Definition of large, complex systems requires an understanding of system performance, cost and risk during each of the system's lifecycle phases (i.e., design, development, testing, deployment and operations). Accurate representations of the system's: (1) functional and physical interfaces are required to facilitate the analysis, design, and integration of the system and its elements; (2) costs, operational plans, and risks are required to balance the programmatic aspects of the system; and (3) performance projections and margins are required to understand payload options. Achieving an understanding of these complex interactions requires the development, analysis and refinement of models and simulations (M&S) across the lifecycle of the system in order to support a variety of analysis activities. Models currently being developed for Exploration Systems and Space Operations are categorized as subjective, constructive, operator-in-the-loop, hardware- and software-in-the-loop, and in-service operations. These models and simulations are used to address requirements generation, design definition, verification of requirements, testing and sustaining engineering. SBIR Topic X1 is aimed at addressing pressing issues that are still lingering in the area of analysis and M&S. Data required to perform analysis and execute models/simulations must be consistent, valid and cohesive across the analyses. Approaches to dealing with analysis data management and manipulation through the lifecycle are sought. The integration of cost and risk models early in the lifecycle of a system’s analyses must be achieved to ensure that programmatic factors drive our plans. Modeling and simulation is key to achieving NASA's vision by providing the data required for early key decision-making.

Sub Topics:

X1.01 Full Data Coherency Systems for Engineering Systems Modeling and Simulation

Lead Center: MSFC

Participating Center(s): ARC, GRC, JPL, LaRC

In addressing the accuracy of analysis results, which are used to make program/project decisions, we typically assess the data, the models/simulations, and the analysts. This subtopic area will address the first of these concerns. Verification and validation approaches typically address the validity of the data used to perform the analysis. However, they do not address the issue associated with data cohesiveness and consistency. An issue in the development of integrated modeling/simulation for complex engineering systems arises when information is fed to the models with inconsistent coherency, where “coherency” is defined as appropriate versions, semantics/syntax, abstraction/resolution, and sequence. When, for example, serial/parallel simulations are run with revised input data from one source, other sources may or may not need to be held constant; similarly, input data of varying heritage, semantics, resolution, etc., may result in unexpected and inaccurate simulations. Proposals are sought for systems that manage full data coherency (not just version or sequence control) in modeling and simulation environments.
Traditional, and at times typical, analysis of new systems involves an assessment of the system's performance independent of the cost and risk associated with the design. Specifically, the cost and risk are assessed after the design, requiring integration “after the fact”. The SE&I process, however, requires a balancing of cost, risk and performance throughout a system's lifecycle. An additional challenge associated with this subtopic area is the use of cost and risk techniques early in the design process where there exists little data (i.e., performance, cost, and risk) from which to draw upon for developing the cost/risk algorithms, associated relationships, and verification/validation artifacts. An approach for integrating cost and risk models early in the assessment, ensuring that they drive the design and not vice-versa, is required to address the challenges in the agency. Proposals are sought to address: (1) the integration of cost and risk models into a seamless integrated solution; (2) the early application of cost and risk modeling into the analysis cycle of a system; and (3) the approach to verification and validation of the integrated cost/risk models.

Another significant concern is the high cost of ground and mission operations. Future ground operations will require
quick and efficient turnaround and processing of spacecraft for launch. In addition, new mission operations concepts must be developed to provide appropriate levels of safety and mission success factors while reducing support staff.

Proposals should be responsive to the overall goals and objectives of NASA's Constellation and Lunar Precursor and Robotic Programs. Proposals may address specific vehicle health management capabilities required for exploration system elements (crewed spacecraft, launch systems, habitats, rovers, etc.). In addition, projects may focus on one or more relevant subsystems such as propulsion, structures, thermal protection systems, power, avionics, life support, and communications. Proposals that involve the use of existing NASA health management testbeds (power, propulsion, systems integration, life support, diagnostics, networking, etc.) for technology validation are strongly encouraged.

Specific technical areas of interest related to integrated systems health management include the following:

- **Methods and tools to enable concurrent design of system function and health management systems.** These methods and tools should provide a means to optimize health management system design at the functional level to decide on failure detection methods, sensor types and locations, and identify additional functionality to safeguard against failures before costly design decisions have been made.

- **Health monitoring and management technologies for increased situational awareness of system health, safety, and margins.** Of special interest are innovative methods for sensor validation, robust state estimation, and model-based methods for fault isolation. Proposals should focus on data analysis and interpretation rather than development of new sensors.

- **Data-driven methods for detection of failure precursors and recognition of anomalous patterns in large data sets.** A specific emphasis is on methods that utilize propulsion system data sets.

- **Concepts for advanced built-in-tests for spacecraft avionics that reduce or eliminate the need for extensive functional verification.** Methods for reducing or disambiguating false alarms on built-in-tests are also of interest.

- **Methods for robust control of critical components, subsystems, and systems and robust execution of critical sequences during flight.** Of special interest are robust recovery methods and innovative approaches to functional redundancy for the purpose of enhancing safety, availability, and maintainability.

- **Prognostic techniques able to anticipate system degradation and enable further improvements in mission success probability, operational effectiveness, and automated recovery of function.** Proposals in this area should focus on systems and components commonly found in spacecraft.

- **Human-system integration methods that are capable of summarizing sensor readings, presenting system status, assessing spacecraft capability and mission readiness, and proposing corrective actions in a manner that does not exceed the capacity of human understanding, especially in high-risk situations requiring rapid human response.** Innovative ways for the health management system to convey a wealth of information quickly and effectively are desired.
X2.02 Spacecraft Autonomy

Lead Center: ARC

Automation and autonomy techniques are key elements in realizing the vision for space exploration. Intelligent automation of systems on crewed vehicles is instrumental for decreasing workload, reducing dependence on Earth-based support staff, enhancing response time, and reducing operations cost. Increased system autonomy for unmanned and manned vehicles reduces operations costs, while increasing operations efficiency and spacecraft capability by reducing the time required for humans to staff flight control positions and interact with the vehicles. To enable the application of intelligent automation and autonomy techniques, configuration and validation issues need to be addressed.

Reusable automation software must be adaptable to new applications without undue difficulty, and easily adjusted as the application operations change. The overhead of applying automation techniques to new applications is one of the two key obstacles to acceptance of such techniques in operations. A variation of the same issue is that of adjustment as requirements and application contexts change, which is inevitable in spacecraft operations.

The software and the adaptation to a given application must also be trusted before it can be accepted. Testing and other techniques are keys to establishing such trust and ensuring the correct function of automation systems. However, in both testing and validation, the complexity of intelligent software has proven to be a major obstacle. This has led to trust and correctness issues being another key obstacle to adoption of intelligent automation systems in both unmanned, and most importantly, in crewed vehicles.

Proposals in this area should include autonomy and automation software architectures that facilitate adaptation and ensure correctness. Specifically, proposals in the following technical areas are of high interest:

- Architectures for decision-making and closed-loop control that can be adapted to new applications with minimal reliance on intelligent systems expertise;
- Methodology and techniques for adapting autonomy software to applications, as well as for reconfiguring the software in response to changes;
- Representation and reasoning techniques for specifying properties for application interfaces, operations flight rules and autonomy software behaviors, and for deriving overall properties for autonomy software applications.

X2.03 Software Engineering Technologies for Human-Rated Spacecraft

Lead Center: ARC

Participating Center(s): GSFC, JPL, JSC

The objective of this subtopic is to bring to fruition software engineering technologies that enable engineers to cost-
effectively develop and maintain NASA mission-critical software systems. Particular emphasis will be on software engineering technologies applicable to the high levels of reliability needed for human-rated space vehicles. A key requirement is that proposals address the usability of software engineering technologies by NASA (including NASA contractors) engineers, and not only specialists.

Many of the capabilities needed for successful human exploration of space will rely on software. In addition to traditional capabilities, such as GNC (guidance, navigation, and control) or C&DH (command and data handling), new capabilities are under development: integrated vehicle health management, autonomous vehicle-centered operations, automated mission operations, and further out - mixed human-robotic teams to accomplish mission objectives. Ensuring that these capabilities are reliable, and can be developed and maintained affordably, will be challenging but critical to NASA's exploration objectives. Proposals should clearly indicate how the technology is expected to address the challenge of reliability and affordability. Mission phases that can be addressed include not only the software life-cycle (requirement engineering through verification and validation) but also upstream activities (e.g., mission planning that incorporates trade-space for software-based capabilities) and post-deployment (e.g., new approaches for computing fault tolerance, rapid reconfiguration, and certification of mission-critical software systems).

Software engineering tools and methods that address reliability for exploration missions are sought. Projects can address technology development and maturation that provide for the following and related capabilities:

- Automated software generation methods from engineering models that are highly reliable;
- Scalable verification technology for complex mission software, e.g., model-checking technology that addresses the 'state explosion' problem and static-analysis technology that addresses mission-critical properties at the system level;
- Automated testing that ensures coverage targeted both at the system level and software level, such as model-based testing where test-case generation and test monitoring are done automatically from system-level models;
- Technology for calibrating software-based simulators and test-beds against high-fidelity hardware-in-the-loop test-beds in order to achieve dependable test coverage;
- Technology for verifying and validating autonomy capabilities including intelligent execution systems, model-based diagnosis, and ISHM;
- Software-based radiation fault tolerance for computation;
- Methods and tools for development and validation of autonomic software systems (systems that are self protecting and self healing).
Moon equatorial regions experience wide temperature swings from -180°C to +130°C during the lunar day/night cycle, and the sustained temperature at the shadowed regions of lunar poles can be as low as -230°C. Mars diurnal temperature changes from about -120°C to +20°C. All exploration endeavors, including robotic, habitat, and ISRU systems that are expected to reliably operate on the Moon or Mars surface for years will need electronics that are able to survive and operate in a wide temperature range and thermal-cycling environment. In addition, the electronics must operate reliably after a total ionizing dose (TID) \( \geq 50 \text{ krad (Si)} \) and provide single-event latchup immunity (SEL) \( \geq 100 \text{ MeV cm}^2/\text{mg} \). The lunar and Martian temperatures are well outside the specification range of military and commercial electronics. While many types of devices, especially Si CMOS transistors, can operate down to low temperatures, there are significant circuit design challenges that need to be addressed, especially in the case of mixed-signal and analog circuits.

In addition, thermal cycling present in lunar and especially Mars environments introduces reliability concerns associated with mechanical stress and fatigue of the IC package. For example, compounds optimized for Earth-like packaging of electronic systems have glass transition temperatures that are within the cycling range of these environments, and cycling of electronic systems packaged using these materials will likely result in package failures. Hence, the choice of packaging technology and material combination used is extremely critical for these missions.

Proposals are sought in the following specific areas:

- Wide temperature (-180°C to +130°C) and low-temperature (-230°C), radiation-tolerant and SEL immune, low power, mixed-signal circuits including analog-to-digital converters, digital-to-analog converters, low-noise pre-amplifiers, voltage and current references, multiplexers, power switches, microcontrollers, and integrated command/control/drive electronics for sensors, actuators, and communications transponders.

- High-density packaging able to survive large numbers of thermal cycles (hundreds) and tolerant of the extreme temperatures of the Moon and Mars, including appropriate selection of packaging materials combinations (substrates, die-attach, encapsulants, etc.) modular system level electronics packaging, including power, command and control, and processing functions, enabling integration of electronics with sensors and actuators elements.

- Radiation-tolerant, SEL immune, wide temperature (-180°C to +130°C), and ultra-low temperature (-230°C) RF electronics for short range and long-range communication systems.

- Computer Aided Design (CAD) tools for predicting the electrical performance, reliability, and life cycle for low-temperature electronic systems and components.

- Physics-based transistor device models valid at temperature ranging from -230°C to +130°C to enable design, verification and fabrication of custom low power mixed-signal and analog circuits.

- Low-temperature (-230°C) circuit design methodologies facilitating novel layout designs for integrated mixed-signal and analog circuits.

Research should be conducted to demonstrate technical feasibility during Phase 1 and show a path toward a Phase 2 hardware/software demonstration, and when possible, deliver a demonstration unit for functional and environmental testing at the completion of the Phase 2 contract.
Environmental Control and Life Support (ECLS) Topic X3

Environmental Control and Life Support (ECLS) encompasses the process technologies and equipment necessary to provide, monitor, and control a livable environment within a crewed spacecraft or surface habitat cabin. Functional areas of interest to this solicitation include atmospheric management; atmosphere revitalization and water recovery systems; waste management; habitation systems including crew accommodations; fire protection systems; and environmental monitoring. Technologies are needed for crewed space exploration missions supporting the Vision for Space Exploration with emphasis on missions to the lunar surface, including short duration lunar sortie missions and long duration lunar outpost. Vehicles of interest include the Lunar Surface Access Module (LSAM) and Lunar Outpost (LO). Special emphasis is placed on development of technologies that will fill existing gaps, have a significant impact on reduction of mass, power, volume and crew time, and increase safety and reliability.

Sub Topics:

X3.01 Spacecraft Cabin Atmospheric Management and Habitation Systems

Lead Center: JSC

Participating Center(s): ARC, GRC, JPL, KSC, MSFC

Atmospheric management and habitation systems supporting critical needs for lunar mission architectures are requested. Vehicles and habitats are expected to be significantly restricted with respect to habitable volume and may operate at reduced atmospheric pressure with elevated oxygen concentrations. Improved non-regenerative and regenerative processes technologies for atmospheric quality control must be developed. The ability to economically supply atmospheric gases and refill storage tanks in flight will be needed. Isolating habitable volumes from surface dust and disposing of accumulated particulate matter will be challenges. Habitation systems must be innovative, extremely space efficient, and re-configurable (dual or multi-use).

Atmospheric Management

Atmospheric management encompasses the range of process technologies and equipment to remove impurities and condition crewed spacecraft and habitat cabin atmospheres, supply and store atmospheric gases, and achieve mass closure by recycling resources and using in situ resources. Process technologies typically involve separations and reactions. Separations-based processes include physical adsorption, absorption, and mechanical filtration processes. Reaction based processes include chemical adsorption, oxidation, and reduction. Techniques for enhancing NASA's present capabilities are sought. Areas of emphasis include:

- Atmospheric Purification and Conditioning: Process technologies for single and dual function atmospheric purification and conditioning based on novel embodiments of commercially available adsorbent, chemisorbent, and catalyst media are required. Novel engineered media substrates to enhance durability, energy efficiency, and mass transfer leading to increased reliability, functional capacity, and smaller size relative to NASA's existing experience are sought. Specific challenges exist for efficiently removing ammonia, formaldehyde, and carbon monoxide from cabin atmospheric gases using process technologies that can be regenerated in place. Process technologies for removing and sequestering carbon dioxide from cabin atmospheric gases via means other than adsorption or chemisorption and conditioning carbon dioxide for use in reduction processes to facilitate cabin mass balance closure are also of interest.
- Supply and Store Atmospheric Gases: Novel means for supplying and storing oxygen and nitrogen under...
sub-critical conditions that lead to enhancements in energy efficiency, reduced mass and volume, and mission flexibility are sought.

- Recycle Resources and Use In Situ Resources: Novel means for supplying atmospheric gases using gas purification process waste products or means to more directly couple carbon dioxide and moisture removal to extract usable oxygen are sought.

**Dust Control and Abatement**

Dust and particulate matter contamination are challenges that must be overcome for lunar and Mars surface exploration. Particulate contamination originating from the external surface environment or from internal sources are both of concern. Development of regenerable process technologies and equipment to minimize the impacts of surface dust on crew health and life support equipment are sought. Novel approaches to isolate habitable volumes from surface dust and to remove dust from the spacecraft atmosphere, space suits and equipment are sought. Candidate technology solutions should provide high efficiency, long-lived removal capacity and be amenable to regeneration in place. Areas of emphasis include:

- Particulate Matter Removal and Disposal: Process technologies for removing and disposing of surface dust and particulate matter are sought. Salient features for this application include capability for regeneration in place, long-lived removal capacity and high efficiency.
- Isolation Technologies: Process technologies and design concepts to isolate habitable volumes from surface dust are sought. Such process technologies and design concepts may employ a variety of techniques to prevent surface dust from being transported through an airlock into the habitable part of the spacecraft or habitat cabin.

**Habitation Systems**

Habitation systems include crew accommodations, provisions, housekeeping and crew interfaces with vehicle systems including life support. Products can include applied research, system analysis, mockup evaluation, functionality demonstrations/tests, and actual prototype hardware. Proposals may address the following considerations and themes: re-configurable crew volumes and work stations for multi-gravity environments (micro and reduced gravity), multi-use work stations, multi-gravity translation strategies, physically and psychologically ergonomic personal volumes, automated deployment, quiescent operations between missions, multi-purpose stowage systems, advanced hygiene systems, automated housekeeping, and commonality of hardware/systems. Specific areas in which advanced habitability system innovations are solicited include:

- Crew Hygiene Systems: Low maintenance/self-cleaning fecal, urine, menstrual, emesis, hand/body wash, and grooming systems. Specific areas include non-foaming separators and no-rinse/non-alcohol hygiene products. Toilet systems should consider air, liquid, vacuum, and low-gravity transport methods. Collected waste should be prepared for recovery or long-term stabilization. Integrated hygiene systems should provide acoustic and odor isolated private crew volumes compatible with multi-gravity interfaces.
- Crew Accommodation Systems: Reconfigurable, deployable, erectable, or inflatable integrated crew accommodations that support crew wardroom, dining, conference, sleeping, relaxation activities and or stowage. May include visual and acoustical isolation, illumination, quiet ventilation/thermal control, audiovisual communication/entertainment, and off-nominal uses (emergency medical or repair) while maintaining hygienic conditions. Stowage systems may include interior/exterior stowage systems for partial gravity environments that maximize usable volume and include contents identification and inventory control systems.
- Clothing Systems: Low mass reusable or long usage clothing options that meet flammability, out gassing, and crew comfort requirements. Cleaning and drying systems for re-use of clothing that have low-water usage, non-toxic cleaning agents compatible with physicochemical or biological water reclamation systems, or that do not require water.
Advanced life support systems will be essential to enable human planetary exploration as outlined in the Vision for Space Exploration. These future systems must provide additional mass balance closure to further reduce logistics requirements and to promote self-sufficiency. Requirements include safe operability in micro- and partial-gravity as well as ambient and reduced-pressure environments, high reliability, regeneration, minimal use of expendables, ease of maintenance, and low system volume, mass and power. Proposals should explicitly describe how the work is expected to improve power, volume, mass, logistics, crew time, safety and/or reliability, giving comparisons to existing state-of-the art technologies. Although this solicitation is directed at technologies for lunar missions, crosscutting technologies that are also applicable to human missions to Mars or that are compatible with both partial and microgravity environments may be of interest. Technologies that perform several functions or that eliminate the need for intermediate processing steps are also of interest. Additional documentation and information can be found at [http://advlifesupport.jsc.nasa.gov](http://advlifesupport.jsc.nasa.gov) [1], including the expected composition of solid wastes and wastewater which can be found within the "Baseline Values and Assumptions Document".

**Water Reclamation**

Efficient, direct treatment of wastewater and product water consisting of urine, wash water, humidity condensate, and/or product water derived from in situ planetary resources to produce potable and hygiene water supplies. Treatment methods for long duration lunar surface missions should seek higher levels of mass closure. Treatment methods for short-to-moderate duration lunar missions (several weeks to several months) may have lower recovery rates:

- Stowable small-scale gravity-independent water treatment units for contingency or back up use for treatment of condensate, contaminated potable water or wastewater, which may incorporate flow-through units such as ion exchange, adsorption, multi-filtration and/or osmotic filtration;
- Disinfection and residual disinfectant technologies for potable water storage and point-of-use that are compatible with wastewater processing systems including biological treatment;
- Techniques to minimize or eliminate biofilms, microbial contamination and/or solids precipitation from potable water, wastewater and water treatment system components such as pipes, tanks, flow meters, check valves, regulators, etc.;
- Physicochemical methods for primary wastewater treatment to reduce total organic carbon from 1000 mg/L to less than 50 mg/L and/or total dissolved solids from 1000 mg/L to less than 100 mg/L; and
- Post-treatment methods to reduce total organic carbon from 100 mg/L to less than 0.25 mg/L in the presence of 50 mg/L bicarbonate ions, 25 mg/L ammonium ions and 25 ppm other inorganic ions.

**Solid Waste Management**

Wastes (trash, food packaging, feces, paper, tape, filters, water brines, clothing, hygiene wipes, etc.) must be managed to protect crew health, safety, and quality of life, to avoid harmful contamination of planetary surfaces, and to recover useful resources. Areas of emphasis include:

- Volume reduction of wet and dry solid wastes;
- Small and compact fecal collection and/or treatment systems;
- Water recovery from wet wastes (including human fecal wastes, food packaging, brines, etc.);
- Stabilization, sterilization, and/or microbial control technologies to minimize or eliminate biological hazards associated with waste;
- Mineralization of wastes (especially fecal) to ash and simple volatile compounds (e.g. carbon dioxide and water);
- Containment of solid waste onboard spacecraft that incorporates odor abatement technology;
- Partial-gravity containment devices or systems with low volume and mass that can maintain isolation of disposed waste on planetary surfaces; and
- Microgravity-compatible technologies for the containment and jettison of solid wastes in space.

**Water Recovery from Byproducts of Water and Waste Processing - Brines and Slurries**

Water recovery systems produce brines and slurries from water processing systems that use technologies such as reverse osmosis and distillation. Dissolved solids and organics can total about 3% to 20% by weight of the solution.
Technologies for recovery of water from brines and slurries, which provide an increased level of mass closure of advanced life support systems, are of interest. The products of these systems may be dry solids and purified water low in total organic carbon.

X3.03 Crewed Spacecraft Environmental Monitoring and Control and Fire Protection Systems

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

Environmental Monitoring and Control

Monitoring technologies are employed to assure that the chemical and microbial content of the air and water environment of the astronaut crew habitat falls within acceptable limits, and that the chemical or biological life support system is functioning properly. The sensors may also provide data to automated control systems.

Technologies should be appropriate for a small crewed mission to the Moon, of duration no more than a few weeks. Emphasis is on major constituents in the air and lunar dust. Extendibility to trace monitoring for longer missions is a plus. Significant improvements are sought in miniaturization, accuracy, precision, and operational reliability, as well as long life, real-time multiple measurement functions, in-line operation, self-calibration, reduction of expendables, low energy consumption, and minimal operator time/maintenance for monitoring and controlling the life-support processes. Proposals should be for either new technologies or combine existing technologies in a new way to simultaneously monitor several major constituents and dust, and/or trace constituents.

- Substances from an external environment such as lunar surface dust may be encountered during astronaut excursions and may be a mechanical or chemical threat both during the external encounter and if brought inside. Monitoring technologies are needed to assess and quantify these threats.
- For longer missions, water monitoring will be required. Needs will include sensitive, fast response, online analytical sensors to monitor suspended liquid droplets, dispersed gas bubbles, and water quality, particularly total organic carbon.
- Monitoring of other species of interest include dissolved gases and ions, and polar organic compounds such as methanol, ethanol, isopropanol, butanol, and acetone in water reclamation processes; and particulate matter, major constituents (such as oxygen, carbon dioxide, and water vapor) and trace gas contaminants (such as ammonia, formaldehyde, ethylene) in air revitalization processes. Both invasive and noninvasive techniques will be considered.
- Monitoring of microbial species, especially pathogens, primarily in water, will be important for longer missions. Enabling technologies may include proper sample preparation and handling, with minimal operator effort and minimal or no reagent usage.
- Crew members will employ software tools to help them interpret sensor data. Methods are sought which will assist the crew in using sensor data to detect and predict failures.

Results of a Phase 1 contract should show feasibility of the technology and approach. A resulting Phase 2 contract should produce at least a prototype demonstration and test of the environmental monitor.

Spacecraft Fire Protection Systems

The objective of fire protection strategies on exploration spacecraft is to quantitatively reduce the likelihood of a fire and reduce the impact to the mission should a fire occur. NASA's fire protection strategy includes: strict control of ignition sources and flammable material, early detection and annunciation of fire signatures, and effective fire suppression and response procedures. While proposals describing innovations in all of these areas are applicable, they are particularly sought in the following areas:

- Advanced fire detection strategies are desired that respond uniquely to one or more fire or pre-fire characteristics such as thermal radiation, smoke, or gaseous product. These sensors should be appropriate
for the unique fire behavior in low- and partial-gravity environments yet effectively discriminate between fire signatures and relevant spacecraft nuisance sources. Fire detection systems particularly attractive for long-duration exploration missions will have reduced mass, power, and volume requirements and exhibit high degrees of reliability, minimal maintenance, and self-calibration.

- Fire suppression technologies for exploration spacecraft and habitats must be applicable for use in a confined habitable volume having an atmosphere of up to 34% \( \text{O}_2 \) by volume and pressures as low as 7.6 psia. These systems would be effective in low- and partial-gravity environments and have minimal mass and volume requirements. Applicable technologies would be highly reliable with little or no maintenance, have multi-use capability and/or be replenishable during a mission, and be compatible with the spacecraft environmental control and life support system.

Results of a Phase 1 contract should show feasibility of the technology and approach. A plan for the demonstration of a prototype to be developed in Phase 2 should also be produced at the end of Phase 1. The Phase 2 contract should produce at least a prototype demonstration and test of the fire detection or suppression system.

Lunar In Situ Resource Utilization (ISRU) Topic X4

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.

Sub Topics:
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.
In early robotic missions, and later in outpost missions, permanently shadowed regions of the Lunar surface (e.g., the bottoms of craters in the polar regions). These areas appear to remain at temperatures of 50°K to 80°K (-223°C to -193°C). Current surface exploration hardware has demonstrated capability to operate in the range of 158K to 273K (-115°C to 0°C) on Mars. However, the technical challenges of developing and demonstrating hardware that can operate over 100°C colder than current capabilities are significant. The major technology drivers of the low temperature mechanism technology development are to significantly enhance operation of mechanized parts by (1) lowering the operating temperature for the life of the component and (2) improving mechanism performance (e.g., torque output, actuation performance, lubrication state) at the lunar environment conditions of cold and vacuum. The targeted application of the technology is to provide for operation of motors and drive systems, lubricated mechanisms, and actuators of lunar rovers and mobility systems, ISRU machinery, robotic systems mechanisms, and surface operations machinery (i.e. cranes, deployment systems, airlocks), lunar sortie and the lunar outpost missions. This topic area is responsible for mid-level technology research, development, and testing through experimental and/or analytical validation.

Sub Topics:

X5.01 Motors and Drive Systems for Cryogenic Environments

Lead Center: GSFC

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

This subtopic focuses on the development of selected hardware and support technologies for motors, drive systems and related mechanisms that will operate in cryogenic temperature environments such as permanently shaded craters on the Moon, and/or on the lunar surface exposed to the day/night cycle. In the former situation such mechanisms may be exposed to, and will need to operate in, sink temperatures as low as approximately 25K. In the latter situation they will need to operate over a temperature sink range of approximately 83K to 146K (-190°C to +127°C). Actual operational temperatures may be somewhat different. The component technologies developed in this effort will be utilized for rovers, operational equipment, instruments, drills, crushers, and other such facilities. The nearer term focus for this effort is for lunar missions, but these technologies should ideally be translatable to applications on Mars. These components must operate in a hard vacuum and/or planetary environment, with partial gravity, and full solar radiation exposure. Additional requirements include high reliability, ease of maintenance, low-system volume, low mass, and minimal power requirements. Low out-gassing is desirable, as are modular design characteristics, fail-safe operation, and reliability for handling fluids, slurries, biomass, particulates, and solids. While dust mitigation is not specifically included in this subtopic, proposed concepts should be cognizant of the need for such technologies.

Specific areas of interest include gear boxes, suspension systems, material components (i.e., wiring, harnesses, insulating materials, and jackets/covers) that are flexible in cryogenic environments; advanced lubricants and lubrication technology; and an accelerated means of life testing for cold temperatures.
Lightweight Structures and Materials Topic X6

The SBIR topic area of Structures and Materials centers on developing lightweight structures technologies to support Lunar Lander, and Lunar Habitats, with relevant technology made available to the CEV and CLV programs. Lightweight structures have been identified as a critical need since the reduction of structural mass translates directly to additional up and down mass capability that would facilitate additional logistics capacity and increased science return for all mission phases. The Lightweight Structures program utilizes and combines multi-center R&D teams into a focused activity for developing lightweight structure technology for the primary load bearing structure of the pressurized elements of the Vision for Space Exploration (VSE) program. In addition, development for non-pressurized primary structures will be considered where there is synergy with the development of the pressurized structures. The major technology drivers of the lightweight structure technology development are to significantly enhance structural systems for man-rated pressurized structures by (1) lowering mass and/or improving efficient volume for reduced launch costs, (2) improving performance to reduce risk and extend life, and (3) improving manufacturing and processing to reduce costs. This topic area is responsible for mid-level technology research, development, and testing through experimental and/or analytical validation. Subtopics in this area include Radiation Shielding Materials, Lightweight Primary Structures, and Advanced Materials.

Sub Topics:

**X6.01 Radiation Shielding Materials and Structures**

Lead Center: LaRC

Participating Center(s): ARC, MSFC

Revolutionary advances in radiation shielding materials and structures technologies are needed to protect humans from the hazards of space radiation during NASA missions. All radiation species are considered, including particulate radiation (electrons, protons, neutrons, alpha particles, light ions, heavy ions, etc.) and including electromagnetic radiation (ultraviolet, x-rays, gamma rays, etc.). All space radiation environments in which humans may travel in the foreseeable future are considered, including low-Earth orbit, geosynchronous orbit, Moon, Mars, etc. The primary areas of interest for this 2006 solicitation are: (1) radiation shielding materials systems for long duration lunar surface protection for humans; and (2) lightweight radiation shielding materials systems for short term in-space operations for humans. Specific areas in which SBIR-developed technologies can contribute to NASA’s overall mission requirements for advanced radiation shielding materials and structures include, but are not limited to, the following:

- New and innovative lightweight radiation shielding materials and structures to shield humans in crew exploration vehicles, large space structures such as space stations, orbiters, landers, rovers, habitats (both rigid and inflatable concepts), spacesuits, etc. The materials emphasis is on non-parasitic radiation shielding materials, or multifunctional materials, where two of the functions are radiation shielding efficiency and structural integrity.
- Radiation laboratory and spaceflight data to validate the shielding effectiveness of radiation shielding materials and structures.
- Physical, mechanical, structural, and other relevant characterization data to validate and qualify multifunctional radiation shielding materials and structures.
- Comprehensive radiation shielding databases to enable designers to incorporate and optimize radiation shielding structural materials into space systems during all the design phases.
- New and innovative processing methods to produce quality-controlled advanced radiation shielding materials of all forms - resins, fibers, fabrics, foams, microcomposites and nanocomposites, fiber-reinforced composites, light alloys, and hybrid materials.
- New and innovative fabrication techniques to fabricate advanced radiation shielding materials into useful products and structural components.
New and innovative manufacturing techniques to produce quality-controlled advanced radiation shielding products and structural components, including innovative scale-up methods for producing quality-controlled viable quantities of advanced radiation shielding materials and structures.

New and innovative commercialization strategies to introduce advanced radiation shielding materials and structures into the marketplace to enable availability of the technologies for use by NASA and the space exploration community.

**X6.02 Lightweight Pressurized Structures Including Inflatables**

**Lead Center:** LaRC  
**Participating Center(s):** GRC, JPL, MSFC

This subtopic solicits innovative structural concepts that support the development of lightweight structures technologies that could be applicable to CEV, CLV and Lunar surface landers and habitats. The targeted innovative lightweight structures are for primary pressurized structures such as cryotanks and crewed vehicles (landers and habitats). Innovations in technology are needed to minimize launch mass and costs, and increase operational volume for minimal launch volumes while at the same time maintain required structural performance for loads and environments. Of particular interest are the following structural concepts:

- Cryotank structural systems that are low mass and minimize cryogen boil-off. These concepts can include new techniques in structural concepts, manufacturing, and incorporation of tank liners or innovative insulating materials that improve on SOA designs used today.
- Lightweight multifunctional structural systems that include radiation shielding, impact shielding, thermal management, damage tolerance and durability, and/or integral diagnostics/health monitoring capabilities are of interest if they can be developed to improve the efficiency (mass/performance) of the structural system over the parasitic systems used today.
- Inflatable structures are considered as viable technique to improve volume for crew in habitats and potentially other crewed vessels. However, areas of risk need to be mitigated to build confidence in the use of these structures. In particular, durability in the presence of micrometeoroid, orbital debris and crew load induced damage, radiation-shielding protection, equipment placement and tie down concepts, and efficient packaging concepts are of interest.

Development of concepts can include structural components, improved low cost manufacturing processes, methods of validation, and/or predictive analysis capabilities. Technological improvements that focus on risk reduction/mitigation, and development of reliable yet robust designs are also being sought under this announcement.

**X6.03 Material Concepts for Lightweight Structure Technology Development**

**Lead Center:** MSFC  
**Participating Center(s):** GRC, LaRC

This subtopic solicits innovative research for advanced material concepts that support the development of lightweight structures technologies that should be applicable for space transportation vehicle systems, propulsion systems, and planetary access and operations. Advanced materials are targeted that could be implemented into structural and propulsion systems for CEV, CLV and lunar mission vehicles, landers, and habitats. Innovations in technology are needed to increase specific strength and stiffness, provide radiation shielding, enable thermal management, and reduce Micrometeoroid/Orbital Debris (MMOD) damage potential while maintaining safety, reliability and reducing costs.
Advanced material systems and their corresponding manufacturing and processing techniques are desired. Examples would include, but are not limited to, advanced polymer matrix, ceramic matrix, and metal matrix composites; high performance metals material systems (e.g. advanced aluminum alloys, titanium alloys, super alloys, refractory alloys); hybrid material systems, multifunctional material systems, self-monitoring and self-healing material systems; and mature applications of nano-structured materials. Processing examples would include, but not limited to, composite fiber tape placement, non-autoclave curing, ceramic processing, freeform fabrication, bonding of composites, metallic thermal spray, and friction stir welding/processing.

Development of concepts can include material system characterization, methods of validation, and/or predictive analysis methods that improve understanding of the technology to reduce risk and need for conservatism in design and demonstration of integrated system performance. Damage tolerance is a specific area of interest to include analytical tools, non destructive evaluation technology and experimental techniques. NDE methods and techniques are needed to include 3D imaging and modeling of defects, and NDE technologies for determining early degradation of composites.

Operations of Exploration Equipment Topic X7

This call for technology development is in direct support of the Exploration Systems Mission Directorate (ESMD) Technology Development Program. The purpose of this research is to develop new technologies to support low-Earth orbit (LEO), robotic precursor, and human exploration missions, providing systems that interact with humans, handle surface equipment and move people and their payloads across planetary surfaces. The objective is to produce new technology that will reduce crew extra-vehicular activity (EVA) and intra-vehicular activity (IVA) workloads and risk in LEO, and Lunar operations and reduce the total mass and volume of equipment and materials required to support missions. The proposals should focus on technology to improve the operations of exploration equipment, allowing for less expensive, more productive and less risky missions. This research will provide technology for the critical functions that fall into three phases of surface exploration. The first phase of surface exploration will be functions that are needed prior to crew arriving at a site. These precursors may be hours, days, weeks or years ahead of the crew landing on the surface. The second phase of surface exploration will be during a crew's stay at the site. The third phase of surface exploration will include long-term maintenance of the facility, as well as supporting science performed between crews.

Sub Topics:

X7.01 Supportability Technologies for Long-Duration Space Missions

Lead Center: JSC
Participating Center(s): LaRC

The objective of this subtopic is to develop technologies that can support the goal of significantly reducing the mass and volume of material required to support long-duration human spaceflight missions. Eventually, as the distance of mission destinations increases, resupply will become impossible. Therefore, unless support materials are prepositioned, it will be necessary for all required materials to be transported with the crew. The difficulty presented by this situation is compounded by the need for more material as mission duration increases. Capabilities to address these issues should be developed and demonstrated in conjunction with long duration lunar missions and, as they reach sufficient maturity, will be valuable enhancements to these missions.

This subtopic seeks proposals addressing maintenance and repair technologies that enable repair of failed
hardware at all levels, technology that supports the production of replacement components during a mission, and technologies that reduce the quantity of material directly supporting the crew. Proposals are sought which address the following technology needs:

- **Compact, portable systems to generate reverse engineering data to support manufacturing of replacement items during a mission.** This will allow generation of a duplicate part based on an existing part if CAD models are not available.

- **Real-time non-destructive evaluation during layer-additive processing for on-the-fly quality control.** This will provide capabilities for in-process quality control and may serve as an input for closed-loop process control. Equipment should be portable, compact, and capable of integration with layer-additive manufacturing systems.

- **Non-destructive material property determination.** This will provide an in-process quality control capability to ensure that material deposited during layer-additive processing meets required material property criteria. Equipment should be portable, compact, and capable of integration with layer-additive manufacturing systems.

- **Recycling/generation of feedstock materials for deposition processes.** This will provide the capability to recycle failed parts and material removed from near-net-shape parts during machining operations to serve as feedstock material for subsequent layer-additive manufacturing. Initial focus should be placed on metallic materials. Additionally, emphasis should be placed on total system mass and volume.

- **Compact, portable multi-axis machining systems.** This will provide subtractive manufacturing capabilities to achieve final design dimensions and surface finishes following layer-additive processes that produce near-net-shape parts. Equipment to accomplish this should be of the minimum mass and volume possible while still providing required capabilities.

- **Compact, portable, vacuum-compatible multi-axis manipulator.** This will provide the capability for complex manipulation of the item itself, the processing equipment, or both during layer-additive manufacturing and machining. To be compatible with the widest variety of candidate processes, manipulation equipment should be vacuum compatible. Additionally, equipment to accomplish this should be of the minimum mass and volume possible while still providing required capabilities.

- **Laundry system.** This will provide the capability for extended reuse of crew clothing. Any laundry system must utilize a minimal amount of water or no water at all. Any water used should be easily recycled - either being reintroduced into the spacecraft water system or recycled internal to the laundry system. Additional emphasis should be placed on the mass and volume of the equipment and minimization of power requirements.

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**X7.02 Human-System Interaction**

**Lead Center:** JSC  
**Participating Center(s):** ARC, JPL, LaRC

The objective of this subtopic is to create an effective and efficient operational interface between a human and a robotic system that is supporting the human. This subtopic seeks to develop automation technology that reduces the risk of Extra-Vehicular Activity (EVA), improves the productivity of Intra-Vehicular Activity (IVA) and facilitates

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remote operations by both flight crew and ground control. Automation and robotics capabilities include the ability to use robots for operational tasks (assembly, maintenance, inspection, payload transport, etc.), real-time advisory systems that will support the space and lunar based crew, and mission operation concepts and systems that link ground supervisors across time delays to remote spacecraft and robots. Proposals are sought which address the following technology needs:

- Telepresence and variable autonomy teleoperation systems that support human and robot teams operating: (1) in a shared space, (2) close but separated, (3) somewhat remote, and far remote. Particular interest is given to systems that flexibly support human-robot operations in the presence of time-delays of up to 10 seconds.

- Software frameworks and interaction infrastructures that facilitate the creation and operation of joint human-agent teams. Conventional control architectures do not adequately address human-system interaction needs, particularly in terms of coordination, teaming, direct and indirect commanding, and information sharing between humans, robots, and distributed software agents. Of particular interest are extensions to existing NASA human-robot architectures and software frameworks including: automatic event and situation summarization, notification and dialogue based on user state (role, availability, location, interface), centralized task coordination/dispatch, user activity monitoring, and automated detection of domain events.

- Adaptive user interfaces including perception (visual gesturing), speech recognition, context awareness, computational cognitive models and/or collaborative 3D graphics, and EVA display devices (i.e., pressure-suit compatible devices and displays). Specific design objectives include enabling more natural interaction with autonomous systems, facilitating situational awareness, increasing overall productivity by reducing the amount of interaction effort the human has with the robot, and flexibly displaying multi-modal and mission-specific data.

- Embedded real-time advisory and action planning systems for fully autonomous integrated systems that support remote and onboard vehicle operations for the Crew Exploration Vehicle (CEV).

- Engineering systems that support flight demonstrations of dexterous robots working with EVA crew using CEV and ISS to prove capabilities for space and lunar operations. This will provide human, robotic and human-robot team options for dexterous EVA tasks, robotic EVA capabilities for excursions into high radiation fields beyond Low Earth Orbit (LEO), and the ability to respond to onboard situations with prompt EVA action.

- Accurate and affordable methods for prototyping and evaluating human-system interaction. This includes model-based simulation and trade studies for analyzing multiple interaction "dimensions" (spatial distribution, autonomy level, team makeup, task dependencies, etc.) and missions (pre-cursor robotic, short-stay sorties, and long-duration outpost).

- Vehicle control systems and navigation sensors that support on-board driving, teleoperation, and autonomous operations. Control systems should support multiple control modes, include activity monitoring and operator intent prediction, and tolerate up to 10 seconds of time-delay. Navigation sensors that utilize passive computer vision (real-time dense stereo, optical flow, etc.) and/or active illumination (for recognizing/tracking non-textured objects and operation in permanently shadowed regions) are of particular interest.
X7.03 Surface Handling and Mobility, Transportation, and Operations Equipment (Lunar or Mars)

Lead Center: JSC

Participating Center(s): ARC, GRC, JPL, LaRC

The objective of this subtopic is to provide new capabilities for delivery, handling, transfer, construction and repackaging of Extra Vehicular Activity (EVA) equipment and preparation of site infrastructure for lunar operations. This includes access/handling and transportation equipment/carriers for delivery and deployment of materials, components, and infrastructure; surface systems for site clearing, pad construction, and regolith manipulation; and commodities distribution systems (including umbilicals) for routing to equipment and infrastructure. These new capabilities are required to make planetary surface missions more reliable, safer, and affordable.

Several vehicle features will be critical to surface operations: expanded mobility, range and duration, life support recharge, crew following, automated path planning, automated driving, and obstacle avoidance. Vehicles with life support recharge capabilities will extend useful EVA time. The ability of a vehicle to follow a crewmember will enable science and exploration support equipment to be carried for the astronaut as well as extend the traverse distances. While the utility of autonomy is easily recognized when the crew is not on the surface, these functions could also be advantageous to long traverses and rescue or emergency operations when crewmembers are present.

Proposals are sought which address the following technology needs:

- Highly reliable and durable surface systems for site preparation, pad construction, site sampling and prospecting are needed for planetary exploration. Sample collection may require excavating, picking, and physical manipulation of materials, as well as tagging and transport to an analysis site. Emphasis will be placed on proposals that address both manned and unmanned vehicle control operating capabilities of the surface system.

- Flexible and adaptive systems to deploy and emplace site infrastructure, such as beacons for communication, survey, navigation, etc. Emphasis should be placed on developing lightweight, power-efficient manipulation devices (dexterous and non-dexterous) that can be deployed on small rovers and that are appropriate for multiple tasks. Much of this activity can be performed with teleoperated and semi-autonomous robots controlled from ground. Some of this activity, however, will also require human presence at the site. In both cases, the effectiveness of Human-Robot interaction (HRI) will have a major impact on the efficiency and productivity of mission operations.

- Access/handling and transportation equipment (including cargo carriers) for delivery and deployment of materials, components, and infrastructure. Vehicle systems that can self-deploy, that can function in rough and steep terrain, and that can controlled at various levels of autonomy are of particular interest.

- Commodities distribution systems (including umbilicals) for routing to equipment and infrastructure. Commodities distribution systems are necessary to interconnect distributed surface assets (e.g., access/handling and transportation equipment, launch and landing systems, communication relays, power plants) to support long-duration sorties and sequential mission architectures.

- Vehicle control architectures that support on-board driving, teleoperation, and autonomous operations. Particular emphasis is placed on architectures that can flexibly support and adapt to multiple control modes, that include activity monitoring and operator intent prediction, and that can tolerate up to 10 seconds of time-delay.

- Highly reliable, durable, and long-life systems (mechanical, electrical, software, power train, lubricants, etc). This includes design and implementation of integrated actuator, suspension and control avionics for surface vehicles and evaluation of test articles in field experiments (preferably in lunar analog
Energy Generation and Storage Topic X8

This topic intends to develop power capabilities that are on the critical path to enabling human exploration beyond Earth orbit. Areas of primary interest are: power generation/actuation for launch vehicles utilizing non-toxic fluids; orbital and planetary surface energy storage; and non-solar power generation. The Exploration Systems Assessment Study (ESAS) architecture desires nontoxic fluids to reduce ground processing facility requirements and to increase safety for the crew. Hydrazine (toxic) is currently used to drive the Solid Rocket Booster (SRB) and Space Shuttle Main Engine (SSME) Auxiliary Power Units (APUs), which in turn provide power for actuation for engine gimbal. Development efforts using nontoxic power generation for launch vehicles is required. ESAS architecture elements, including the Crew Exploration Vehicle (CEV), Lunar Surface Access Module (LSAM), robotic missions, and surface systems, require long-life/ high-capacity/high-density energy storage on the order of up to 10 kW. Lithium ion batteries are required to be human-rated at load profiles that are currently higher than state-of-the-art, and, are required to operate over a greater range of temperatures for the lunar environment. The ESAS architecture requires advanced fuel cells to meet LSAM and surface system design margins. Fuel cell systems provide power largely independent of environment (solar incidence), which allows greater mission flexibility and will typically provide larger power levels for less total mass for short-duration missions. The exploration architecture identifies permanent human lunar habitation shortly following a set of crewed sortie missions. The permanent habitation phase requires lunar night stays, extended EVAs, expanded science and surface operations and the utilization of ISRU to demonstrate and validate capabilities needed for Mars exploration. The expected power requirements will exceed that practically furnished by conventional technologies. The ESAS study identified surface nuclear fission systems to satisfy the power requirements for lunar extended stays, particularly at non-polar regions and nuclear power extensibility to Mars exploration.

Sub Topics:

X8.01 Non-Toxic Launch Vehicle Power for Thrust Vector and Engine Actuation

Lead Center: GRC
Participating Center(s): MSFC

The next generation of NASA launch vehicles and spacecraft will minimize the use of hydraulic power systems due to their inherent inefficiencies. These hydraulic systems will be replaced with all electric power components. NASA is interested in optimizing these electric components to maximize system reliability and efficiency while minimizing overall size and mass. Of particular need are electric actuation systems, including electromechanical (EMA) and electrohydrostatic (EHA). These are important in order to realize the full potential of the more electric power systems. The actuator systems will consist of both the actuator and associated controls. These systems will be used for a number of applications including thrust vector control, engine actuation and vehicle surface actuation. The technology would directly benefit programs such as Constellation which have a variety of requirements for the Crew Launch Vehicle, Cargo Launch Vehicle, Lunar Surface Access Module, and others. These systems may range from a few horsepower to greater than 50 horsepower, and the associated electronics may see temperature extremes up to 175°C. To make electric actuation a more viable option, improvements in mass, size, efficiency and power density are sought for both the actuator and associated controls. Current state-of-the-art actuators suitable for engine thrust vector control on a launch vehicle have a power density of 1kW/kg for duplex drives (two motors driving one transmission, not including inverters and controllers). Innovations are sought to increase this power density to at least twice the SOA. In addition, state-of-the-art controllers can be 20 - 50% of the actuator size and weight alone, therefore novel approaches to minimizing controller mass and volume are sought. Innovative approaches to redundant electric actuator systems and redundancy systems management will also be considered.
which would help reach the single fault tolerant vehicle requirements. Technologies of specific interest include:

- Lightweight, high power density electric actuators and controls in the 5 - 10 hp range for use on vehicles such as Crew Launch Vehicle and Earth Departure Stage, with an actuator density goal of 2kW/kg and controller density of at least 1.5 kW/kg;
- Lightweight, high power density electric actuators and controls suitable for 30 - 60 hp applications on vehicles such as Cargo Launch, with an actuator density goal of 2kW/kg and controller density of at least 1.5 kW/kg;
- Actuation and control technologies capable of operating over wide temperature ranges - up to a chassis temperature of 175°C;
- Novel redundant EA systems and redundancy management approaches for single fault-tolerant vehicle applications.

X8.02 Space Based Nuclear Fission Power Technologies

Lead Center: GRC

NASA is interested in the development of highly advanced systems, subsystems and components for use with fission power systems for future Lunar and Mars robotic and manned missions. Anticipated power levels range from 10's of kilowatts to 100's of kilowatts. Proposals are sought for critical technologies for fission power systems to meet the following anticipated missions and applications.

The current Vision for Exploration identifies the first human lunar landing in 2018 with subsequent long duration lunar stays of approximately 6 months in 2022. Fission-based systems are anticipated to enable the long duration stay over the lunar night. Initial planetary base power levels are anticipated to be between 30 - 50 kWe.

Planetary surface human base applications may include: habitats, resource processing and propellant production/liquefaction/maintenance, surface mobility for both robotic and piloted rovers, excavating and mining equipment and science stations. Human Mars mission activities could require power in the 100 kWe range.

Potentially, robotic outpost as a precursor to human Mars exploration with 50 - 500 day stays could be the proving ground for smaller fission systems. A 20 - 30 kWe system could support science applications such as: deep drilling, resource production demos, rovers, weather stations, etc.

Specific technology topics of interest are:
Advanced, high efficiency, high temperature power conversion > 20%, 25 kWe to 100 kWe unit size;

- Electrical power management, control and distribution. 1000 - 5000 V;
- High temperature, low mass thermal management/heat rejection 2;
- Deployment systems/mechanisms for large radiators, surface mobility systems for remote emplacement of power systems, innovative methodology for use of indigenous shielding materials;
- High temperature materials or coatings compatibility with local soil and atmospheric environments;
- Systems/technologies to mitigate planetary surface environments. Dust accumulation, wind, planetary atmospheres (CO\textsubscript{2}, corrosive soils, etc.);
- Power system design considerations for long life (> 5 years), autonomous control and operation, including sensor technologies;
- Radiation tolerant systems and materials (including lunar, Mars and in-space environments) for robust, long life operation;
- Innovative methodologies and approaches to accelerated life testing.

In addition to reducing overall system mass, volume and cost, increased safety and reliability are of extreme importance. It is envisioned that these technologies would be used on robotic and human missions and it is to NASA's advantage to develop those technologies that transcend robotic to human mission requirements with a minimum of redesign. Technologies that easily and efficiently scale in power output and can be used in a host of applications (high commonality) are desired.

X8.03 Space Rated Batteries and Fuel Cells for Surface Systems

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

Human-rated energy storage devices are required to enable future robotic and human exploration missions. Advanced battery, fuel cell and regenerative fuel cell systems are sought for use in a wide range of Exploration mission applications including portable power for landers, rovers, and astronaut equipment, and stationary energy storage applications such as base power, and storage systems for crew exploration vehicles and spacecraft. Technology advances that will reduce the weight and volume, improve the efficiency, life, safety, system simplicity and reliability of electrochemical systems, specifically rechargeable batteries and fuel cell systems are desired. The specific advancements of interest are outlined below.

Advanced Secondary Battery Systems

Areas of emphasis for advanced battery systems include technology advancements that contribute to the following cell-level performance goals: specific energy > 180 Wh/kg, calendar life >15 years, and operating temperature
range -60°C to 60°C and cycle life at 100% DOD > 2000 cycles. Systems that combine all of the above characteristics and demonstrate a high degree of safety are desired.

Specific technology areas sought are improved component materials that include non-toxic cathodes with specific capacities in excess of 250 mAh/g at the C rate and 25°C, and electrolytes that provide safe, non-flammable, non-hazardous operation. Cells that exhibit tolerance to mild abuse such as overcharge and over temperature are desirable. Chemistries and/or cell design capable of rapid recharge (Kanazawa and Kazuhisa, 1994).

Innovative concepts for the design and management of packaged battery modules with specific energy >140 Wh/kg and energy density > 300 Wh/l are of keen interest.

Proposals addressing micro-batteries, structural batteries, and/or integrated power generation and are sought.

**Fuel Cell Systems**

Fuel cell (FC) systems with power capabilities in the range of 100-1000 watts and 1-10 kW are of interest, as are regenerative fuel cell (RFC) energy storage systems in the 10 - 25 kW power range.

Specifically, technological advances are sought for FC/RFC based systems that contribute to system simplicity and improved reliability through (1) innovative, integrated system-level design concepts, and (2) passive ancillary components. An example of these advances at the system level is primary and/or regenerative fuel cell systems that minimize or eliminate reactant re-circulation external to the stacks themselves. Examples at the component level include replacement of pumps and other active, motorized mechanical ancillary components with passive devices that perform the functions of both reactant management and thermal control.

Advanced FC/RFC development at both the system and component levels should focus exclusively on proton-exchange-membrane PEM technology utilizing pure hydrogen, oxygen, and water as reactants.

**Propulsion and Propellant Storage Topic X9**

The Exploration Systems architecture presents some propulsion challenges that require new technologies to be
developed. Some of these technologies are affordable high reliability booster engines; long term cryogenic propellant storage, management, and acquisition; deep throttle cryogenic propellant space engines; cryogenic propellant reaction control engines; and non-toxic storable propellant space engines. Furthermore, specific technologies are required in valves, regulators, combustion devices, turbopumps, ignition, instrumentation, modeling, controls, materials and structures, pressurization, mass gauging, and cryogenic fluid management. The anticipated technologies to be proposed are expected to be capable of being made flight qualified and certified for the flight systems and dates to meet mission requirements.

Sub Topics:

X9.01 Long Term Cryogenic Propellant Storage, Management, and Acquisition

Lead Center: GRC

Participating Center(s): ARC, GSFC, JSC, MSFC

This subtopic includes technologies for long term cryogenic propellant storage, management and acquisition applications in-space as well as on the lunar surface. These technologies will impact cryogenic systems for space transportation orbit transfer vehicles, space power systems, spaceports, spacesuits, lunar habitation systems, robotics, and in situ propellant systems. Each of these applications has unique performance requirements that need to be met. The sizes of these systems range from the small (3 for supercritical air and payload cooling) to very large (> 3400 m$^3$ for LOX and LH$_2$ propellant storage). Advanced cryogenic technologies are being solicited for all these applications. Proposed technologies should offer enhanced safety, reliability, or economic efficiency over current state-of-the-art, or should feature enabling technologies to allow NASA to meet future space exploration goals.

Technology focus areas are divided as follows: fluid transfer/liquid acquisition devices, mass gauging/advanced instrumentation, passive systems, storage and distribution components, and refrigeration systems. Innovative concepts are requested for cryogenic insulation systems, fluid system components, and instrumentation. Cryogenic propellants such as hydrogen, methane, and oxygen are required for many current and future space missions. Operating efficiency and reliability of these cryogenic systems must be improved considering the launch environment, operations in a space environment, and system life, cost, and safety. This subtopic solicits unique and innovative concepts in the following technologies:

**Fluid Transfer/Liquid Acquisition Devices**

Liquid acquisition devices capable of preventing gas ingestion into engine feed lines in low gravity, analytical models of LAD’s to predict LAD performance in low gravity and to determine the effect of autogenous/non-autogenous pressurants on LAD wicking capability, techniques to minimize vaporization inside the LAD channel caused by incident heating through tank wall/lines and/or changes in tank pressure.

**Mass Gauging/Advanced Instrumentation**

Methods of determining liquid quantity gauging in propellant tanks in low gravity, high accuracy differential pressure transducers which can operate submerged in liquid cryogen and in-space fluid leak detectors.

**Passive Systems**

Advanced insulation technology including low loss cryogenic propellant tank penetrations and insulation materials capable of retaining structural integrity while accommodating large operating temperatures ranging from cryogenic to elevated temperature conditions, advanced tank support systems capable of supporting tanks during the launch environment, but decoupling on on-orbit to minimize thermal loads and passive thermal control designs for cryogenic fluid storage on the lunar surface.
Storage and Distribution Components

Advanced low-gravity submersible pumps and helium compressors designed specifically for in-space cryogenic operation, low heat leak cryogenic quick disconnects capable of sealing against the vacuum of space, long-life, low power valves for LO\textsubscript{2} and LH\textsubscript{2} capable of sealing at cryogenic temperatures, being cycled many times without consuming pressurant gas and with minimal thermal loss and pressure drop.

Refrigeration Systems

Advanced LO\textsubscript{2} and LH\textsubscript{2} cryocooler concepts for in-space operation that are reliable, lightweight, low input power and capable of removing 5 to 10 watts of heat at 77 K and at 20 K, respectively, concepts to integrate Broad Area Cooling (removing heat over large areas and long distances) into in-space storage of LO\textsubscript{2} and/or LH\textsubscript{2} and heat exchanger designs for large-scale storage systems designed densification of LO\textsubscript{2} and LH\textsubscript{2}.

X9.02 Innovative Booster Engine Manufacturing, Components, and Health Management

Lead Center: MSFC

The goal of this subtopic is the development of innovative components, manufacturing techniques, health management systems, and design and analysis tools for boost propulsion. Although solid or hybrid rocket propulsion is specifically emphasized, compelling proposals related to liquid engine boost propulsion are also invited. Technologies that would contribute to increased mass fraction and decreased sensitivity to manufacturing and handling effects are particularly welcome, as are those that would reduce the time, cost, and complexity associated with designing and manufacturing large booster rockets. Specific areas of interest include:

- Concepts for solid or hybrid propulsion systems and related components that would lead to increased payload mass fraction over current solid rocket motors;
- Concepts for solid or hybrid auxiliary propulsion systems that can be throttled to provide enhanced vehicle maneuverability;
- Health management technologies, including embedded sensors and modeling methodologies, that would improve the ability to monitor the reliability of solid or hybrid rockets during manufacturing, handling, and flight;
- Manufacturing techniques that allow for reductions in the cost and schedule required to fabricate and test solid or hybrid rockets;
- Propulsion system concepts, components, and fabrication processes designed to reduce the production costs of liquid propellant rocket engines for large expendable boosters;
- Improved design and analysis tools that enhance the engineering evaluation of advanced chemical propulsion system concepts;
• Test data that provides for validation of existing design and analysis tools; and

• New propellant ingredients or formulations that would increase the propellant specific impulse while maintaining a Department of Transportation Class 1.3 hazard classification. Proposals that would experimentally synthesize and characterize new ingredients, or formulate and demonstrate new propellants, are highly encouraged, whereas proposals that rely heavily on the screening of potential new ingredients by quantum chemistry or other computational and theoretical methods are discouraged.

Proposals that address more than one of these items are highly encouraged.

X9.03 Cryogenic and Non-Toxic Storable Propellant Space Engines

Lead Center: GRC

Participating Center(s): JSC

This subtopic intends to examine a range of key technology options associated with cryogenic and non-toxic storable propellant space engines. This engine technology is solicited for use in lieu of the toxic but currently operational nitrogen tetroxide and monomethylhydrazine engine technology, which has recently seen performance improvements from 310 to 325 seconds of specific impulse using advanced rhenium thrust chamber technology. Performance improvements are a consideration, but are not the main objective of this solicitation. The Space Shuttle Orbiter Upgrade Program identified non-toxic reaction control system (RCS) propulsion as a key technology to reduce vehicle operations costs on the ground, and estimated that a significant reduction in RCS propulsion system cost is possible by the use of non-toxic propellants. In addition, the use of astronaut extravehicular activity for in-space refueling of space systems or the refueling of vehicles with humans aboard such as the International Space Station is extremely hazardous with toxic propellants. These safety concerns drive mission planners to the use of more costly propulsion modules that are fueled and sealed on the ground.

The general objectives of this solicitation derive from the NASA goals of safe, reliable, affordable and effective human and robotic missions in support of the overall U.S. Vision for Space Exploration. Successful proposals will be focused investments that systematically validate and/or invalidate key technologies and design concepts that might transform how the U.S. will pursue future space exploration goals.

The specific technology to be supported by this subtopic is multi-use in-space cryogenic and non-toxic storable propellant rockets. This technology includes the development and demonstration of key operational and performance characteristics of a range of new space engines, i.e., orbit transfer, descent, ascent, and pulsing attitude control engines. These engines can be compatible with the future use of in situ propellants such as oxygen and hydrogen or methane, but propellants consistent with low cost ground operations such as ethanol, JP-5 and nitrous oxide and monopropellants are also solicited.

Proposals are solicited for both thruster development and thruster component technologies such as, but not limited to, long-life, highly reliable ignition systems, durable, low-mass propellant injectors, and long-life combustion chamber designs. Proposals are also solicited for propulsion system component technologies such as valves, instrumentation, controls, multi-purpose structures and both electric and turbine driven pumps. Examples include,
but are not limited to, highly-reliable, long-life, fast-acting cryogenic valves that tolerate high thermal loading due to heat soak-back in low-thrust, pulsing propulsion systems; cryogenic instrumentation such as pressure and temperature sensors that will operate for months/years instead of hours; and high-reliability, long-life turbopump bearings. Technologies are also solicited that enable deep-throttling turbopumps to operate at off-design flow coefficients while eliminating flow instabilities such as cavitating surge. Examples include, but are not limited to, inducer designs that can operate with a high degree of vapor content or cavitation in the propellant flow and pump diffusion systems with reduced sensitivity to flow separations. Strategies for engine and component protection from dust, radiation, and other environmental effects are also solicited. Finally, proposals are solicited for modeling efforts that enable reduced thruster development costs and schedules.

X9.04 Nuclear Thermal Propulsion

Lead Center: GRC
Participating Center(s): MSFC

NASA is interested in the development of critical technologies for first in-space applications of solid core nuclear thermal propulsion (NTP) systems for use in future human exploration missions. For short round trip missions to Mars, NTP systems may be enabling by helping to reduce launch mass to reasonable values and by also increasing the payload delivered for Mars human exploration missions.

Preliminary solid core NTP system concepts could be based on a high thrust/high Isp (~850 - 950s) NTP system that would use a fission reactor with U-235 fuel as its source of thermal energy. During the short primary propulsion maneuvers of a typical conceptual mission, large quantities of thermal power (100's of MWt) would be produced within the NTP system and removed using LH$_2$ propellant that is pumped through the engine's reactor core. The superheated hydrogen gas is then exhausted out the engine's nozzle to generate thrust. Representative ranges of engine performance include: (1) hydrogen exhaust temperatures ~2500 - 2900 K, (2) propellant flow rates ~7 - 13 kg/s, (3) chamber pressures ~500 - 1500 psi, and (4) nozzle expansion area ratio ~200:1 - 500:1.

Proposals are sought to further improve factors contributing to safety, performance, reliability, and life as well as reduce projected weight and costs for the first in-space NTP systems, subsystems, and components beyond that in previously achieved ground test systems. Proposals are solicited in the following key technology/concept areas:

- High temperature, low burn-up carbide- and ceramic-metallic (cermet)-based nuclear fuels with improved coatings and/or claddings to reduce fission product gas release into the engine's H$_2$ exhaust stream;
- Reliable, high temperature materials, fabrication techniques, and concepts for non-reactor portions of NTP systems;
- Light-weight, multi-use shielding materials and designs;
- High temperature, radiation tolerant instrumentation and avionics for engine health monitoring. Non-invasive designs for measuring neutron flux (outside of reactor), chamber temperature, operating pressure, and H$_2$ propellant flow rates over wide range of temperatures are desired;
• Long life, lightweight, reliable hydrogen turbopump designs and technologies;

• Lightweight, long life, high heat flux thrust chambers, regenerative-cooled nozzles and radiation-cooled skirt extensions that are compatible with hot hydrogen;

• Radiation tolerant materials compatible with above engine subsystem applications and operating environments.

Thermal Protection Topic X10

The Thermal Protection System (TPS) protects a spacecraft from the severe heating encountered during hypersonic flight through a planetary atmosphere. In general, there are two classes of TPS: reusable and ablative. Typically, reusable TPS applications are limited to relatively mild entry environments like that of Space Shuttle. No change in the mass or properties of the TPS material results from entry with a significant amount of energy being re-radiated from the heated surface and the remainder conducted into the TPS material. Typically, a surface coating with high emissivity (to maximize the amount of energy re-radiated) and with low surface catalycity (to minimize convective heating by suppressing surface recombination of dissociated boundary layer species) is employed. The primary insulation has low thermal conductivity to minimize the mass of material required to insulate the primary structure. Ablative TPS materials, in contrast, accommodate high heating rates and heat loads through phase change and mass loss. All NASA planetary entry probes to date have used ablative TPS. Most ablative TPS materials are reinforced composites employing organic resins as binders. When heated, the resin pyrolyzes producing gaseous products that are heated as they percolate toward the surface thus transferring some energy from the solid to the gas. Additionally, the injection of the pyrolysis gases into the boundary layer alters the boundary layer properties resulting in reduced convective heating. However, the gases may undergo chemical reactions with the boundary layer gases that could return heat to the surface. Furthermore, chemical reactions between the surface material and boundary layer species can result in consumption of the surface material leading to surface recession. Those reactions can be endothermic (vaporization, sublimation) or exothermic (oxidation) and will have an important impact on net energy to the surface. Clearly, in comparison to reusable TPS materials, the interaction of ablative TPS materials with the surrounding gas environment is much more complex as there are many more mechanisms to accommodate the entry heating. NASA has successfully tackled the complexity of thermal protection systems for numerous missions to inner and outer planets in our solar system in the past; the knowledge gained has been invaluable but incomplete. Future missions will be more demanding. For example, if existing materials were to be used for the proposed Mars Sample Return mission, the TPS mass fraction would be on the order of 40%. The potential savings that could be achieved with some investment in TPS technology development is sizeable.

Sub Topics:

X10.01 Ablative Thermal Protection System for CEV

Lead Center: ARC
Participating Center(s): JSC, LaRC

The Crew Exploration Vehicle (CEV) will first be used for transporting crew and cargo to the Space Station and later for the human exploration of the Moon and Mars. The Thermal Protection System (TPS) for the CEV will have to protect the crew and cargo from entry heating at entry velocities of approximately 8 km/s for Space Station missions, 11 km/s for lunar return missions, up to 8 km/s for Martian aerocapture and entry, and between 12 - 15 km/s for Martian return missions. Ablative TPS is an enabling technology for all CEV superorbital reentry missions.
Ablation Modeling

The heat shield for CEV will employ a TPS material that pyrolyzes and ablates at high temperature for mass-efficient rejection of the aerothermal heat load. Pyrolysis is an internal decomposition of the solid that releases gaseous species, whereas ablation is a combination of processes that consume heat shield surface material (including chemical reactions, melting, and vaporization). For the design and sizing of TPS materials, it is imperative to have reliable simulation tools that can compute surface recession rate, in-depth pyrolysis, and internal temperature histories under general heating conditions. In addition, lunar and Martian reentry environment heating will consist of significant radiation from the shock layer. The models need to include the effect of not only convective but radiative heating as well.

Therefore, advances are sought in modeling of radiation, gas surface interactions, ablation mechanisms, pyrolysis, and other processes such as coking and charring. Specifically for charring, advances are sought in the development of a low density charring ablator model to give insight into how conductivity changes as function of temperature and pressure for the virgin material and for the material as it pyrolyzes.

Instrumentation

TPS sensors and experimental diagnostic tools are required to provide traceability of TPS sizing tools, design, and material performance. Traceability will lead to higher fidelity design tools, which in turn will lead to risk reduction and decreased heat shield mass on missions requiring atmospheric aerocapture or entry/reentry. Decreasing heat shield mass will enable certain missions that are not otherwise feasible and directly increase payload. Heat flux sensors and surface recession diagnostic tools are essential to advancing the state of TPS traceability for material modeling and aerothermal simulation.

Advances in the understanding of how heat flux sensor performance changes upon integration of the sensors into TPS materials in ablative environments through simulation or experimental investigation are sought. Specifically, the following list of sensor materials is of primary interest:

- Type K, C, R, and S thermocouples
- Sapphire windows
- Inconel superalloys
- Pure platinum
- Teflon

For surface recession, advances in optical methods (photometrics/tomography) are sought.

Non-destructive Testing Techniques and Novel Techniques for Material Characterization
The CEV heat shield will be the largest ever built. During manufacturing and integration, it will be necessary to understand the variability in material properties, to determine voids and inclusions, to assess bondline integrity, and to ensure that the established flight heat shield requirements are met.

For this purpose, advances in NDE and proposals of novel techniques for material characterization applicable for ablative TPS are sought.

**Ablation Materials Development**

Early NASA missions employed new ablative TPS materials that were tailored to each specific entry environment. However, after Mars Viking, NASA-sponsored ablative TPS development essentially ceased as the research focus shifted to reusable TPS in support of the Space Shuttle. For example, the Pioneer Venus (1978) and Galileo (1995) missions employed carbon phenolic TPS material that had previously been developed by the United States Air Force for ballistic missile applications. Over the past 40 years, NASA has adopted a risk averse philosophy relative to TPS, i.e. use what was used before since it has been flight-qualified. For Mars Direct Return, the entry velocities will be in the range of 12-15 km/s. Heritage carbon phenolic can satisfy Mars Return requirements however the TPS mass fraction would be less than optimal. Thus, advances toward new reliable and efficient TPS materials are desired. Similarly, development of adhesives, joints, penetrations, and seals are of equal importance and advances are sought.

**Thermal Management Topic X11**

All spacecraft and extraterrestrial bases require thermal management systems. The long duration lunar bases that are foreseen in 15 years will present several challenges to the design and operation of active thermal control systems. Even though system design may be easier for the reduced gravity of the Moon than it is for the microgravity case of a spacecraft, the large variations in thermal environment and the risk of contamination by lunar dust will complicate system design. Innovative thermal systems and components are needed for this next phase of human space exploration.

**Sub Topics:**

**X11.01 Thermal Control for Lunar Surface Systems**

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

The lunar environment presents several challenges to the design and operation of active thermal control systems. During the Apollo program, landings were located and timed to occur at lunar twilight, resulting in a benign thermal environment. The long duration lunar bases that are foreseen in 15 years will see large variations in their thermal environment during the Moon’s day/night cycle. Long stays remote from low-Earth orbit will require lightweight, but
Innovative thermal management components and systems are needed to accomplish the rejection of heat from lunar bases. Advances are sought in the general areas of radiators, thermal control loops and equipment, heat pumps, and thermal storage devices.

For radiators on the Moon, lightweight deployable radiators are required that will operate at temperatures between 150 and 300K. Shading devices and strategies would allow them to reject more heat in the hot lunar environment. In addition, variable emissivity coatings would prevent freezing during the long, cold, lunar night. Also, the dusty environment of an active lunar base will require dust mitigation and removal techniques to maintain radiator performance over the long term.

Heat pumps (especially high lift) may be required for heat rejection in the lunar environment.

The lunar base active thermal control system will include high efficiency, long life mechanical pumps. Lightweight, high-performance thermal switches plus thermal energy storage and rejection devices could be used to accommodate the extremes of the available heat rejection. Part of the thermal control system in the lunar base is likely to be a condensing heat exchanger, which should be designed to preclude microbial growth.

Thermal management of the lunar habitat, landers, and rovers may require mechanically pumped two-phase fluid loops. Innovative design of the loops and components is needed.

A scaling methodology is needed to allow long term 1-g testing of two-phase systems (including pumped two-phase loops, heat pumps, and condensing heat exchangers) representative of the 1/6th Earth-normal gravity of the Moon.

Lightweight, low volume, robust Extravehicular Activity (EVA) systems are needed that maximize human productivity and improve the capability to perform useful work tasks on the lunar surface. Low-venting or non-venting regenerable support subsystem(s) are needed for crewmember cooling, heat rejection, and removal of expired water vapor. Lightweight and freezable radiators will be needed for thermal control. Innovative direct crewmember thermal control garments are sought, i.e., variable conductivity flexible suit layups that can function as a heat sink for high metabolic loads and as an insulator during period of low physical activity.
Space Human Factors and Food Systems Topic X12

The new Vision for Space Exploration encompasses needs for innovative technologies in the areas of Space Human Factors and Food Systems. Operations in confined, isolated, and foreign environments can lead to impairments of human performance and behavioral health problems. Furthermore, the development of new vehicles for the human exploration of space provides the ideal opportunity to build the human element into the man-machine system at the outset, greatly simplifying activities and reducing the overall costs to the program. Additionally, significant advancements in food technologies will be needed for long-duration missions for both Lunar and Mars missions. Subtopic X12.01 Food and Galley seeks innovative technologies for providing shelf-stable food with a shelf-life of 3 - 5 years, new food packaging technologies that eliminate or minimize waste, and new technologies for on-orbit meal preparation and dining. Subtopic X12.02 Space Human Factors seeks models for predicting human performance in flight environments and activities, tools for designing and evaluating human interfaces, just-in-time information tools to aid astronauts in routine and emergency operations, as well as acoustic monitoring and abatement technologies for in-flight use.

Subtopics:

**X12.01 Food Access Beyond Low Earth Orbit**

**Lead Center:** JSC

**Participating Center(s):** JSC

Exploration missions beyond low Earth orbit greatly limit allowable consumables and require development of innovative low maintenance, reconfigurable, reusable, or self-sufficient food production. Since regularly timed resupply will not be possible for a Mars mission, all the prepackaged shelf-stable food, ingredients, and equipment to provide a complete diet for six crewmembers for more than three years will have to be provided at the beginning of the mission. Advancements are necessary to develop a combination of extended duration shelf-life stored foods augmented with fresh foods.

Safe, nutritious, acceptable, and varied shelf-stable foods with a shelf life of 3 - 5 years will be required to support the crew during future exploration missions to the Moon or Mars. Development of shelf-stable food items that use high-quality ingredients is important to maintaining a healthy diet and the psychosocial well being of the crew. Shelf-life extension may be attained through new food preservation methods and/or packaging. Once on the lunar or planetary surface, it may be possible to use bulk packaging of meals or snack items. These food products will require specialized processing conditions and packaging materials.

Current food packaging technologies represent a potentially significant trash-management problem for exploration-class missions to the Moon or Mars. New food packaging technologies are needed that minimize waste by using high barrier packaging with less mass and volume and/or by using packaging. Another opportunity would be development of a packaging material that can readily be reused by the crew to make objects of value to the space flight mission. All packaging materials must have adequate oxygen and water barrier properties to maintain the foods’ 3 - 5 year shelf life.

Food preparation systems will be required to heat and rehydrate the shelf stable food items and to prepare meals from the processed and resupplied items. Technologies to support on-orbit crew meal storage, preparation, dining activities, and trash dispensing are being sought.

Food quality and safety are essential components in the maintenance of crew health and well-being. Efforts should be focused on control of food spoilage and food quality throughout the entire shelf life of the food. Effects of
radiation on the stored food system quality are also needed. Food quality and safety efforts should be focused on identification and control of microbial agents of food spoilage, including the development of countermeasures to ameliorate their effects through food processing and food packaging.

X12.02 Long-Duration Space Human Factors

Lead Center: JSC
Participating Center(s): ARC

The long-term goal of this subtopic is to enable planning, designing, training, and executing long-duration human space missions that are up to 5 years without re-supply and real-time communications to Earth. Specifically, the focus of this subtopic is on the development of innovative crew equipment, technologies for human performance assessment/modeling/enhancement, and design tools for engineers to incorporate human factors engineering requirements into hardware and software. Proposals that aim at developing and addressing the following specific technology needs are solicited.

Technologies are needed for monitoring and maintaining human performance non-intrusively. Specifically, the technologies we seek are (1) minimally invasive and un-obtrusive devices and techniques to monitor the behavior and performance (physical, cognitive, perceptual, etc.) of individuals and teams during long-duration space flights or analog missions, as well as (2) embedded measures to detect significant changes in crew readiness to perform physical or cognitive tasks.

Methods and models are needed for predicting human performance. The particular technologies we seek are (1) methods and models for predicting effects on physical performance by encumbrances of clothing, space suits, etc., (2) models for predicting effects of physical environment (e.g., lighting, noise, temperature, contaminants) on human performance, (3) models to simulate and optimize interactions between humans and equipment/vehicle, (4) capability to implement time-delay algorithm and functionality into simulations for higher fidelity and effectiveness, and (5) models for predicting performance due to the effects of cognitive changes.

Cost-effective and reliable tools are needed for aiding the design and evaluation of human-system interfaces for speed, accuracy, and acceptability. The particular tools we seek shall (1) provide automated analysis of computer-user interfaces for complex display systems to conduct objective review of displays and controls, (2) determine compliance with guidelines and standards, and/or (3) offer quantitative measures of the effectiveness of user interfaces for task-sensitive evaluations.

Tools are needed to facilitate user interface design for human computer interfaces, procedures, labels, and instructions. These tools shall assist the designer in incorporating contextual information such as the user's task, the user's knowledge, and the system's limitations.

Tools are needed to build just-in-time system and operational information software that aid human users to conduct routine and emergency operations and activities. Such tools shall be either (1) effective and efficient job aids (e.g.,
"intelligent" manuals, checklists, and warnings) to support designing flexible interfaces between users and large information systems, or (2) methods for developing "facilitators" (procedures, labels, etc.) adapted for developing space vehicle and payload applications.

Acoustic monitoring systems are needed to accurately and autonomously monitor acoustic sound pressure and noise exposure levels in long-duration space vehicles. These technologies shall provide (1) acoustic sensor systems consisting of fixed and/or crew-worn transducers, (2) sound pressure level information as a function of frequency and/or time, (3) typical sound level meter and acoustic dosimeter functionality, and (4) the capability for autonomous operations and data transfer. Operation and data acquisition parameters of such systems shall be controllable either by ground personnel or the crew.

Innovative acoustic flight materials are needed for noise abatement. These materials shall function as acoustic absorbers, barriers, vibration isolators, dampers, spacecraft wall treatments, transparent containment, or combinations of these. These materials must be shown to satisfy space flight material requirements, such as off-gassing and flammability, and shall be easy to apply to hardware. The acoustic properties of these materials' shall be demonstrated through absorption or transmission loss testing, or by other standard acoustic testing techniques.

Space Radiation Topic X13

The space radiation environment is very different from the terrestrial radiation environment. It includes high-energy protons from solar activity as well as energetic heavy ions from galactic cosmic sources and their secondaries generated in vehicle structures. The success of future human exploration missions, especially future missions beyond low Earth orbit will depend on technologies that will allow astronauts to safely live and work in the space radiation environment. Technologies that will allow NASA to measure the biological effects of the unique types of radiation in the space environment are necessary to elucidate the types of countermeasures that are required and their efficacy. Subtopic X13.01, Radiation Health, seeks innovative technologies for increasing the throughput and capabilities in heavy ion beam experiments for radiobiology at the Brookhaven National Laboratory, automated and high-throughput techniques for identifying small scale cellular radiation damage from protons or heavy ions, and radiation dosimeters for manned and unmanned spaceflight.

Sub Topics:

X13.01 Space Radiation Health Research Technology

Lead Center: JSC
Participating Center(s): ARC, LaRC

The goal of the NASA Space Radiation Research Program is to assure that we can safely live and work in the space radiation environment, anywhere, any time. Space radiation is distinct from terrestrial forms of radiation, being comprised of high-energy protons and heavy ions and their secondaries produced in shielding and tissue.
The Radiation Program Element uses the NASA Research Announcement as a primary means of soliciting research to reduce the uncertainties in risk projections, however, there are specific areas where the SBIR technologies can potentially contribute to NASA's overall goal:

**Ground-based Heavy Ion Accelerator Research Support Equipment**

NASA utilizes Facilities at Brookhaven National Laboratory (BNL) (for more information see [www.bnl.gov/medical/NASA/NSRL_description.asp](http://www.bnl.gov/medical/NASA/NSRL_description.asp)) to conduct fundamental radiobiology and physics experiments. However the Facilities at BNL were not developed with NASA's high number of investigators in mind, thus there are areas where technology developments can improve efficiency and throughput. Technologies of specific interest include, but are not limited to, the following:

- Advanced animal support equipment, sample holders, live imaging of samples on the beam line during heavy ion irradiation, or specimen transport systems that allow remote transport into and out of the target areas and precise positioning of specimens in the beam line with minimal human interaction in the target areas;
- Environmental control for cell studies while in the beam line, and automated fixation capabilities to perfuse small cell and tissue samples directly after exposure to the ion beam;
- Advanced detector systems to provide rapid assessments of elemental fluence spectra and neutron fluence spectra following heavy ion irradiation of biological or shielding samples.

**High Throughput Genomic Analysis Techniques**

Following low dose irradiation of cells by protons and heavy ions, damage is localized to only a very few cells. The ability to separate cells with or without genetic changes in an automated manner is of interest. Current technologies are inefficient in identifying small-scale genetic changes (less than several thousand base-pairs (Mbp)) under these conditions. Technologies of interest are:

- Complementary technologies to the fluorescence in situ hybridization (FISH) method used to score large scale (>1 Mbp) genetic changes to chromosomes following low dose irradiation in order to rapidly score small-scale genetic changes;
- Imaging techniques to rapidly identify with high accuracy undamaged cells from a cell population irradiated at low doses.

**Reliable Radiation Dosimeters for Manned and Unmanned Spaceflight**

Current environment dosimeters have exceeded their designed lifetimes and should be replaced. These include small active dosimeters to monitor individual astronauts’ exposure, Tissue Equivalent Proportional Counters (TEPC), Charged Particle Directional Spectrometer (CPDS) capable of internal and external deployment, and externally deployed electron and neutron detectors. New software needs to be fault tolerant and updated to current operating systems, new hardware and software must be fully documented (schematics, etc.). Areas of interest are:
Advanced spaceflight detector systems to provide reliable environment data for a specific spectrum of energies, including real time dosimetry providing dose and particle types, and energies and cumulative dosimeters, for characterizing space environments for use onboard spacecraft and planetary surfaces, as well as alarm systems for Solar Particle Events. Dosimeters should provide time resolved linear energy transfer (LET) data and have embedded LET-based quality factor algorithms for determining dose equivalent. The expected radiation environment includes protons from 10 MeV to 1 GeV, electrons from .5 Mev to 7 Mev, primary and secondary HZEs (He to Fe) from 10 MeV/amu to 1 Gev/amu and secondary neutrons from 1 Mev to 200 Mev. NASA acknowledges the difficulty in measuring secondary neutrons from interactions of protons and heavy ions with spacecraft structures and has particular interest in this area.

Exploration Medical Capabilities Topic X14

Human exploration capabilities must keep the crew healthy so they can adequately perform their mission and return safely to Earth. These two subtopics seek innovative technologies in Human Health Countermeasures and Autonomous Medical Care to prevent degradations in performance and health from the adverse physiological responses to the space flight environment and to provide medical support in both normal activities and medical emergencies. They assure that there will be no long-term adverse health consequences while supporting a healthy and productive sustained human presence. The Lunar In Situ Autonomous Health Monitoring (X14.02) subtopic seeks an innovative multiparameter monitoring system suitable for monitoring astronaut health during Extravehicular Activity on the lunar surface which can also find use in intravehicular medical monitoring and care. The Health Preservation in the Space Environment (X14.01) subtopic seeks either an instrumented treadmill or resistance exercise system suitable for flight mission and ground research use, a method for monitoring the effectiveness of pharmaceuticals in space, instrumentation for non-invasive measurement of intracranial pressure during space flight, or a non-invasive method for assessing strength via micro- and macro-architecture.

Sub Topics:

X14.01 Health Preservation in the Space Environment

Lead Center: JSC

Participating Center(s): ARC, GRC

Living and functioning efficiently and safely in space and in the hypogravity of the Moon (1/6g) or Mars (3/8g), requires an understanding of the effects of micro- and hypogravity and other space-environment related factors on human physiology responses and adaptations to a unique set of imposed demands. As a result, a variety of countermeasures are needed to mitigate the deleterious changes that occur during space flight and upon subsequent exposure to reduced-gravitational environments. The ability to monitor the effectiveness of countermeasures and alterations in human physiology during space exploration missions, particularly when several countermeasures are used concurrently, is equally important.

This subtopic seeks innovative technologies in several very specific key areas. As launch costs relate directly to mass and volume, instruments and sensors must be small and lightweight with an emphasis on multi-functional capabilities. Low power consumption is a major factor, as are design enhancements to improve the operation, design reliability, and maintainability of these instruments in the environment of space and on planetary surfaces. As the efficient use of time is extremely important, innovative instrumentation setup, ease of usage, improved astronaut (patient) comfort, noninvasive sensors, and easy-to-read information displays are also very important considerations. Extended shelf-life and ambient storage conditions of consumables are also key necessities. Ability
to operate in 0g, 1/6g, and 3/8g become more important as we march towards human Moon and Mars missions.

**Exercise and Related Hardware**

Miniaturized exercise hardware (treadmill or resistance exercise); physiological monitoring devices; and metabolic gas (carbon dioxide, oxygen) analysis systems for use with exercise and miniaturized interactive feedback and entertainment systems. A tool or toolkit should simulate and visualize the exercise device design and performance. A comprehensive, scaled 3D/virtual human model interface would be valuable to show biomechanical and kinetic effects of the exercise device. Relative physiological data from anthropometry to stress/fatigue to trauma/insult onset should be targeted.

**Noninvasive Pharmacotherapy and Monitoring**

Development of innovative technologies resulting in noninvasive methods for diagnosis, treatment, and therapeutic drug monitoring is needed to facilitate effective pharmacotherapy of humans in space. Many questions remain about the effectiveness of pharmaceuticals in micro- and hypogravity environments, which may interfere with their activity by sensitizing or desensitizing the crew member or interfering in other ways with the desired physiological effect. Micro-encapsulation of drugs and development of novel drug delivery systems under micro- and hypogravity conditions. Devices for continual monitoring of physiology during pharmacotherapy would also be advantageous to ensure that on-orbit expression of therapies relates to on-earth histories.

**Instrumentation for Noninvasive Measurement of Intracranial Pressure During Space Flight**

Abrupt transitions between differing gravitational environments have profound physiologic impacts on human space travelers. For instance, immediately following insertion of the spacecraft into Earth orbit, cephalad fluid shifting occurs. Over the next several days, all crewmembers onboard suffer from what has been termed Space Adaptation Syndrome (SAS) that varies in severity from person to person. The prevailing theory for the appearance of the constellation of symptoms (headache, malaise, vomiting, vertigo, etc.) which comprise this syndrome implicates a "sensory conflict" in information provided by the adapting vestibular system and by visual inputs. Another theory implicates the increased intracranial pressure (ICP) that likely accompanies the cephalad fluid shifts in the genesis of SAS. Additionally, decreased ICP following return to Earth's gravity may explain symptoms experienced by many crewmembers. Thus, novel approaches to noninvasive measurement of ICP are needed to determine the etiology and pathogenesis of the untoward physiologic effects that plague human space travelers during abrupt transitions between different gravitational environments. A more complete understanding of these phenomena will lead to better prevention and treatment modalities that will in turn decrease risks to the health and performance of crewmembers during transitional periods of both high to low and low to high gravity environments.

**Noninvasive Technology to Assess Bone Micro- and Macroarchitecture**

A complete assessment of bone strength will better monitor life-time skeletal integrity and will generate data critical for developing probability fracture risk models in younger crew members. Novel technology for non-invasive assessments of "bone quality" indices such as microarchitecture, macroarchitecture and trabecular bone mineral density (BMD).
Exploration missions to the lunar surface will be characterized by science goals and objectives which will require
crewmembers to actively investigate the accessible exterior environment via Extravehicular Activity (EVA). During
the EVA sorties, it will be critical for the crewmembers to be able to monitor their personal health status and to
make decisions based on feedback from intrinsic biomedical monitoring systems. Furthermore, it will be necessary
to simplify these systems for rapid donning and doffing, automatic checkout capability, annunciation and guidance
during suit anomalies, and ensuring the health and safety of each crewmember. Therefore, the sensors that will be
used for biomedical monitoring need to be low profile (perhaps incorporated into an undergarment), accurate,
reliable, and with as few wires as possible. In addition, the use of electrodes with electrode gel and overtapes has
not been highly successful, resulting in skin irritation, adhesion problems, stowage concerns and limited
life/inventory issues. Furthermore, our experience has demonstrated that commonality between and among
systems is highly beneficial. For this reason, the biomedical sensors used for monitoring EVA should be applicable
for intravehicular use as well. Some of the parameters that would be desirable for EVA monitoring include:

- Metabolic Rate
- Heart Rate
- Thermal Control
- ECG (possible)
- Oxygen Consumption Rate
- CO₂ Level (in the oronasal area)
- CO₂ Generation Rate
- Core and/or Skin Temperature
- Radiation Monitoring (possible)
- Oxygen Saturation Level

In addition, development of device(s) capable of being used in an IVA system which is common with the EVA
system is highly desirable. All of these, whether used for IVA or EVA, must be comfortable for the crewmember,
allow the crewmember to continue performing tasks, and must not preclude normal activities when used for IVA
monitoring (e.g. hygiene, eating, working at the computer, and exercising).
Full Data Coherency Systems for Engineering Systems Modeling and Simulation Topic X1.01
In addressing the accuracy of analysis results, which are used to make program/project decisions, we typically assess the data, the models/simulations, and the analysts. This subtopic area will address the first of these concerns. Verification and validation approaches typically address the validity of the data used to perform the analysis. However, they do not address the issue associated with data cohesiveness and consistency. An issue in the development of integrated modeling/simulation for complex engineering systems arises when information is fed to the models with inconsistent coherency, where “coherency” is defined as appropriate versions, semantics/syntax, abstraction/resolution, and sequence. When, for example, serial/parallel simulations are run with revised input data from one source, other sources may or may not need to be held constant; similarly, input data of varying heritage, semantics, resolution, etc., may result in unexpected and inaccurate simulations. Proposals are sought for systems that manage full data coherency (not just version or sequence control) in modeling and simulation environments.

Sub Topics:
  System Lifecycle Integration of Cost and Risk Models Topic X1.02
Traditional, and at times typical, analysis of new systems involves an assessment of the system's performance independent of the cost and risk associated with the design. Specifically, the cost and risk are assessed after the design, requiring integration “after the fact”. The SE&I process, however, requires a balancing of cost, risk and performance throughout a system's lifecycle. An additional challenge associated with this subtopic area is the use of cost and risk techniques early in the design process where there exists little data (i.e., performance, cost, and risk) from which to draw upon for developing the cost/risk algorithms, associated relationships, and verification/validation artifacts. An approach for integrating cost and risk models early in the assessment, ensuring that they drive the design and not vice-versa, is required to address the challenges in the agency. Proposals are sought to address: (1) the integration of cost and risk models into a seamless integrated solution; (2) the early application of cost and risk modeling into the analysis cycle of a system; and (3) the approach to verification and validation of the integrated cost/risk models.

Sub Topics:
  Integrated Systems Health Management Topic X2.01
In order to increase the safety and effectiveness of future spacecraft and launch vehicles, innovative health management technologies are required throughout the system lifecycle including design, development, test, validation, integration, operation, maintenance, and disposition. Traditional means of supporting vehicle health, such as invasive inspections, are extremely limited in their utility for exploration missions. Other solutions, such as ground-based monitoring of telemetry data, become less useful as communication delays or bottlenecks increase. Under these circumstances, autonomous and automated solutions to systems health management provide the best means of increasing crew safety and mission success probability for future space exploration missions.
Another significant concern is the high cost of ground and mission operations. Future ground operations will require quick and efficient turnaround and processing of spacecraft for launch. In addition, new mission operations concepts must be developed to provide appropriate levels of safety and mission success factors while reducing support staff.

Proposals should be responsive to the overall goals and objectives of NASA’s Constellation and Lunar Precursor and Robotic Programs. Proposals may address specific vehicle health management capabilities required for exploration system elements (crewed spacecraft, launch systems, habitats, rovers, etc.). In addition, projects may focus on one or more relevant subsystems such as propulsion, structures, thermal protection systems, power, avionics, life support, and communications. Proposals that involve the use of existing NASA health management testbeds (power, propulsion, systems integration, life support, diagnostics, networking, etc.) for technology validation are strongly encouraged.

Specific technical areas of interest related to integrated systems health management include the following:

- Methods and tools to enable concurrent design of system function and health management systems. These methods and tools should provide a means to optimize health management system design at the functional level to decide on failure detection methods, sensor types and locations, and identify additional functionality to safeguard against failures before costly design decisions have been made.

- Health monitoring and management technologies for increased situational awareness of system health, safety, and margins. Of special interest are innovative methods for sensor validation, robust state estimation, and model-based methods for fault isolation. Proposals should focus on data analysis and interpretation rather than development of new sensors.

- Data-driven methods for detection of failure precursors and recognition of anomalous patterns in large data sets. A specific emphasis is on methods that utilize propulsion system data sets.

- Concepts for advanced built-in-tests for spacecraft avionics that reduce or eliminate the need for extensive functional verification. Methods for reducing or disambiguating false alarms on built-in-tests are also of interest.

- Methods for robust control of critical components, subsystems, and systems and robust execution of critical sequences during flight. Of special interest are robust recovery methods and innovative approaches to functional redundancy for the purpose of enhancing safety, availability, and maintainability.

- Prognostic techniques able to anticipate system degradation and enable further improvements in mission success probability, operational effectiveness, and automated recovery of function. Proposals in this area should focus on systems and components commonly found in spacecraft.

- Human-system integration methods that are capable of summarizing sensor readings, presenting system status, assessing spacecraft capability and mission readiness, and proposing corrective actions in a manner that does not exceed the capacity of human understanding, especially in high-risk situations requiring rapid human response. Innovative ways for the health management system to convey a wealth of information quickly and effectively are desired.
Automated and autonomy techniques are key elements in realizing the vision for space exploration. Intelligent automation of systems on crewed vehicles is instrumental for decreasing workload, reducing dependence on Earth-based support staff, enhancing response time, and reducing operations cost. Increased system autonomy for unmanned and manned vehicles reduces operations costs, while increasing operations efficiency and spacecraft capability by reducing the time required for humans to staff flight control positions and interact with the vehicles. To enable the application of intelligent automation and autonomy techniques, configuration and validation issues need to be addressed.

Reusable automation software must be adaptable to new applications without undue difficulty, and easily adjusted as the application operations change. The overhead of applying automation techniques to new applications is one of the two key obstacles to acceptance of such techniques in operations. A variation of the same issue is that of adjustment as requirements and application contexts change, which is inevitable in spacecraft operations.

The software and the adaptation to a given application must also be trusted before it can be accepted. Testing and other techniques are keys to establishing such trust and ensuring the correct function of automation systems. However, in both testing and validation, the complexity of intelligent software has proven to be a major obstacle. This has led to trust and correctness issues being another key obstacle to adoption of intelligent automation systems in both unmanned, and most importantly, in crewed vehicles.

Proposals in this area should include autonomy and automation software architectures that facilitate adaptation and ensure correctness. Specifically, proposals in the following technical areas are of high interest:

- Architectures for decision-making and closed-loop control that can be adapted to new applications with minimal reliance on intelligent systems expertise;
- Methodology and techniques for adapting autonomy software to applications, as well as for reconfiguring the software in response to changes;
- Representation and reasoning techniques for specifying properties for application interfaces, operations flight rules and autonomy software behaviors, and for deriving overall properties for autonomy software applications.
Many of the capabilities needed for successful human exploration of space will rely on software. In addition to traditional capabilities, such as GNC (guidance, navigation, and control) or C&DH (command and data handling), new capabilities are under development: integrated vehicle health management, autonomous vehicle-centered operations, automated mission operations, and further out - mixed human-robotic teams to accomplish mission objectives. Ensuring that these capabilities are reliable, and can be developed and maintained affordably, will be challenging but critical to NASA’s exploration objectives. Proposals should clearly indicate how the technology is expected to address the challenge of reliability and affordability. Mission phases that can be addressed include not only the software life-cycle (requirement engineering through verification and validation) but also upstream activities (e.g., mission planning that incorporates trade-space for software-based capabilities) and post-deployment (e.g., new approaches for computing fault tolerance, rapid reconfiguration, and certification of mission-critical software systems).

Software engineering tools and methods that address reliability for exploration missions are sought. Projects can address technology development and maturation that provide for the following and related capabilities:

- Automated software generation methods from engineering models that are highly reliable;
- Scalable verification technology for complex mission software, e.g., model-checking technology that addresses the 'state explosion' problem and static-analysis technology that addresses mission-critical properties at the system level;
- Automated testing that ensures coverage targeted both at the system level and software level, such as model-based testing where test-case generation and test monitoring are done automatically from system-level models;
- Technology for calibrating software-based simulators and test-beds against high-fidelity hardware-in-the-loop test-beds in order to achieve dependable test coverage;
- Technology for verifying and validating autonomy capabilities including intelligent execution systems, model-based diagnosis, and ISHM;
- Software-based radiation fault tolerance for computation;
- Methods and tools for development and validation of autonomic software systems (systems that are self protecting and self healing).

Sub Topics:
- Low Temperature, Radiation Hardened Avionics Topic X2.04
Moon equatorial regions experience wide temperature swings from -180°C to +130°C during the lunar day/night cycle, and the sustained temperature at the shadowed regions of lunar poles can be as low as -230°C. Mars diurnal temperature changes from about -120°C to +20°C. All exploration endeavors, including robotic, habitat, and ISRU systems that are expected to reliably operate on the Moon or Mars surface for years will need electronics that are able to survive and operate in a wide temperature range and thermal-cycling environment. In addition, the electronics must operate reliably after a total ionizing dose (TID) \( \geq 50 \) krads (Si) and provide single-event latchup immunity (SEL) \( \geq 100 \) MeV cm\(^2\)/mg. The lunar and Martian temperatures are well outside the specification range of military and commercial electronics. While many types of devices, especially Si CMOS transistors, can operate down to low temperatures, there are significant circuit design challenges that need to be addressed, especially in the case of mixed-signal and analog circuits.
In addition, thermal cycling present in lunar and especially Mars environments introduces reliability concerns associated with mechanical stress and fatigue of the IC package. For example, compounds optimized for Earth-like packaging of electronic systems have glass transition temperatures that are within the cycling range of these environments, and cycling of electronic systems packaged using these materials will likely result in package failures. Hence, the choice of packaging technology and material combination used is extremely critical for these missions.

Proposals are sought in the following specific areas:

- **Wide temperature (-180°C to +130°C) and low-temperature (-230°C), radiation-tolerant and SEL immune, low power, mixed-signal circuits including analog-to-digital converters, digital-to-analog converters, low-noise pre-amplifiers, voltage and current references, multiplexers, power switches, microcontrollers, and integrated command/control/drive electronics for sensors, actuators, and communications transponders.**

- **High-density packaging able to survive large numbers of thermal cycles (hundreds) and tolerant of the extreme temperatures of the Moon and Mars, including appropriate selection of packaging materials combinations (substrates, die-attach, encapsulants, etc.) modular system level electronics packaging, including power, command and control, and processing functions, enabling integration of electronics with sensors and actuators elements.**

- **Radiation-tolerant, SEL immune, wide temperature (-180°C to +130°C), and ultra-low temperature (-230°C) RF electronics for short range and long-range communication systems.**

- **Computer Aided Design (CAD) tools for predicting the electrical performance, reliability, and life cycle for low-temperature electronic systems and components.**

- **Physics-based transistor device models valid at temperature ranging from -230°C to +130°C to enable design, verification and fabrication of custom low power mixed-signal and analog circuits.**

- **Low-temperature (-230°C) circuit design methodologies facilitating novel layout designs for integrated mixed-signal and analog circuits.**

Research should be conducted to demonstrate technical feasibility during Phase 1 and show a path toward a Phase 2 hardware/software demonstration, and when possible, deliver a demonstration unit for functional and environmental testing at the completion of the Phase 2 contract.
Spacecraft Cabin Atmospheric Management and Habitation Systems Topic X3.01

Atmospheric management and habitation systems supporting critical needs for lunar mission architectures are requested. Vehicles and habitats are expected to be significantly restricted with respect to habitable volume and may operate at reduced atmospheric pressure with elevated oxygen concentrations. Improved non-regenerative and regenerative processes technologies for atmospheric quality control must be developed. The ability to economically supply atmospheric gases and refill storage tanks in flight will be needed. Isolating habitable volumes from surface dust and disposing of accumulated particulate matter will be challenges. Habitation systems must be innovative, extremely space efficient, and re-configurable (dual or multi-use).

**Atmospheric Management**

Atmospheric management encompasses the range of process technologies and equipment to remove impurities and condition crewed spacecraft and habitat cabin atmospheres, supply and store atmospheric gases, and achieve mass closure by recycling resources and using in situ resources. Process technologies typically involve separations and reactions. Separations-based processes include physical adsorption, absorption, and mechanical filtration processes. Reaction based processes include chemical adsorption, oxidation, and reduction. Techniques for enhancing NASA’s present capabilities are sought. Areas of emphasis include:

- **Atmospheric Purification and Conditioning**: Process technologies for single and dual function atmospheric purification and conditioning based on novel embodiments of commercially available adsorbent, chemisorbent, and catalyst media are required. Novel engineered media substrates to enhance durability, energy efficiency, and mass transfer leading to increased reliability, functional capacity, and smaller size relative to NASA’s existing experience are sought. Specific challenges exist for efficiently removing ammonia, formaldehyde, and carbon monoxide from cabin atmospheric gases using process technologies that can be regenerated in place. Process technologies for removing and sequestering carbon dioxide from cabin atmospheric gases via means other than adsorption or chemisorption and conditioning carbon dioxide for use in reduction processes to facilitate cabin mass balance closure are also of interest.

- **Supply and Store Atmospheric Gases**: Novel means for supplying and storing oxygen and nitrogen under sub-critical conditions that lead to enhancements in energy efficiency, reduced mass and volume, and mission flexibility are sought.

- **Recycle Resources and Use In Situ Resources**: Novel means for supplying atmospheric gases using gas purification process waste products or means to more directly couple carbon dioxide and moisture removal to extract usable oxygen are sought.

**Dust Control and Abatement**

Dust and particulate matter contamination are challenges that must be overcome for lunar and Mars surface exploration. Particulate contamination originating from the external surface environment or from internal sources are both of concern. Development of regenerable process technologies and equipment to minimize the impacts of surface dust on crew health and life support equipment are sought. Novel approaches to isolate habitable volumes from surface dust and to remove dust from the spacecraft atmosphere, space suits and equipment are sought. Candidate technology solutions should provide high efficiency, long-lived removal capacity and be amenable to regeneration in place. Areas of emphasis include:

- **Particulate Matter Removal and Disposal**: Process technologies for removing and disposing of surface dust and particulate matter are sought. Salient features for this application include capability for regeneration in place, long-lived removal capacity and high efficiency.

- **Isolation Technologies**: Process technologies and design concepts to isolate habitable volumes from surface dust are sought. Such process technologies and design concepts may employ a variety of techniques to prevent surface dust from being transported through an airlock into the habitable part of the spacecraft or habitat cabin.

**Habitation Systems**

Habitation systems include crew accommodations, provisions, housekeeping and crew interfaces with vehicle systems including life support. Products can include applied research, system analysis, mockup evaluation, functionality demonstrations/tests, and actual prototype hardware. Proposals may address the following considerations and themes: re-configurable crew volumes and work stations for multi-gravity environments (micro and reduced gravity), multi-use work stations, multi-gravity translation strategies, physically and psychologically
ergonomic personal volumes, automated deployment, quiescent operations between missions, multi-purpose stowage systems, advanced hygiene systems, automated housekeeping, and commonality of hardware/systems.

Specific areas in which advanced habitability system innovations are solicited include:

- **Crew Hygiene Systems**: Low maintenance/self-cleaning fecal, urine, menstrual, emesis, hand/body wash, and grooming systems. Specific areas include non-foaming separators and no-rinse/non-alcohol hygiene products. Toilet systems should consider air, liquid, vacuum, and low-gravity transport methods. Collected waste should be prepared for recovery or long-term stabilization. Integrated hygiene systems should provide acoustic and odor isolated private crew volumes compatible with multi-gravity interfaces.

- **Crew Accommodation Systems**: Reconfigurable, deployable, erectable, or inflatable integrated crew accommodations that support crew wardroom, dining, conference, sleeping, relaxation activities and or stowage. May include visual and acoustical isolation, illumination, quiet ventilation/thermal control, audiovisual communication/entertainment, and off-nominal uses (emergency medical or repair) while maintaining hygienic conditions. Stowage systems may include interior/exterior stowage systems for partial gravity environments that maximize usable volume and include contents identification and inventory control systems.

- **Clothing Systems**: Low mass reusable or long usage clothing options that meet flammability, out gassing, and crew comfort requirements. Cleaning and drying systems for re-use of clothing that have low-water usage, non-toxic cleaning agents compatible with physicochemical or biological water reclamation systems, or that do not require water.

**Sub Topics:**

**Water Processing and Waste Management Topic X3.02**

Advanced life support systems will be essential to enable human planetary exploration as outlined in the Vision for Space Exploration. These future systems must provide additional mass balance closure to further reduce logistics requirements and to promote self-sufficiency. Requirements include safe operability in micro- and partial-gravity as well as ambient and reduced-pressure environments, high reliability, regeneration, minimal use of expendables, ease of maintenance, and low system volume, mass and power. Proposals should explicitly describe how the work is expected to improve power, volume, mass, logistics, crew time, safety and/or reliability, giving comparisons to existing state-of-the art technologies. Although this solicitation is directed at technologies for lunar missions, crosscutting technologies that are also applicable to human missions to Mars or that are compatible with both partial and microgravity environments may be of interest. Technologies that perform several functions or that eliminate the need for intermediate processing steps are also of interest. Additional documentation and information can be found at [http://advlifesupport.jsc.nasa.gov](http://advlifesupport.jsc.nasa.gov) [1], including the expected composition of solid wastes and wastewater which can be found within the "Baseline Values and Assumptions Document".

**Water Reclamation**

Efficient, direct treatment of wastewater and product water consisting of urine, wash water, humidity condensate, and/or product water derived from in situ planetary resources to produce potable and hygiene water supplies. Treatment methods for long duration lunar surface missions should seek higher levels of mass closure. Treatment methods for short-to-moderate duration lunar missions (several weeks to several months) may have lower recovery rates.

- **Stowable small-scale gravity-independent water treatment units** for contingency or back up use for treatment of condensate, contaminated potable water or wastewater, which may incorporate flow-through units such as ion exchange, adsorption, multi-filtration and/or osmotic filtration;

- Disinfection and residual disinfectant technologies for potable water storage and point-of-use that are compatible with wastewater processing systems including biological treatment;

- Techniques to minimize or eliminate biofilms, microbial contamination and/or solids precipitation from potable water, wastewater and water treatment system components such as pipes, tanks, flow meters, check valves, regulators, etc.;

- Physicochemical methods for primary wastewater treatment to reduce total organic carbon from 1000 mg/L to less than 50 mg/L and/or total dissolved solids from 1000 mg/L to less than 100 mg/L; and

- Post-treatment methods to reduce total organic carbon from 100 mg/L to less than 0.25 mg/L in the
presence of 50 mg/L bicarbonate ions, 25 mg/L ammonium ions and 25 ppm other inorganic ions.

Solid Waste Management
Wastes (trash, food packaging, feces, paper, tape, filters, water brines, clothing, hygiene wipes, etc.) must be managed to protect crew health, safety, and quality of life, to avoid harmful contamination of planetary surfaces, and to recover useful resources. Areas of emphasis include:

- Volume reduction of wet and dry solid wastes;
- Small and compact fecal collection and/or treatment systems;
- Water recovery from wet wastes (including human fecal wastes, food packaging, brines, etc.);
- Stabilization, sterilization, and/or microbial control technologies to minimize or eliminate biological hazards associated with waste;
- Mineralization of wastes (especially fecal) to ash and simple volatile compounds (e.g. carbon dioxide and water);
- Containment of solid waste onboard spacecraft that incorporates odor abatement technology;
- Partial-gravity containment devices or systems with low volume and mass that can maintain isolation of disposed waste on planetary surfaces; and
- Microgravity-compatible technologies for the containment and jettison of solid wastes in space.

Water Recovery from Byproducts of Water and Waste Processing - Brines and Slurries
Water recovery systems produce brines and slurries from water processing systems that use technologies such as reverse osmosis and distillation. Dissolved solids and organics can total about 3% to 20% by weight of the solution. Technologies for recovery of water from brines and slurries, which provide an increased level of mass closure of advanced life support systems, are of interest. The products of these systems may be dry solids and purified water low in total organic carbon.

Sub Topics:
- Crewed Spacecraft Environmental Monitoring and Control and Fire Protection Systems Topic X3.03

Environmental Monitoring and Control
Monitoring technologies are employed to assure that the chemical and microbial content of the air and water environment of the astronaut crew habitat falls within acceptable limits, and that the chemical or biological life support system is functioning properly. The sensors may also provide data to automated control systems.

Technologies should be appropriate for a small crewed mission to the Moon, of duration no more than a few weeks. Emphasis is on major constituents in the air and lunar dust. Extendibility to trace monitoring for longer missions is a plus. Significant improvements are sought in miniaturization, accuracy, precision, and operational reliability, as well as long life, real-time multiple measurement functions, in-line operation, self-calibration, reduction of expendables, low energy consumption, and minimal operator time/maintenance for monitoring and controlling the life-support processes. Proposals should be for either new technologies or combine existing technologies in a new way to simultaneously monitor several major constituents and dust, and/or trace constituents.

- Substances from an external environment such as lunar surface dust may be encountered during astronaut excursions and may be a mechanical or chemical threat both during the external encounter and if brought inside. Monitoring technologies are needed to assess and quantify these threats.
- For longer missions, water monitoring will be required. Needs will include sensitive, fast response, online analytical sensors to monitor suspended liquid droplets, dispersed gas bubbles, and water quality, particularly total organic carbon.
- Monitoring of other species of interest include dissolved gases and ions, and polar organic compounds such as methanol, ethanol, isopropanol, butanol, and acetone in water reclamation processes; and particulate matter, major constituents (such as oxygen, carbon dioxide, and water vapor) and trace gas contaminants (such as ammonia, formaldehyde, ethylene) in air revitalization processes. Both invasive and noninvasive techniques will be considered.
- Monitoring of microbial species, especially pathogens, primarily in water, will be important for longer missions. Enabling technologies may include proper sample preparation and handling, with minimal
operator effort and minimal or no reagent usage.

- Crew members will employ software tools to help them interpret sensor data. Methods are sought which will assist the crew in using sensor data to detect and predict failures.

Results of a Phase 1 contract should show feasibility of the technology and approach. A resulting Phase 2 contract should produce at least a prototype demonstration and test of the environmental monitor.

**Spacecraft Fire Protection Systems**

The objective of fire protection strategies on exploration spacecraft is to quantitatively reduce the likelihood of a fire and reduce the impact to the mission should a fire occur. NASA's fire protection strategy includes: strict control of ignition sources and flammable material, early detection and annunciation of fire signatures, and effective fire suppression and response procedures. While proposals describing innovations in all of these areas are applicable, they are particularly sought in the following areas:

- Advanced fire detection strategies are desired that respond uniquely to one or more fire or pre-fire characteristics such as thermal radiation, smoke, or gaseous product. These sensors should be appropriate for the unique fire behavior in low- and partial-gravity environments yet effectively discriminate between fire signatures and relevant spacecraft nuisance sources. Fire detection systems particularly attractive for long-duration exploration missions will have reduced mass, power, and volume requirements and exhibit high degrees of reliability, minimal maintenance, and self-calibration.

- Fire suppression technologies for exploration spacecraft and habitats must be applicable for use in a confined habitable volume having an atmosphere of up to 34% O₂ by volume and pressures as low as 7.6 psia. These systems would be effective in low- and partial-gravity environments and have minimal mass and volume requirements. Applicable technologies would be highly reliable with little or no maintenance, have multi-use capability and/or be replenishable during a mission, and be compatible with the spacecraft environmental control and life support system.

Results of a Phase 1 contract should show feasibility of the technology and approach. A plan for the demonstration of a prototype to be developed in Phase 2 should also be produced at the end of Phase 1. The Phase 2 contract should produce at least a prototype demonstration and test of the fire detection or suppression system.

**Sub Topics:**

Lunar Regolith Excavation and Material Handling Topic X4.01

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 (notional depth 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.

Sub Topics:
  Oxygen Production from Lunar Regolith Topic X4.02
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.
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.

Motors and Drive Systems for Cryogenic Environments Topic X5.01
This subtopic focuses on the development of selected hardware and support technologies for motors, drive systems and related mechanisms that will operate in cryogenic temperature environments such as permanently shaded craters on the Moon, and/or on the lunar surface exposed to the day/night cycle. In the former situation such mechanisms may be exposed to, and will need to operate in, sink temperatures as low as approximately 25K. In the latter situation they will need to operate over a temperature sink range of approximately 83K to 146K (-190°C to +127°C). Actual operational temperatures may be somewhat different. The component technologies developed in this effort will be utilized for rovers, operational equipment, instruments, drills, crushers, and other such facilities. The nearer term focus for this effort is for lunar missions, but these technologies should ideally be translatable to applications on Mars. These components must operate in a hard vacuum and/or planetary environment, with partial gravity, and full solar radiation exposure. Additional requirements include high reliability, ease of maintenance, low-system volume, low mass, and minimal power requirements. Low out-gassing is desirable, as are modular design characteristics, fail-safe operation, and reliability for handling fluids, slurries, biomass, particulates, and solids. While dust mitigation is not specifically included in this subtopic, proposed concepts should be cognizant of the need for such technologies.

Specific areas of interest include gear boxes, suspension systems, material components (i.e., wiring, harnesses, insulating materials, and jackets/covers) that are flexible in cryogenic environments; advanced lubricants and lubrication technology; and an accelerated means of life testing for cold temperatures.
Revolutionary advances in radiation shielding materials and structures technologies are needed to protect humans from the hazards of space radiation during NASA missions. All radiation species are considered, including particulate radiation (electrons, protons, neutrons, alpha particles, light ions, heavy ions, etc.) and including electromagnetic radiation (ultraviolet, x-rays, gamma rays, etc.). All space radiation environments in which humans may travel in the foreseeable future are considered, including low-Earth orbit, geosynchronous orbit, Moon, Mars, etc. The primary areas of interest for this 2006 solicitation are: (1) radiation shielding materials systems for long duration lunar surface protection for humans; and (2) lightweight radiation shielding materials systems for short term in-space operations for humans. Specific areas in which SBIR-developed technologies can contribute to NASA’s overall mission requirements for advanced radiation shielding materials and structures include, but are not limited to, the following:

- New and innovative lightweight radiation shielding materials and structures to shield humans in crew exploration vehicles, large space structures such as space stations, orbiters, landers, rovers, habitats (both rigid and inflatable concepts), spacesuits, etc. The materials emphasis is on non-parasitic radiation shielding materials, or multifunctional materials, where two of the functions are radiation shielding efficiency and structural integrity.
- Radiation laboratory and spaceflight data to validate the shielding effectiveness of radiation shielding materials and structures.
- Physical, mechanical, structural, and other relevant characterization data to validate and qualify multifunctional radiation shielding materials and structures.
- Comprehensive radiation shielding databases to enable designers to incorporate and optimize radiation shielding structural materials into space systems during all the design phases.
- New and innovative processing methods to produce quality-controlled advanced radiation shielding materials of all forms - resins, fibers, fabrics, foams, microcomposites and nanocomposites, fiber-reinforced composites, light alloys, and hybrid materials.
- New and innovative fabrication techniques to fabricate advanced radiation shielding materials into useful products and structural components.
- New and innovative manufacturing techniques to produce quality-controlled advanced radiation shielding products and structural components, including innovative scale-up methods for producing quality-controlled viable quantities of advanced radiation shielding materials and structures.
- New and innovative commercialization strategies to introduce advanced radiation shielding materials and structures into the marketplace to enable availability of the technologies for use by NASA and the space exploration community.

Sub Topics:
Lightweight Pressurized Structures Including Inflatable Topic X6.02
This subtopic solicits innovative structural concepts that support the development of lightweight structures technologies that could be applicable to CEV, CLV and Lunar surface landers and habitats. The targeted innovative lightweight structures are for primary pressurized structures such as cryotanks and crewed vehicles (landers and habitats). Innovations in technology are needed to minimize launch mass and costs, and increase operational volume for minimal launch volumes while at the same time maintain required structural performance for loads and environments. Of particular interest are the following structural concepts:
• Cryotank structural systems that are low mass and minimize cryogen boil-off. These concepts can include new techniques in structural concepts, manufacturing, and incorporation of tank liners or innovative insulating materials that improve on SOA designs used today.
• Lightweight multifunctional structural systems that include radiation shielding, impact shielding, thermal management, damage tolerance and durability, and/or integral diagnostics/health monitoring capabilities are of interest if they can be developed to improve the efficiency (mass/performance) of the structural system over the parasitic systems used today.
• Inflatable structures are considered as viable technique to improve volume for crew in habitats and potentially other crewed vessels. However, areas of risk need to be mitigated to build confidence in the use of these structures. In particular, durability in the presence of micrometeoroid, orbital debris and crew load induced damage, radiation-shielding protection, equipment placement and tie down concepts, and efficient packaging concepts are of interest.

Development of concepts can include structural components, improved low cost manufacturing processes, methods of validation, and/or predictive analysis capabilities. Technological improvements that focus on risk reduction/mitigation, and development of reliable yet robust designs are also being sought under this announcement.

Sub Topics:
  Material Concepts for Lightweight Structure Technology Development Topic X6.03
This subtopic solicits innovative research for advanced material concepts that support the development of lightweight structures technologies that should be applicable for space transportation vehicle systems, propulsion systems, and planetary access and operations. Advanced materials are targeted that could be implemented into structural and propulsion systems for CEV, CLV and lunar mission vehicles, landers, and habitats. Innovations in technology are needed to increase specific strength and stiffness, provide radiation shielding, enable thermal management, and reduce Micrometeoroid/Orbital Debris (MMOD) damage potential while maintaining safety, reliability and reducing costs.

Advanced material systems and their corresponding manufacturing and processing techniques are desired. Examples would include, but are not limited to, advanced polymer matrix, ceramic matrix, and metal matrix composites; high performance metals material systems (e.g. advanced aluminum alloys, titanium alloys, super alloys, refractory alloys); hybrid material systems, multifunctional material systems, self-monitoring and self-healing material systems; and mature applications of nano-structured materials. Processing examples would include, but not limited to, composite fiber tape placement, non-autoclave curing, ceramic processing, freeform fabrication, bonding of composites, metallic thermal spray, and friction stir welding/processing.

Development of concepts can include material system characterization, methods of validation, and/or predictive analysis methods that improve understanding of the technology to reduce risk and need for conservatism in design and demonstration of integrated system performance. Damage tolerance is a specific area of interest to include analytical tools, non destructive evaluation technology and experimental techniques. NDE methods and techniques are needed to include 3D imaging and modeling of defects, and NDE technologies for determining early degradation of composites.

Sub Topics:
  Supportability Technologies for Long-Duration Space Missions Topic X7.01
The objective of this subtopic is to develop technologies that can support the goal of significantly reducing the mass and volume of material required to support long-duration human spaceflight missions. Eventually, as the distance of mission destinations increases, resupply will become impossible. Therefore, unless support materials are prepositioned, it will be necessary for all required materials to be transported with the crew. The difficulty presented
by this situation is compounded by the need for more material as mission duration increases. Capabilities to address these issues should be developed and demonstrated in conjunction with long duration lunar missions and, as they reach sufficient maturity, will be valuable enhancements to these missions.

This subtopic seeks proposals addressing maintenance and repair technologies that enable repair of failed hardware at all levels, technology that supports the production of replacement components during a mission, and technologies that reduce the quantity of material directly supporting the crew. Proposals are sought which address the following technology needs:

- Compact, portable systems to generate reverse engineering data to support manufacturing of replacement items during a mission. This will allow generation of a duplicate part based on an existing part if CAD models are not available.

- Real-time non-destructive evaluation during layer-additive processing for on-the-fly quality control. This will provide capabilities for in-process quality control and may serve as an input for closed-loop process control. Equipment should be portable, compact, and capable of integration with layer-additive manufacturing systems.

- Non-destructive material property determination. This will provide an in-process quality control capability to ensure that material deposited during layer-additive processing meets required material property criteria. Equipment should be portable, compact, and capable of integration with layer-additive manufacturing systems.

- Recycling/generation of feedstock materials for deposition processes. This will provide the capability to recycle failed parts and material removed from near-net-shape parts during machining operations to serve as feedstock material for subsequent layer-additive manufacturing. Initial focus should be placed on metallic materials. Additionally, emphasis should be placed on total system mass and volume.

- Compact, portable multi-axis machining systems. This will provide subtractive manufacturing capabilities to achieve final design dimensions and surface finishes following layer-additive processes that produce near-net-shape parts. Equipment to accomplish this should be of the minimum mass and volume possible while still providing required capabilities.

- Compact, portable, vacuum-compatible multi-axis manipulator. This will provide the capability for complex manipulation of the item itself, the processing equipment, or both during layer-additive manufacturing and machining. To be compatible with the widest variety of candidate processes, manipulation equipment should be vacuum compatible. Additionally, equipment to accomplish this should be of the minimum mass and volume possible while still providing required capabilities.

- Laundry system. This will provide the capability for extended reuse of crew clothing. Any laundry system must utilize a minimal amount of water or no water at all. Any water used should be easily recycled - either being reintroduced into the spacecraft water system or recycled internal to the laundry system. Additional emphasis should be placed on the mass and volume of the equipment and minimization of power requirements.

Sub Topics:
Human-System Interaction Topic X7.02
The objective of this subtopic is to create an effective and efficient operational interface between a human and a robotic system that is supporting the human. This subtopic seeks to develop automation technology that reduces
the risk of Extra-Vehicular Activity (EVA), improves the productivity of Intra-Vehicular Activity (IVA) and facilitates remote operations by both flight crew and ground control. Automation and robotics capabilities include the ability to use robots for operational tasks (assembly, maintenance, inspection, payload transport, etc.), real-time advisory systems that will support the space and lunar based crew, and mission operation concepts and systems that link ground supervisors across time delays to remote spacecraft and robots. Proposals are sought which address the following technology needs:

- Telepresence and variable autonomy teleoperation systems that support human and robot teams operating: (1) in a shared space, (2) close but separated, (3) somewhat remote, and far remote. Particular interest is given to systems that flexibly support human-robot operations in the presence of time-delays of up to 10 seconds.

- Software frameworks and interaction infrastructures that facilitate the creation and operation of joint human-agent teams. Conventional control architectures do not adequately address human-system interaction needs, particularly in terms of coordination, teaming, direct and indirect commanding, and information sharing between humans, robots, and distributed software agents. Of particular interest are extensions to existing NASA human-robot architectures and software frameworks including: automatic event and situation summarization, notification and dialogue based on user state (role, availability, location, interface), centralized task coordination/dispatch, user activity monitoring, and automated detection of domain events.

- Adaptive user interfaces including perception (visual gesturing), speech recognition, context awareness, computational cognitive models and/or collaborative 3D graphics, and EVA display devices (i.e., pressure-suit compatible devices and displays). Specific design objectives include enabling more natural interaction with autonomous systems, facilitating situational awareness, increasing overall productivity by reducing the amount of interaction effort the human has with the robot, and flexibly displaying multi-modal and mission-specific data.

- Embedded real-time advisory and action planning systems for fully autonomous integrated systems that support remote and onboard vehicle operations for the Crew Exploration Vehicle (CEV).

- Engineering systems that support flight demonstrations of dexterous robots working with EVA crew using CEV and ISS to prove capabilities for space and lunar operations. This will provide human, robotic and human-robot team options for dexterous EVA tasks, robotic EVA capabilities for excursions into high radiation fields beyond Low Earth Orbit (LEO), and the ability to respond to onboard situations with prompt EVA action.

- Accurate and affordable methods for prototyping and evaluating human-system interaction. This includes model-based simulation and trade studies for analyzing multiple interaction "dimensions" (spatial distribution, autonomy level, team makeup, task dependencies, etc.) and missions (pre-cursor robotic, short-stay sorties, and long-duration outpost).

- Vehicle control systems and navigation sensors that support on-board driving, teleoperation, and autonomous operations. Control systems should support multiple control modes, include activity monitoring and operator intent prediction, and tolerate up to 10 seconds of time-delay. Navigation sensors that utilize passive computer vision (real-time dense stereo, optical flow, etc.) and/or active illumination (for recognizing/tracking non-textured objects and operation in permanently shadowed regions) are of particular interest.

Sub Topics:
Surface Handling and Mobility, Transportation, and Operations Equipment (Lunar or Mars) Topic X7.03
The objective of this subtopic is to provide new capabilities for delivery, handling, transfer, construction and
repackaging of Extra Vehicular Activity (EVA) equipment and preparation of site infrastructure for lunar operations. This includes access/handling and transportation equipment/carriers for delivery and deployment of materials, components, and infrastructure; surface systems for site clearing, pad construction, and regolith manipulation; and commodities distribution systems (including umbilicals) for routing to equipment and infrastructure. These new capabilities are required to make planetary surface missions more reliable, safer, and affordable.

Several vehicle features will be critical to surface operations: expanded mobility, range and duration, life support recharge, crew following, automated path planning, automated driving, and obstacle avoidance. Vehicles with life support recharge capabilities will extend useful EVA time. The ability of a vehicle to follow a crewmember will enable science and exploration support equipment to be carried for the astronaut as well as extend the traverse distances. While the utility of autonomy is easily recognized when the crew is not on the surface, these functions could also be advantageous to long traverses and rescue or emergency operations when crewmembers are present.

Proposals are sought which address the following technology needs:

- Highly reliable and durable surface systems for site preparation, pad construction, site sampling and prospecting are needed for planetary exploration. Sample collection may require excavating, picking, and physical manipulation of materials, as well as tagging and transport to an analysis site. Emphasis will be placed on proposals that address both manned and unmanned vehicle control operating capabilities of the surface system.

- Flexible and adaptive systems to deploy and emplace site infrastructure, such as beacons for communication, survey, navigation, etc. Emphasis should be placed on developing lightweight, power-efficient manipulation devices (dexterous and non-dexterous) that can be deployed on small rovers and that are appropriate for multiple tasks. Much of this activity can be performed with teleoperated and semi-autonomous robots controlled from ground. Some of this activity, however, will also require human presence at the site. In both cases, the effectiveness of Human-Robot interaction (HRI) will have a major impact on the efficiency and productivity of mission operations.

- Access/handling and transportation equipment (including cargo carriers) for delivery and deployment of materials, components, and infrastructure. Vehicle systems that can self-deploy, that can function in rough and steep terrain, and that can controlled at various levels of autonomy are of particular interest.

- Commodities distribution systems (including umbilicals) for routing to equipment and infrastructure. Commodities distribution systems are necessary to interconnect distributed surface assets (e.g., access/handling and transportation equipment, launch and landing systems, communication relays, power plants) to support long-duration sorties and sequential mission architectures.

- Vehicle control architectures that support on-board driving, teleoperation, and autonomous operations. Particular emphasis is placed on architectures that can flexibly support and adapt to multiple control modes, that include activity monitoring and operator intent prediction, and that can tolerate up to 10 seconds of time-delay.

- Highly reliable, durable, and long-life systems (mechanical, electrical, software, power train, lubricants, etc). This includes design and implementation of integrated actuator, suspension and control avionics for surface vehicles and evaluation of test articles in field experiments (preferably in lunar analog environments).
Sub Topics:

Non-Toxic Launch Vehicle Power for Thrust Vector and Engine Actuation Topic X8.01
The next generation of NASA launch vehicles and spacecraft will minimize the use of hydraulic power systems due to their inherent inefficiencies. These hydraulic systems will be replaced with all electric power components. NASA is interested in optimizing these electric components to maximize system reliability and efficiency while minimizing overall size and mass. Of particular need are electric actuation systems, including electromechanical (EMA) and electrohydrostatic (EHA). These are important in order to realize the full potential of the more electric power systems. The actuator systems will consist of both the actuator and associated controls. These systems will be used for a number of applications including thrust vector control, engine actuation and vehicle surface actuation. The technology would directly benefit programs such as Constellation which have a variety of requirements for the Crew Launch Vehicle, Cargo Launch Vehicle, Lunar Surface Access Module, and others. These systems may range from a few horsepower to greater than 50 horsepower, and the associated electronics may see temperature extremes up to 175°C. To make electric actuation a more viable option, improvements in mass, size, efficiency and power density are sought for both the actuator and associated controls. Current state-of-the-art actuators suitable for engine thrust vector control on a launch vehicle have a power density of 1kW/kg for duplex drives (two motors driving one transmission, not including inverters and controllers). Innovations are sought to increase this power density to at least twice the SOA. In addition, state-of-the-art controllers can be 20 - 50% of the actuator size and weight alone, therefore novel approaches to minimizing controller mass and volume are sought. Innovative approaches to redundant electric actuator systems and redundancy systems management will also be considered which would help reach the single fault tolerant vehicle requirements. Technologies of specific interest include:

- Lightweight, high power density electric actuators and controls in the 5 - 10 hp range for use on vehicles such as Crew Launch Vehicle and Earth Departure Stage, with an actuator density goal of 2kW/kg and controller density of at least 1.5 kW/kg;
- Lightweight, high power density electric actuators and controls suitable for 30 - 60 hp applications on vehicles such as Cargo Launch, with an actuator density goal of 2kW/kg and controller density of at least 1.5 kW/kg;
- Actuation and control technologies capable of operating over wide temperature ranges - up to a chassis temperature of 175°C;
- Novel redundant EA systems and redundancy management approaches for single fault-tolerant vehicle applications.

Sub Topics:

Space Based Nuclear Fission Power Technologies Topic X8.02
NASA is interested in the development of highly advanced systems, subsystems and components for use with fission power systems for future Lunar and Mars robotic and manned missions. Anticipated power levels range from 10’s of kilowatts to 100’s of kilowatts. Proposals are sought for critical technologies for fission power systems to meet the following anticipated missions and applications.

The current Vision for Exploration identifies the first human lunar landing in 2018 with subsequent long duration lunar stays of approximately 6 months in 2022. Fission-based systems are anticipated to enable the long duration
stay over the lunar night. Initial planetary base power levels are anticipated to be between 30 - 50 kWe.

Planetary surface human base applications may include: habitats, resource processing and propellant production/liquefaction/maintenance, surface mobility for both robotic and piloted rovers, excavating and mining equipment and science stations. Human Mars mission activities could require power in the 100 kWe range.

Potentially, robotic outpost as a precursor to human Mars exploration with 50 - 500 day stays could be the proving ground for smaller fission systems. A 20 - 30 kWe system could support science applications such as: deep drilling, resource production demos, rovers, weather stations, etc.

Specific technology topics of interest are:

- Advanced, high efficiency, high temperature power conversion > 20%, 25 kWe to 100 kWe unit size;
- Electrical power management, control and distribution. 1000 - 5000 V;
- High temperature, low mass thermal management/heat rejection 2;
- Deployment systems/mechanisms for large radiators, surface mobility systems for remote emplacement of power systems, innovative methodology for use of indigenous shielding materials;
- High temperature materials or coatings compatibility with local soil and atmospheric environments;
- Systems/technologies to mitigate planetary surface environments. Dust accumulation, wind, planetary atmospheres (CO₂, corrosive soils, etc.);
- Power system design considerations for long life (> 5 years), autonomous control and operation, including sensor technologies;
- Radiation tolerant systems and materials (including lunar, Mars and in-space environments) for robust, long life operation;
- Innovative methodologies and approaches to accelerated life testing.

In addition to reducing overall system mass, volume and cost, increased safety and reliability are of extreme importance. It is envisioned that these technologies would be used on robotic and human missions and it is to NASA's advantage to develop those technologies that transcend robotic to human mission requirements with a minimum of redesign. Technologies that easily and efficiently scale in power output and can be used in a host of applications (high commonality) are desired.

Sub Topics:
- Space Rated Batteries and Fuel Cells for Surface Systems Topic X8.03

Human-rated energy storage devices are required to enable future robotic and human exploration missions.
Advanced battery, fuel cell and regenerative fuel cell systems are sought for use in a wide range of Exploration mission applications including portable power for landers, rovers, and astronaut equipment, and stationary energy storage applications such as base power, and storage systems for crew exploration vehicles and spacecraft. Technology advances that will reduce the weight and volume, improve the efficiency, life, safety, system simplicity and reliability of electrochemical systems, specifically rechargeable batteries and fuel cell systems are desired. The specific advancements of interest are outlined below.

**Advanced Secondary Battery Systems**

Areas of emphasis for advanced battery systems include technology advancements that contribute to the following cell-level performance goals: specific energy > 180 Wh/kg, calendar life > 15 years, and operating temperature range -60°C to 60°C and cycle life at 100% DOD > 2000 cycles. Systems that combine all of the above characteristics and demonstrate a high degree of safety are desired.

Specific technology areas sought are improved component materials that include non-toxic cathodes with specific capacities in excess of 250 mAh/g at the C rate and 25°C, and electrolytes that provide safe, non-flammable, non-hazardous operation. Cells that exhibit tolerance to mild abuse such as overcharge and over temperature are desirable. Chemistries and/or cell design capable of rapid recharge (Innovative concepts for the design and management of packaged battery modules with specific energy > 140 Wh/kg and energy density > 300 Wh/l are of keen interest.

Proposals addressing micro-batteries, structural batteries, and/or integrated power generation and are sought.

**Fuel Cell Systems**

Fuel cell (FC) systems with power capabilities in the range of 100-1000 watts and 1-10 kW are of interest, as are regenerative fuel cell (RFC) energy storage systems in the 10 - 25 kW power range.

Specifically, technological advances are sought for FC/RFC based systems that contribute to system simplicity and improved reliability through (1) innovative, integrated system-level design concepts, and (2) passive ancillary components. An example of these advances at the system level is primary and/or regenerative fuel cell systems that minimize or eliminate reactant re-circulation external to the stacks themselves. Examples at the component level include replacement of pumps and other active, motorized mechanical ancillary components with passive devices that perform the functions of both reactant management and thermal control.

Advanced FC/RFC development at both the system and component levels should focus exclusively on proton-exchange-membrane PEM technology utilizing pure hydrogen, oxygen, and water as reactants.
Sub Topics:

Long Term Cryogenic Propellant Storage, Management, and Acquisition Topic X9.01

This subtopic includes technologies for long term cryogenic propellant storage, management and acquisition applications in-space as well as on the lunar surface. These technologies will impact cryogenic systems for space transportation orbit transfer vehicles, space power systems, spaceports, spacesuits, lunar habitation systems, robotics, and in situ propellant systems. Each of these applications has unique performance requirements that need to be met. The sizes of these systems range from the small (3 for supercritical air and payload cooling) to very large (> 3400 m³ for LOX and LH₂ propellant storage). Advanced cryogenic technologies are being solicited for all these applications. Proposed technologies should offer enhanced safety, reliability, or economic efficiency over current state-of-the-art, or should feature enabling technologies to allow NASA to meet future space exploration goals.

Technology focus areas are divided as follows: fluid transfer/liquid acquisition devices, mass gauging/advanced instrumentation, passive systems, storage and distribution components, and refrigeration systems. Innovative concepts are requested for cryogenic insulation systems, fluid system components, and instrumentation. Cryogenic propellants such as hydrogen, methane, and oxygen are required for many current and future space missions. Operating efficiency and reliability of these cryogenic systems must be improved considering the launch environment, operations in a space environment, and system life, cost, and safety. This subtopic solicits unique and innovative concepts in the following technologies:

**Fluid Transfer/Liquid Acquisition Devices**

Liquid acquisition devices capable of preventing gas ingestion into engine feed lines in low gravity, analytical models of LAD’s to predict LAD performance in low gravity and to determine the effect of autogenous/non-autogenous pressurants on LAD wicking capability, techniques to minimize vaporization inside the LAD channel caused by incident heating through tank wall/lines and/or changes in tank pressure.

**Mass Gauging/Advanced Instrumentation**

Methods of determining liquid quantity gauging in propellant tanks in low gravity, high accuracy differential pressure transducers which can operate submerged in liquid cryogen and in-space fluid leak detectors.

**Passive Systems**

Advanced insulation technology including low loss cryogenic propellant tank penetrations and insulation materials capable of retaining structural integrity while accommodating large operating temperatures ranging from cryogenic to elevated temperature conditions, advanced tank support systems capable of supporting tanks during the launch environment, but decoupling on on-orbit to minimize thermal loads and passive thermal control designs for cryogenic fluid storage on the lunar surface.

**Storage and Distribution Components**

Advanced low-gravity submersible pumps and helium compressors designed specifically for in-space cryogenic
operation, low heat leak cryogenic quick disconnects capable of sealing against the vacuum of space, long-life, low power valves for LO$_2$ and LH$_2$ capable of sealing at cryogenic temperatures, being cycled many times without consuming pressurant gas and with minimal thermal loss and pressure drop.

**Refrigeration Systems**

Advanced LO$_2$ and LH$_2$ cryocooler concepts for in-space operation that are reliable, lightweight, low input power and capable of removing 5 to 10 watts of heat at 77 K and at 20 K, respectively, concepts to integrate Broad Area Cooling (removing heat over large areas and long distances) into in-space storage of LO$_2$ and/or LH$_2$ and heat exchanger designs for large-scale storage systems designed densification of LO$_2$ and LH$_2$.

**Sub Topics:**

Innovative Booster Engine Manufacturing, Components, and Health Management Topic X9.02

The goal of this subtopic is the development of innovative components, manufacturing techniques, health management systems, and design and analysis tools for boost propulsion. Although solid or hybrid rocket propulsion is specifically emphasized, compelling proposals related to liquid engine boost propulsion are also invited. Technologies that would contribute to increased mass fraction and decreased sensitivity to manufacturing and handling effects are particularly welcome, as are those that would reduce the time, cost, and complexity associated with designing and manufacturing large booster rockets. Specific areas of interest include:

- Concepts for solid or hybrid propulsion systems and related components that would lead to increased payload mass fraction over current solid rocket motors;
- Concepts for solid or hybrid auxiliary propulsion systems that can be throttled to provide enhanced vehicle maneuverability;
- Health management technologies, including embedded sensors and modeling methodologies, that would improve the ability to monitor the reliability of solid or hybrid rockets during manufacturing, handling, and flight;
- Manufacturing techniques that allow for reductions in the cost and schedule required to fabricate and test solid or hybrid rockets;
- Propulsion system concepts, components, and fabrication processes designed to reduce the production costs of liquid propellant rocket engines for large expendable boosters;
- Improved design and analysis tools that enhance the engineering evaluation of advanced chemical propulsion system concepts;
- Test data that provides for validation of existing design and analysis tools; and
- New propellant ingredients or formulations that would increase the propellant specific impulse while maintaining a Department of Transportation Class 1.3 hazard classification. Proposals that would experimentally synthesize and characterize new ingredients, or formulate and demonstrate new propellants, are highly encouraged, whereas proposals that rely heavily on the screening of potential new ingredients by quantum chemistry or other computational and theoretical methods are discouraged.
Proposals that address more than one of these items are highly encouraged.

Sub Topics:

Cryogenic and Non-Toxic Storable Propellant Space Engines Topic X9.03
This subtopic intends to examine a range of key technology options associated with cryogenic and non-toxic storable propellant space engines. This engine technology is solicited for use in lieu of the toxic but currently operational nitrogen tetroxide and monomethylhydrazine engine technology, which has recently seen performance improvements from 310 to 325 seconds of specific impulse using advanced rhenium thrust chamber technology. Performance improvements are a consideration, but are not the main objective of this solicitation. The Space Shuttle Orbiter Upgrade Program identified non-toxic reaction control system (RCS) propulsion as a key technology to reduce vehicle operations costs on the ground, and estimated that a significant reduction in RCS propulsion system cost is possible by the use of non-toxic propellants. In addition, the use of astronaut extravehicular activity for in-space refueling of space systems or the refueling of vehicles with humans aboard such as the International Space Station is extremely hazardous with toxic propellants. These safety concerns drive mission planners to the use of more costly propulsion modules that are fueled and sealed on the ground.

The general objectives of this solicitation derive from the NASA goals of safe, reliable, affordable and effective human and robotic missions in support of the overall U.S. Vision for Space Exploration. Successful proposals will be focused investments that systematically validate and/or invalidate key technologies and design concepts that might transform how the U.S. will pursue future space exploration goals.

The specific technology to be supported by this subtopic is multi-use in-space cryogenic and non-toxic storable propellant rockets. This technology includes the development and demonstration of key operational and performance characteristics of a range of new space engines, i.e., orbit transfer, descent, ascent, and pulsing attitude control engines. These engines can be compatible with the future use of in situ propellants such as oxygen and hydrogen or methane, but propellants consistent with low cost ground operations such as ethanol, JP-5 and nitrous oxide and monopropellants are also solicited.

Proposals are solicited for both thruster development and thruster component technologies such as, but not limited to, long-life, highly reliable ignition systems, durable, low-mass propellant injectors, and long-life combustion chamber designs. Proposals are also solicited for propulsion system component technologies such as valves, instrumentation, controls, multi-purpose structures and both electric and turbine driven pumps. Examples include, but are not limited to, highly-reliable, long-life, fast-acting cryogenic valves that tolerate high thermal loading due to heat soak-back in low-thrust, pulsing propulsion systems; cryogenic instrumentation such as pressure and temperature sensors that will operate for months/years instead of hours; and high-reliability, long-life turbopump bearings. Technologies are also solicited that enable deep-throttling turbopumps to operate at off-design flow coefficients while eliminating flow instabilities such as cavitating surge. Examples include, but are not limited to, inducer designs that can operate with a high degree of vapor content or cavitation in the propellant flow and pump diffusion systems with reduced sensitivity to flow separations. Strategies for engine and component protection from dust, radiation, and other environmental effects are also solicited. Finally, proposals are solicited for modeling efforts that enable reduced thruster development costs and schedules.
Nuclear Thermal Propulsion Topic X9.04
NASA is interested in the development of critical technologies for first in-space applications of solid core nuclear thermal propulsion (NTP) systems for use in future human exploration missions. For short round trip missions to Mars, NTP systems may be enabling by helping to reduce launch mass to reasonable values and by also increasing the payload delivered for Mars human exploration missions.

Preliminary solid core NTP system concepts could be based on a high thrust/high Isp (~850 - 950s) NTP system that would use a fission reactor with U-235 fuel as its source of thermal energy. During the short primary propulsion maneuvers of a typical conceptual mission, large quantities of thermal power (100's of MWt) would be produced within the NTP system and removed using LH₂ propellant that is pumped through the engine's reactor core. The superheated hydrogen gas is then exhausted out the engine's nozzle to generate thrust. Representative ranges of engine performance include: (1) hydrogen exhaust temperatures ~2500 - 2900 K, (2) propellant flow rates ~7 - 13 kg/s, (3) chamber pressures ~500 - 1500 psi, and (4) nozzle expansion area ratio ~200:1 - 500:1.

Proposals are sought to further improve factors contributing to safety, performance, reliability, and life as well as reduce projected weight and costs for the first in-space NTP systems, subsystems, and components beyond that in previously achieved ground test systems. Proposals are solicited in the following key technology/concept areas:

- High temperature, low burn-up carbide- and ceramic-metallic (cermet)-based nuclear fuels with improved coatings and/or claddings to reduce fission product gas release into the engine's H₂ exhaust stream;
- Reliable, high temperature materials, fabrication techniques, and concepts for non-reactor portions of NTP systems;
- Light-weight, multi-use shielding materials and designs;
- High temperature, radiation tolerant instrumentation and avionics for engine health monitoring. Non-invasive designs for measuring neutron flux (outside of reactor), chamber temperature, operating pressure, and H₂ propellant flow rates over wide range of temperatures are desired;
- Long life, lightweight, reliable hydrogen turbopump designs and technologies;
- Lightweight, long life, high heat flux thrust chambers, regenerative-cooled nozzles and radiation-cooled skirt extensions that are compatible with hot hydrogen;
- Radiation tolerant materials compatible with above engine subsystem applications and operating environments.

Sub Topics:
Ablative Thermal Protection System for CEV Topic X10.01
The Crew Exploration Vehicle (CEV) will first be used for transporting crew and cargo to the Space Station and later for the human exploration of the Moon and Mars. The Thermal Protection System (TPS) for the CEV will have to protect the crew and cargo from entry heating at entry velocities of approximately 8 km/s for Space Station
missions, 11 km/s for lunar return missions, up to 8 km/s for Martian aerocapture and entry, and between 12 - 15 km/s for Martian return missions. Ablative TPS is an enabling technology for all CEV superorbital reentry missions.

Ablation Modeling

The heat shield for CEV will employ a TPS material that pyrolyzes and ablates at high temperature for mass-efficient rejection of the aerothermal heat load. Pyrolysis is an internal decomposition of the solid that releases gaseous species, whereas ablation is a combination of processes that consume heat shield surface material (including chemical reactions, melting, and vaporization). For the design and sizing of TPS materials, it is imperative to have reliable simulation tools that can compute surface recession rate, in-depth pyrolysis, and internal temperature histories under general heating conditions. In addition, lunar and Martian reentry environment heating will consist of significant radiation from the shock layer. The models need to include the effect of not only convective but radiative heating as well.

Therefore, advances are sought in modeling of radiation, gas surface interactions, ablation mechanisms, pyrolysis, and other processes such as coking and charring. Specifically for charring, advances are sought in the development of a low density charring ablator model to give insight into how conductivity changes as function of temperature and pressure for the virgin material and for the material as it pyrolyzes.

Instrumentation

TPS sensors and experimental diagnostic tools are required to provide traceability of TPS sizing tools, design, and material performance. Traceability will lead to higher fidelity design tools, which in turn will lead to risk reduction and decreased heat shield mass on missions requiring atmospheric aerocapture or entry/reentry. Decreasing heat shield mass will enable certain missions that are not otherwise feasible and directly increase payload. Heat flux sensors and surface recession diagnostic tools are essential to advancing the state of TPS traceability for material modeling and aerothermal simulation.

Advances in the understanding of how heat flux sensor performance changes upon integration of the sensors into TPS materials in ablative environments through simulation or experimental investigation are sought. Specifically, the following list of sensor materials is of primary interest:

- Type K, C, R, and S thermocouples
- Sapphire windows
- Inconel superalloys
- Pure platinum
- Teflon

For surface recession, advances in optical methods (photometrics/tomography) are sought.
Non-destructive Testing Techniques and Novel Techniques for Material Characterization

The CEV heat shield will be the largest ever built. During manufacturing and integration, it will be necessary to understand the variability in material properties, to determine voids and inclusions, to assess bondline integrity, and to ensure that the established flight heat shield requirements are met.

For this purpose, advances in NDE and proposals of novel techniques for material characterization applicable for ablative TPS are sought.

Ablation Materials Development

Early NASA missions employed new ablative TPS materials that were tailored to each specific entry environment. However, after Mars Viking, NASA-sponsored ablative TPS development essentially ceased as the research focus shifted to reusable TPS in support of the Space Shuttle. For example, the Pioneer Venus (1978) and Galileo (1995) missions employed carbon phenolic TPS material that had previously been developed by the United States Air Force for ballistic missile applications. Over the past 40 years, NASA has adopted a risk averse philosophy relative to TPS, i.e. use what was used before since it has been flight-qualified. For Mars Direct Return, the entry velocities will be in the range of 12-15 km/s. Heritage carbon phenolic can satisfy Mars Return requirements however the TPS mass fraction would be less than optimal. Thus, advances toward new reliable and efficient TPS materials are desired. Similarly, development of adhesives, joints, penetrations, and seals are of equal importance and advances are sought.

Sub Topics:

Thermal Control for Lunar Surface Systems Topic X11.01

The lunar environment presents several challenges to the design and operation of active thermal control systems. During the Apollo program, landings were located and timed to occur at lunar twilight, resulting in a benign thermal environment. The long duration lunar bases that are foreseen in 15 years will see large variations in their thermal environment during the Moon's day/night cycle. Long stays remote from low-Earth orbit will require lightweight, but robust and reliable systems.

Innovative thermal management components and systems are needed to accomplish the rejection of heat from lunar bases. Advances are sought in the general areas of radiators, thermal control loops and equipment, heat pumps, and thermal storage devices.

For radiators on the Moon, lightweight deployable radiators are required that will operate at temperatures between 150 and 300K. Shading devices and strategies would allow them to reject more heat in the hot lunar environment. In addition, variable emissivity coatings would prevent freezing during the long, cold, lunar night. Also, the dusty environment of an active lunar base will require dust mitigation and removal techniques to maintain radiator
performance over the long term.

Heat pumps (especially high lift) may be required for heat rejection in the lunar environment.

The lunar base active thermal control system will include high efficiency, long life mechanical pumps. Lightweight, high-performance thermal switches plus thermal energy storage and rejection devices could be used to accommodate the extremes of the available heat rejection. Part of the thermal control system in the lunar base is likely to be a condensing heat exchanger, which should be designed to preclude microbial growth.

Thermal management of the lunar habitat, landers, and rovers may require mechanically pumped two-phase fluid loops. Innovative design of the loops and components is needed.

A scaling methodology is needed to allow long term 1-g testing of two-phase systems (including pumped two-phase loops, heat pumps, and condensing heat exchangers) representative of the 1/6th Earth-normal gravity of the Moon.

Lightweight, low volume, robust Extravehicular Activity (EVA) systems are needed that maximize human productivity and improve the capability to perform useful work tasks on the lunar surface. Low-venting or non-venting regenerable support subsystem(s) are needed for crewmember cooling, heat rejection, and removal of expired water vapor. Lightweight and freezable radiators will be needed for thermal control. Innovative direct crewmember thermal control garments are sought, i.e., variable conductivity flexible suit layups that can function as a heat sink for high metabolic loads and as an insulator during period of low physical activity.

Sub Topics:
Food Access Beyond Low Earth Orbit Topic X12.01
Exploration missions beyond low Earth orbit greatly limit allowable consumables and require development of innovative low maintenance, reconfigurable, reusable, or self-sufficient food production. Since regularly timed resupply will not be possible for a Mars mission, all the prepackaged shelf-stable food, ingredients, and equipment to provide a complete diet for six crewmembers for more than three years will have to be provided at the beginning of the mission. Advancements are necessary to develop a combination of extended duration shelf-life stored foods augmented with fresh foods.

Safe, nutritious, acceptable, and varied shelf-stable foods with a shelf life of 3 - 5 years will be required to support the crew during future exploration missions to the Moon or Mars. Development of shelf-stable food items that use high-quality ingredients is important to maintaining a healthy diet and the psychosocial well being of the crew. Shelf-
life extension may be attained through new food preservation methods and/or packaging. Once on the lunar or planetary surface, it may be possible to use bulk packaging of meals or snack items. These food products will require specialized processing conditions and packaging materials.

Current food packaging technologies represent a potentially significant trash-management problem for exploration-class missions to the Moon or Mars. New food packaging technologies are needed that minimize waste by using high barrier packaging with less mass and volume and/or by using packaging. Another opportunity would be development of a packaging material that can readily be reused by the crew to make objects of value to the space flight mission. All packaging materials must have adequate oxygen and water barrier properties to maintain the foods' 3 - 5 year shelf life.

Food preparation systems will be required to heat and rehydrate the shelf stable food items and to prepare meals from the processed and resupplied items. Technologies to support on-orbit crew meal storage, preparation, dining activities, and trash dispensing are being sought.

Food quality and safety are essential components in the maintenance of crew health and well-being. Efforts should be focused on control of food spoilage and food quality throughout the entire shelf life of the food. Effects of radiation on the stored food system quality are also needed. Food quality and safety efforts should be focused on identification and control of microbial agents of food spoilage, including the development of countermeasures to ameliorate their effects through food processing and food packaging.

Sub Topics:

Long-Duration Space Human Factors Topic X12.02
The long-term goal of this subtopic is to enable planning, designing, training, and executing long-duration human space missions that are up to 5 years without re-supply and real-time communications to Earth. Specifically, the focus of this subtopic is on the development of innovative crew equipment, technologies for human performance assessment/modeling/enhancement, and design tools for engineers to incorporate human factors engineering requirements into hardware and software. Proposals that aim at developing and addressing the following specific technology needs are solicited.

Technologies are needed for monitoring and maintaining human performance non-intrusively. Specifically, the technologies we seek are (1) minimally invasive and un-obtrusive devices and techniques to monitor the behavior and performance (physical, cognitive, perceptual, etc.) of individuals and teams during long-duration space flights or analog missions, as well as (2) embedded measures to detect significant changes in crew readiness to perform physical or cognitive tasks.

Methods and models are needed for predicting human performance. The particular technologies we seek are (1) methods and models for predicting effects on physical performance by encumbrances of clothing, space suits, etc., (2) models for predicting effects of physical environment (e.g., lighting, noise, temperature, contaminants) on human performance, (3) models to simulate and optimize interactions between humans and equipment/vehicle, (4) capability to implement time-delay algorithm and functionality into simulations for higher fidelity and effectiveness, and (5) models for predicting performance due to the effects of cognitive changes.
Cost-effective and reliable tools are needed for aiding the design and evaluation of human-system interfaces for speed, accuracy, and acceptability. The particular tools we seek shall (1) provide automated analysis of computer-user interfaces for complex display systems to conduct objective review of displays and controls, (2) determine compliance with guidelines and standards, and/or (3) offer quantitative measures of the effectiveness of user interfaces for task-sensitive evaluations.

Tools are needed to facilitate user interface design for human computer interfaces, procedures, labels, and instructions. These tools shall assist the designer in incorporating contextual information such as the user's task, the user's knowledge, and the system's limitations.

Tools are needed to build just-in-time system and operational information software that aid human users to conduct routine and emergency operations and activities. Such tools shall be either (1) effective and efficient job aids (e.g., "intelligent" manuals, checklists, and warnings) to support designing flexible interfaces between users and large information systems, or (2) methods for developing "facilitators" (procedures, labels, etc.) adapted for developing space vehicle and payload applications.

Acoustic monitoring systems are needed to accurately and autonomously monitor acoustic sound pressure and noise exposure levels in long-duration space vehicles. These technologies shall provide (1) acoustic sensor systems consisting of fixed and/or crew-worn transducers, (2) sound pressure level information as a function of frequency and/or time, (3) typical sound level meter and acoustic dosimeter functionality, and (4) the capability for autonomous operations and data transfer. Operation and data acquisition parameters of such systems shall be controllable either by ground personnel or the crew.

Innovative acoustic flight materials are needed for noise abatement. These materials shall function as acoustic absorbers, barriers, vibration isolators, dampers, spacecraft wall treatments, transparent containment, or combinations of these. These materials must be shown to satisfy space flight material requirements, such as off-gassing and flammability, and shall be easy to apply to hardware. The acoustic properties of these materials' shall be demonstrated through absorption or transmission loss testing, or by other standard acoustic testing techniques.

Sub Topics:

Space Radiation Health Research Technology Topic X13.01

The goal of the NASA Space Radiation Research Program is to assure that we can safely live and work in the space radiation environment, anywhere, any time. Space radiation is distinct from terrestrial forms of radiation, being comprised of high-energy protons and heavy ions and their secondaries produced in shielding and tissue. The Radiation Program Element uses the NASA Research Announcement as a primary means of soliciting research to reduce the uncertainties in risk projections, however, there are specific areas where the SBIR technologies can potentially contribute to NASA's overall goal:
Ground-based Heavy Ion Accelerator Research Support Equipment

NASA utilizes Facilities at Brookhaven National Laboratory (BNL) (for more information see www.bnl.gov/medical/NASA/NSRL_description.asp) to conduct fundamental radiobiology and physics experiments. However the Facilities at BNL were not developed with NASA's high number of investigators in mind, thus there are areas where technology developments can improve efficiency and throughput. Technologies of specific interest include, but are not limited to, the following:

- Advanced animal support equipment, sample holders, live imaging of samples on the beam line during heavy ion irradiation, or specimen transport systems that allow remote transport into and out of the target areas and precise positioning of specimens in the beam line with minimal human interaction in the target areas;

- Environmental control for cell studies while in the beam line, and automated fixation capabilities to perfuse small cell and tissue samples directly after exposure to the ion beam;

- Advanced detector systems to provide rapid assessments of elemental fluence spectra and neutron fluence spectra following heavy ion irradiation of biological or shielding samples.

High Throughput Genomic Analysis Techniques

Following low dose irradiation of cells by protons and heavy ions, damage is localized to only a very few cells. The ability to separate cells with or without genetic changes in an automated manner is of interest. Current technologies are inefficient in identifying small-scale genetic changes (less than several thousand base-pairs (Mbp)) under these conditions. Technologies of interest are:

- Complementary technologies to the fluorescence in situ hybridization (FISH) method used to score large scale (>1 Mbp) genetic changes to chromosomes following low dose irradiation in order to rapidly score small-scale genetic changes;

- Imaging techniques to rapidly identify with high accuracy undamaged cells from a cell population irradiated at low doses.

Reliable Radiation Dosimeters for Manned and Unmanned Spaceflight

Current environment dosimeters have exceeded their designed lifetimes and should be replaced. These include small active dosimeters to monitor individual astronauts' exposure, Tissue Equivalent Proportional Counters (TEPC), Charged Particle Directional Spectrometer (CPDS) capable of internal and external deployment, and externally deployed electron and neutron detectors. New software needs to be fault tolerant and updated to current operating systems, new hardware and software must be fully documented (schematics, etc.). Areas of interest are:

- Advanced spaceflight detector systems to provide reliable environment data for a specific spectrum of energies, including real time dosimetry providing dose and particle types, and energies and cumulative
dosimeters, for characterizing space environments for use onboard spacecraft and planetary surfaces, as well as alarm systems for Solar Particle Events. Dosimeters should provide time resolved linear energy transfer (LET) data and have embedded LET-based quality factor algorithms for determining dose equivalent. The expected radiation environment includes protons from 10 Mev to 1 GeV, electrons from .5 Mev to 7 Mev, primary and secondary HZEs (He to Fe) from 10 Mev/amu to 1 Gev/amu and secondary neutrons from 1 Mev to 200 Mev. NASA acknowledges the difficulty in measuring secondary neutrons from interactions of protons and heavy ions with spacecraft structures and has particular interest in this area.

Sub Topics:
Health Preservation in the Space Environment Topic X14.01
Living and functioning efficiently and safely in space and in the hypogravity of the Moon (1/6g) or Mars (3/8g), requires an understanding of the effects of micro- and hypogravity and other space-environment related factors on human physiology responses and adaptations to a unique set of imposed demands. As a result, a variety of countermeasures are needed to mitigate the deleterious changes that occur during space flight and upon subsequent exposure to reduced-gravitational environments. The ability to monitor the effectiveness of countermeasures and alterations in human physiology during space exploration missions, particularly when several countermeasures are used concurrently, is equally important.

This subtopic seeks innovative technologies in several very specific key areas. As launch costs relate directly to mass and volume, instruments and sensors must be small and lightweight with an emphasis on multi-functional capabilities. Low power consumption is a major factor, as are design enhancements to improve the operation, design reliability, and maintainability of these instruments in the environment of space and on planetary surfaces. As the efficient use of time is extremely important, innovative instrumentation setup, ease of usage, improved astronaut (patient) comfort, noninvasive sensors, and easy-to-read information displays are also very important considerations. Extended shelf-life and ambient storage conditions of consumables are also key necessities. Ability to operate in 0g, 1/6g, and 3/8g become more important as we march towards human Moon and Mars missions.

Exercise and Related Hardware

Miniaturized exercise hardware (treadmill or resistance exercise); physiological monitoring devices; and metabolic gas (carbon dioxide, oxygen) analysis systems for use with exercise and miniaturized interactive feedback and entertainment systems. A tool or toolkit should simulate and visualize the exercise device design and performance. A comprehensive, scaled 3D/virtual human model interface would be valuable to show biomechanical and kinetic effects of the exercise device. Relative physiological data from anthropometry to stress/fatigue to trauma/insult onset should be targeted.

Noninvasive Pharmacotherapy and Monitoring

Development of innovative technologies resulting in noninvasive methods for diagnosis, treatment, and therapeutic drug monitoring is needed to facilitate effective pharmacotherapy of humans in space. Many questions remain about the effectiveness of pharmaceuticals in micro- and hypogravity environments, which may interfere with their activity by sensitizing or desensitizing the crew member or interfering in other ways with the desired physiological effect. Micro-encapsulation of drugs and development of novel drug delivery systems under micro- and hypogravity conditions. Devices for continual monitoring of physiology during pharmacotherapy would also be advantageous to ensure that on-orbit expression of therapies relates to on-earth histories.
Instrumentation for Noninvasive Measurement of Intracranial Pressure During Space Flight

Abrupt transitions between differing gravitational environments have profound physiologic impacts on human space travelers. For instance, immediately following insertion of the spacecraft into Earth orbit, cephalad fluid shifting occurs. Over the next several days, all crewmembers onboard suffer from what has been termed Space Adaptation Syndrome (SAS) that varies in severity from person to person. The prevailing theory for the appearance of the constellation of symptoms (headache, malaise, vomiting, vertigo, etc.) which comprise this syndrome implicates a "sensory conflict" in information provided by the adapting vestibular system and by visual inputs. Another theory implicates the increased intracranial pressure (ICP) that likely accompanies the cephalad fluid shifts in the genesis of SAS. Additionally, decreased ICP following return to Earth's gravity may explain symptoms experienced by many crewmembers. Thus, novel approaches to noninvasive measurement of ICP are needed to determine the etiology and pathogenesis of the untoward physiologic effects that plague human space travelers during abrupt transitions between different gravitational environments. A more complete understanding of these phenomena will lead to better prevention and treatment modalities that will in turn decrease risks to the health and performance of crewmembers during transitional periods of both high to low and low to high gravity environments.

Noninvasive Technology to Assess Bone Micro- and Macroarchitecture

A complete assessment of bone strength will better monitor life-time skeletal integrity and will generate data critical for developing probability fracture risk models in younger crew members. Novel technology for non-invasive assessments of "bone quality" indices such as microarchitecture, macroarchitecture and trabecular bone mineral density (BMD).

Sub Topics:

Lunar In Situ Autonomous Health Monitoring Topic X14.02

Exploration missions to the lunar surface will be characterized by science goals and objectives which will require crewmembers to actively investigate the accessible exterior environment via Extravehicular Activity (EVA). During the EVA sorties, it will be critical for the crewmembers to be able to monitor their personal health status and to make decisions based on feedback from intrinsic biomedical monitoring systems. Furthermore, it will be necessary to simplify these systems for rapid donning and doffing, automatic checkout capability, annunciation and guidance during suit anomalies, and ensuring the health and safety of each crewmember. Therefore, the sensors that will be used for biomedical monitoring need to be low profile (perhaps incorporated into an undergarment), accurate, reliable, and with as few wires as possible. In addition, the use of electrodes with electrode gel and overtapes has not been highly successful, resulting in skin irritation, adhesion problems, stowage concerns and limited life/inventory issues. Furthermore, our experience has demonstrated that commonality between and among systems is highly beneficial. For this reason, the biomedical sensors used for monitoring EVA should be applicable for intravehicular use as well. Some of the parameters that would be desirable for EVA monitoring include:

- Metabolic Rate
- Heart Rate
- Thermal Control
- ECG (possible)
- Oxygen Consumption Rate
- CO₂ Level (in the oronasal area)
- CO₂ Generation Rate
- Core and/or Skin Temperature
- Radiation Monitoring (possible)
- Oxygen Saturation Level

In addition, development of device(s) capable of being used in an IVA system which is common with the EVA system is highly desirable. All of these, whether used for IVA or EVA, must be comfortable for the crewmember, allow the crewmember to continue performing tasks, and must not preclude normal activities when used for IVA monitoring (e.g. hygiene, eating, working at the computer, and exercising).