and need to process 100's of times their own mass of extracted resource in their useful lifetimes. Hardware must also be able to operate in wide temperature ranges (-160°C to 123°C), abrasive environments, and partial-gravity. In addition, the maintenance, human supervision, crew operation, and crew training required for these systems must be minimal and affordable. Excavation metrics of interest include: excavation rate (kg/hr), excavation efficiency (power required/excavation rate), and excavation depth and berm height. Specific areas of interest include:

- Evaluation of granular physics in low gravity and development of models and its effect on material excavation and handling;
- Dust-insensitive and/or abrasion-resistant excavation hardware, actuators, seals and bearings; and
- Dust mitigation and construction techniques to minimize dust generation around landing pads, habitats, dust-sensitive instruments, and airlocks.
- Low energy excavation techniques for excavating compacted lunar regolith down to 50 cm.

X4.02 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 excavation and material transportation and chemically, electrically, and/or thermally extracting oxygen from the metal and non-metal compounds in lunar regolith. Other resources of interest, such as silicon, iron, titanium, aluminum, etc. may also be processed in the future based on technologies developed for oxygen production.

To maximize the benefits of incorporating ISRU capabilities into missions, oxygen production from regolith systems must require the minimum amount of mass and power to meet production rates and need to process 100's of times their own mass of extracted resource in their useful lifetimes. Hardware must also be able to operate in abrasive environments and partial-gravity, and may need to be shut down for extended periods of time during lunar night if power is not available. In addition, the maintenance, human supervision, crew operation, and crew training required for these systems must be minimal and affordable. Process evaluation metrics of interest include: oxygen production rate (kg/hr), oxygen production efficiency (Watts per mass of product produced per hour), percentage oxygen extracted from regolith, closed loop operations (minimal if any feedstocks from Earth), and mass of Earth consumables used per mass of oxygen produced. Specific areas of interest include:

- Solar thermal concentrators and furnaces (> 1000°C and > 2000°C);
• Processes to extract oxygen from lunar regolith, excluding production techniques that utilize hydrogen, carbon monoxide, and/or methane reduction of regolith. Consideration needs to be given to examining the impact of shutting down to a minimal level during lunar night if processing power is not available;

• Processes to extract silicon from lunar regolith;

• Regolith feed inlet designs and sealing mechanisms that allow continuous feed or large number of cycles for batch processing that are tolerant to dust/abrasion and high temperatures (> 1000°C), and allow minimal loss of processing reagent and product gases;

• Spent regolith outlet inlet designs and sealing mechanisms that maximize thermal management and minimize processing reagent and product losses; and

• Long-life electrodes/electrolytes for electrolysis-based regolith processing concepts.

X4.03 Lunar Polar Resource Prospecting and Collection

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

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;

• 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 (> 50 times) use at a wide range of temperatures (40K - 500K nominal and up to 1500K maximum) in abrasive, electrostatic, high vacuum environment; and

• Regolith thermal processing concepts that maximize heat transfer and minimize processing times for regolith with low thermal conductivity.