This Topic covers a range of key technology options associated with future lunar and planetary surface exploration and operations for a range of increasingly-ambitious human and robotic mission options through the development of in situ resource utilization technologies, highly-capable surface mobility systems, and various supporting infrastructures. Key objectives are derived from the goals of safe/reliable, affordable and effective future human and robotic lunar and planetary surface exploration in support of the U.S. Vision for Space Exploration.

Subtopics

X9.01 In-Situ Resource Utilization & Space Manufacturing

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

The goals of using resources that are available at the site of exploration and pursuing the philosophy of "living off the land" instead of bringing it all the way from Earth are to achieve a reduction in launch and delivered mass for exploration missions, a reduction in mission risk and cost, enable new missions not possible without in situ resource utilization (ISRU), and to expanded the human presence in space. 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). Experience with the Mir and International Space Station, and the recent grounding of the Shuttle fleet, have highlighted the need for backup caches or independent life support consumable production capabilities, and a different paradigm for repair of failed hardware from the traditional orbital replacement unit (ORU) spares and replacement approach for future long duration missions. Lastly, for future astronauts to safely stay on the Moon or Mars for extended periods of time, surface construction and utility/infrastructure growth capabilities for items such as radiation protection, power generation, habitation space, and surface mobility will be required or the cost and risk of these missions will be prohibitive. However, before ISRU capabilities are incorporated into mission architectures, Earth and flight demonstrations of critical processes and systems will be required to validate performance goals and increase confidence in mission planners.

Proposals for ISRU are requested in four subtopic areas: in situ Resource Extraction and Separation, in situ Resource Processing and Refining, Surface Manufacturing, and Surface Construction. Areas of interest for each of these four subtopic areas are defined below. Acceptable proposals can either address a single subtopic or can include concepts that encompass more then one subtopic into an integrated system. ISRU technologies or...
processes proposed for this subtopic must be shown to be beneficial compared to bringing everything from Earth. Proposals must also demonstrate an understanding of any past work, competing processes, and the current state-of-the-art with respect to the technology or process being proposed. To distinguish work supported under this subtopic from related work not using *in situ* resources, successful proposal must show some understanding of the native resource properties and the environmental conditions involved in their use. Proposals that can support future flight demonstrations of ISRU that are scalable to human mission requirements are encouraged, and point of departure mission information is provided below to help provide size and rate parameters for technologies and processes of interest. Proposals that support lunar ISRU applications or both lunar and Mars ISRU applications may be weighted higher then proposals that solely support Mars ISRU applications.

**In Situ Resource Extraction and Separation**

*In situ* Resource Extraction and Separation capabilities include resource characterization, prospecting, excavation, and delivery to resource processing units, and simple extraction and separation of desired resources from the bulk resource (including atmospheres). To be successfully implemented, *in situ* Resource Extraction and Separation proposals must minimize the mass which must be brought from the Earth, including the mass of the required power system and Earth-supplied processing consumables, and produce 100s of times their own mass of extracted resource in their useful lifetimes. These processes may also be required to operate in extreme temperature and abrasive environments, and in micro-g (asteroids, comets, Mars moons, etc.) or partial-g (e.g., Moon and Mars). In addition, the maintenance, human supervision, crew operation, and crew training required for process operation must be minimal and affordable. Specific areas of interest include:

- Technologies, processes, and systems for robotic precursor and early human missions to the Moon in the areas of resource characterization, excavation and extraction of lunar resources (especially in the polar regions), and performing initial resource separation and collection of water, regolith volatiles, or feedstock for Surface Manufacturing, Surface Construction, or *in situ* Resource Processing;
- Technologies, processes, and systems for robotic precursor missions to Mars in the areas of resource characterization, excavation and extraction of Mars resources, and performing initial resource separation and collection of atmospheric gases, regolith water/volatiles, or feedstock for *in situ* Resource Processing; and
- Evaluation of granular physics in low gravity and development of models and its effect on material excavation and handling; and developing dust-insensitive excavation hardware, actuators, and bearings particularly for lunar resource extraction.

**In Situ Resource Processing and Refining**

The purpose of this subtopic is to identify and experimentally validate single and multi-step *in situ* Resource Processing and Refining units that have the potential for achieving the goals for ISRU stated previously. Such processes may include thermal, chemical, and electrical processing of extracted resources into useful products. *In situ* Processing and Refining includes efficient and economical production of propellants, fuel cell reagents, life support gases and water, manufacturing feedstock (such as silicon, aluminum, iron, and polymers) for use in Surface Manufacturing, and construction feedstock (concrete, wires, trusses, etc.) for use in Surface Construction from resources that have been extracted and separated using processes defined and developed under *in situ* Resource Excavation and Separation. To be successfully implemented, *in situ* Resource Processing and Refining proposals must minimize the mass which must be brought from the Earth, including the mass of the required power system and Earth-supplied processing consumables, and produce 100s to 1000s of times their own mass of product in their useful lifetimes. These processes may also be required to operate in extreme temperature and abrasive environments, and micro-g or partial-gravity. In addition, the maintenance, human supervision, crew operation, and crew training required for process operation must be minimal and affordable. Process evaluation metrics include: mass of product made per hour, final mass of product per mass of processor, Watts per mass of
product produced per hour, percentage conversion of resources into product in single pass, and mass of Earth consumables used per mass of \textit{in situ} product made. Specific areas of interest include:

- Technologies, processes, and systems for robotic precursor and early human missions to the Moon in the areas of processing of lunar resources into oxygen, propellants, and feedstock for \textit{in situ} manufacturing or surface construction;

- Technologies, processes, and systems for robotic precursor missions or eventual human missions to Mars, which produce mission critical consumables, such as oxygen, propellants, life support gases, fuel cell reagents, and \textit{in situ} manufacturing feedstock. Robotic and human missions to Mars that consider initial or evolutionary use of ISRU consumables currently assume the use of liquid oxygen and hydrocarbon fuel (methane, propane, methanol, ethanol, or low freezing point mixtures) propellants for propulsion systems and mobile fuel cell power systems; and

- Developing and evaluating seals for high temperature multi-temperature and operation cycle regolith processors, water electrolysis and carbon dioxide electrolysis units; developing and evaluating low gas loss regolith inlet and outlet units (seals, augers, hoppers) for regolith processing; and developing and evaluating 0-g water separation, and separation of nitrogen from carbon dioxide are of particular interest for lunar and Mars resource processing.

**Surface Manufacturing \textit{w/In Situ Materials}**

The purpose of the Surface Manufacturing element of the ISRU subtopic is to identify and experimentally validate capabilities that include production of sub-element and replacement components, assembly of complex products, and manufacturing support equipment to ensure parts/products manufactured meet required dimensions and specifications. Surface Manufacturing can use either \textit{in situ} or Earth-supplied feedstock, however the long-term goal is to exclusively use \textit{in situ} processed feedstock. Therefore, minimum requirements for process feedstock are advantageous to prevent excessive feedstock processing requirements (i.e., raw aluminum metal vs. specific aluminum alloy characteristics). For \textit{in situ} manufacturing to be beneficial compared to bringing everything from Earth, some or all of the following attributes are required: ability to create wide variety of shapes and sizes, ability to utilize multiple feedstocks (plastic, metal, and ceramics), produce greater than its own mass of product and the mass of potential Earth supplied spares, operate in partial-g environments, and require a minimum of maintenance, human supervision, crew operation, and crew training. Specific areas of interest include:

- Additive Manufacturing Techniques;

- Subtractive Manufacturing Techniques;

- Formative Manufacturing Techniques; and

- Part Assembly/Integration.

**Manufacturing Support Processes**

Proposals that demonstrate manufacturing flexibility capabilities, such as part size, part complexity, and material feedstock for manufacturing while recognizing the mass, volume, and power limitations of future space habitats and delivery systems are highly encouraged.
Surface Construction with In Situ Materials

The purpose of this subtopic is to identify and experimentally validate surface construction techniques that can be applied on the Moon and Mars for future human exploration missions. Early construction capabilities in the form of site preparation and shielding for lander plume debris, meteorites, and solar/galactic radiation can significantly reduce hardware and crew health concerns for missions exceeding several days and returning to the same site of exploration. Also, the ability to construct hardware bunkers, habitats, and power generation, management, and distribution capabilities is essential for mass efficient infrastructure growth on the Moon and Mars. These processes may also be required to operate in extreme temperature and abrasive environments, and micro-g or partial-gravity. Specific areas of interest include:

- Construction techniques for robotic precursor and early human missions that support site planning and preparation and the use, manipulation, and placement of raw materials and expected feedstock materials from in situ Resource Processing and Refining for lander plume debris, meteorites, and solar/galactic radiation shielding;
- Construction techniques for robotic precursor and early human missions that support bunker and habitat structure construction using and manipulating raw and expected feedstock;
- Construction techniques that can be demonstrated on robotic precursor missions that demonstrate dust mitigation concepts for surface mobility around landing pads, habitats, dust-sensitive instruments, and airlocks; and
- Lunar in situ fabrication techniques that can be demonstrated on robotic precursor missions that enable growth in solar power generation, storage, management, and distribution capabilities using raw materials, expected feedstock. Demonstrations can initially assume use of Earth supplied consumables in small amounts.

Point of Departure Mission Information for Proposals

For processing concepts that can be used on robotic precursor missions, payload masses (including rovers) are typically below 300 kilograms (kg). Robotic precursor concepts must demonstrate critical functions and must be scalable to human mission needs. Excavation and separation proposals must show supportability to future resource processing needs.

Excavation, separation, and processing needs for lunar missions depend on the resource of interest, location, and concentration of the resource and the processing technology considered. Mars sample return missions that incorporate in situ propellant production require atmospheric carbon dioxide collection and possibly atmospheric or regolith water extraction to support the production of 300 kg to 2000 kg of propellant depending on the size of the sample and whether the mission is a Mars orbit rendezvous or direct Earth return mission. Breathing rates for astronauts are approximately 0.07 kg of oxygen (O\textsubscript{2})/person/hour in habitats and 0.1 kg O\textsubscript{2}/person/hour for Extra-Vehicular Activities (EVAs). Early human lunar mission surface durations may vary from 3 to 45 days and can include from 2 to 6 crewmembers. Lunar human landers require approximately 5000 to 8000 kg of propellant for ascent and approximately 15,000 to 25,000 kg for landing and ascent combined. Mars mission surface durations are 30 to 90 days for opposition class missions and 450 to 600 days for conjunction class missions. Mars human ascent vehicles typically require 20,000 to 30,000 kg of propellant. Fuel cell reagent consumption rates depend on the power required for the application, the reagents, and the fuel cell technology used. EVA suits and small rovers can require 500W to 1 KW of power/hour, unpressurized rovers can require 3 to 6 KW of power/hour and pressurized rovers can require 10 KW/hour and above.
X9.02 Surface Mobility/Mechanisms

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

This subtopic seeks innovative mobility and mechanisms technologies for robotic systems, crew vehicles, and cargo systems for robotic lunar and Mars missions.

Precursor Mobility Systems

Precursor mobility systems address development of hardware and software mobility technologies for precursor lunar missions that also support missions to Mars. Topics include enabling technologies for modular robotic systems, alternative mobility systems, and the development of software to autonomously control and integrate mobility technologies. Mechanisms include traditional wheel motor and harmonic drives, distributed mechanical drives, traction drives, tracked drives, and walking mechanisms.

Proposals may also focus on surface systems for autonomous robotic outposts. Emphasis is placed on the ability to test, verify, and validate such system prototypes in representative laboratory and field environments. The applicable technologies and design concepts span the full range of surface mobility including high dexterity robotic scouts, long-range navigation on the lunar surface, and robotic systems for structural construction, inspection and repair.

This year, emphasis is placed on: 1) modular robotic systems and subsystems (mechanical and electrical), 2) assembly and control of modular systems, and 3) alternative mobility systems such as inflatable systems or tracked vehicles, and walking systems.

Crew Mobility Systems

We will also consider highly innovative mobility technology in specific support of crew and cargo vehicles. Proposals addressing this area should focus on space-relevant hardware, mobility options, crew transports over rough terrain, and logistical issues such as ingress/egress and loading/unloading.