The Exploration Development Technology Program leads the Agency in the development of advanced software and information technology capabilities and research for Exploration Systems. They perform mission-driven research and development to enable new system functionality, reduce risk, and enhance the capability for NASA’s explorations missions. NASA’s focus has clarified around Exploration, and the agencies expertise and capabilities are being called upon to support these missions. The Crew Exploration Vehicle (CEV) and teams of humans and robots working in space will all require advances in integrated systems health management, autonomous systems for the crew and mission operations, radiation hardened processing, and reliable, dependable software. Exploration requires the best of the nation’s technical community to step up to providing the technologies, engineering, and systems to regain the frontiers of the Moon, to extend our reach to Mars, and to explore the beyond. These advanced Avionics and Software technologies will be implemented in the CEV, Crew Launch Vehicle (CLV), and robotic missions; embedded in operations; flown on spacecraft; and used by astronauts.

Sub Topics:

X1.01 Automation for Vehicle and Habitat Operations

Lead Center: ARC

Participating Center(s): JPL, JSC

Automation and autonomy are key elements in realizing the vision for space exploration. Constellation systems that would benefit from automation and autonomy include crewed vehicle systems, surface robots, habitats, and infrastructure (in situ resource utilization, power systems, etc.). Needed capabilities range from decision support systems in Mission Control to autonomous robotic operations for the Moon and Mars. These capabilities will be instrumental for decreasing workload, reducing dependence on Earth-based support staff, enhancing response time, and releasing crew and operators from routine tasks to focus on those requiring human judgment. In addition, significant reductions in Mission Risk can be achieved through the use of automated checking and enforcing of flight rules and constraints.

The NASA Exploration Technology Development Program (ETDP) has been developing a set of core autonomy capabilities that can adjust the level of human interaction from fully supervised to fully autonomous. To further the application of adjustable automation and autonomy, development is needed in three broad areas:

- Execution tools;
- Decision support systems;
- Trustable systems.
Execution Tools

Executives are a key autonomy capability. However, support tools are needed to facilitate the authoring and validation of execution scripts. Tools that are not tied specifically to one executive would provide NASA the most flexibility in applying such tools across projects. Examples of needed capabilities include:

- Graphical tool for monitoring and debugging plan execution;
- Graphical tool for creating and editing execution scripts;
- Tools for authoring and validating execution plans;
- User friendly abstraction of low-level execution languages by adding syntactic enhancements.

Decision Support Systems

Decision support systems amplify the efficiency of operators by providing the information they need when and where they need it. As the complexity of the constellation system increases, so must the capabilities of decision support systems. Decision support tools are needed that:

- Command and supervise complex tasks while projecting the outcome of actions and identify potential problems;
- Understand system state, including visualization and summarization;
- Allow the system to interact with a user when generating the plan and allow evaluation of alternate courses of action;
- Integration of a planning and scheduling system as part of an on-board, closed loop controller;
- Scale up existing techniques to larger problem applications.

Trustable Systems

Systems that support or interact with crew require a very high level of reliability. Tools are needed that improve the reliability and trustworthiness of autonomous systems. These include:

- Ability to predict what the system will do;
- Guarantees of behavioral properties;
- Other properties that increase the operator’s trust;
- Verifiability (e.g., restricted executive languages that facilitate model-based verification).

To enable the application of intelligent automation and autonomy techniques, the technologies need to address two significant challenges: configuration management and software validation.
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 address the definition of autonomy and automation software architectures that facilitate adaptation and ensure correctness.

X1.02 Reliable Software for Exploration Systems

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

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. It will be challenging, but critical to NASA's exploration objectives to ensure that these capabilities are reliable and can be developed and maintained affordably. 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 Integrated Systems Health Management (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).

X1.03 Radiation Hardened/Tolerant and Low temperature Electronics and Processors

Lead Center: LaRC

Participating Center(s): GSFC, MSFC

Electronic technologies that are to be used in near-term exploration activities must be capable of operating on the lunar and/or Martian surfaces. Systems will need to operate across a wide temperature range and must survive frequent (and often rapid) thermal-cycling. For example, the Moon's equatorial regions experience 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. Likewise, the diurnal temperature on Mars spans from about -120°C to +20°C. While many types of devices can operate down to very low temperatures (e.g., SiGE HBT's), there are significant circuit design challenges that need to be addressed.

Thermal cycling present in lunar and Martian environments introduces reliability concerns associated with mechanical stress and fatigue of components and integrated circuits. For example, thermal cycling may result in mechanical or packaging related fractures. The selection of appropriate materials is therefore critical to developing suitable electronic products.

In addition, electronic systems and/or components must be radiation tolerant, operating reliably after receiving a total ionizing dose (TID) greater than but not equal to 50 krads (Si) and providing single-event latchup immunity (SEL) greater than but not equal to 100 MeV cm²/mg.

Proposals are sought in the following specific areas:
• Wide temperature (-180°C to +130°C) and low-temperature (-230°C), radiation-tolerant, low-power 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, and drive electronics for sensors, actuators, and communications transponders.

• Packaging capable of surviving numerous thermal cycles and tolerant of the extreme temperatures on the Moon and Mars. This includes the use of appropriate materials including substrates, die-attach, encapsulants, thermal compounds, etc.

• Tightly-integrated electronic sensor and actuator modules that include power, command and control, and processing. Such modules should be capable of operating at the lunar and/or Martian temperature extremes.

• Radiation-tolerant, SEL immune, wide temperature (-180°C to +130°C), and 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 and wide-temperature electronic systems and components.

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

• Circuit design and layout methodologies/techniques that facilitate improved low-temperature (-230°C) analog and mixed-signal circuit performance.

• Radiation-tolerant processors with significantly improved throughput and processing efficiencies. Chip-level (not board-level) technologies optimized for numerically intensive algorithms and applications with the following minimum performance metrics are sought:
  
  - Sustained throughput - 2 GMACS (16-bit operations);
  - Power efficiency - 1 GMACS/W (16-bit operations);
  - Total ionizing dose - 100 krad;
  - Single event upset rate - 10-10 errors / bit-day;
  - Single event latchup - greater than 75 MeV/cm²/mg;
  - Operational temperature range - -55°C to +125°C.

Proposals should demonstrate a working knowledge of temperature concerns, whether they be mechanical (material transition points, thermal stress, fatigue, fracture, etc.) or electrical (carrier freezeout, base-emitter injection efficiency, leakage, threshold voltage dependency, Johnson noise, charge trapping, kink effect, etc.).

Research should be conducted in two phases. During Phase 1, research should demonstrate the technical feasibility and show a path towards a hardware/software demonstration. During Phase 2, emphasis should be placed on developing and demonstrating the technology under relevant test conditions. Additionally, a path should be outlined that shows how the technology could be commercialized or further developed into space-worthy systems. When applicable, researchers should deliver a demonstration unit for functional and environmental testing at the completion of the Phase 2 contract.
Innovative health management technologies are needed throughout NASA's Constellation architecture in order to increase the safety and mission-effectiveness of future spacecraft and launch vehicles. In human space flight, a significant concern for NASA is the safety of ground and flight crews under off-nominal or failure conditions. The new Ares Crew Launch Vehicle will provide the means to abort the crew using a launch abort system. In case of a catastrophic failure during launch or ascent, the decision to abort the crew needs to be made within a very brief timeframe and with high certainty: either false positive or false negative crew abort indications carry a large safety and cost burden. Furthermore, the Constellation architecture allows for fully-automated crew abort under certain circumstances, increasing the accuracy and sensitivity requirements on the system health management function for the Ares launch vehicle and the Orion crew capsule.

There are other health and status requirements beyond launch and ascent. Traditional means of verifying space system health and status, such as caution and warning systems that are triggered by off-nominal sensor values are rather limited in their utility. In addition to issues such as sensor failures and false alarms, redline-triggered caution and warning events are difficult to interpret, often requiring involvement of large numbers of mission support staff to isolate a failure and initiate a recovery procedure. Health and status methods that depend on support from the ground are likely to become a safety liability as communication delays or bottlenecks increase (e.g., lunar trips). 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. For deployment on human missions, health management systems must be treated as Class A human-rated systems as defined by NASA procedural requirements (NPR 7150.2) and must undergo formal verification and validation.

Future ground operations will require quick and efficient turnaround and processing of spacecraft for launch. In addition, new operations concepts must be developed to provide a high level of safety and mission assurance while reducing ground processing and mission support staff. New methods driven by health management innovation may be used to curtail system lifecycle costs through more cost-effective inspection and certification of flight systems, as well as more cost-effective management of ground and mission operations.

Proposals should be responsive to the overall goals and objectives of NASA's Constellation and Lunar Precursors and Robotics 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 solid rocket motors, liquid propulsion systems, structures and mechanisms, thermal protection systems, power, avionics, life support, and communications. Proposals that involve the use of existing testbeds or facilities at one of the participating NASA centers (ARC, MSFC, KSC, or JPL) for technology validation and maturation are strongly encouraged.

Specific technical areas of interest related to integrated systems health management include the following:
• Methods and tools to enable early-stage design of health management functionality during the development of space 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.

• Innovative methods for sensor validation and robust state estimation in the presence of inherently unreliable sensors. Proposals should focus on data analysis and interpretation using legacy sensors rather than development of new sensors or sensor systems.

• Model-based methods for fault detection and isolation in rocket propulsion systems based on existing sensor suites during pre-launch propellant loading and during mission operations.

• Concepts for advanced built-in-tests for spacecraft avionics that reduce or eliminate the need for extensive functional verification and to predict remaining life of avionics systems based on usage history.

• Methods for robust control of critical components, subsystems, and systems and robust execution of critical sequences during launch operations or 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.

• Innovative human-system integration methods that can convey a wealth of health and status information to flight crews, ground and mission support staff quickly and effectively, especially under off-nominal and emergency conditions.

• Verification and validation techniques for advanced fault detection and prognostic capabilities leading to certification for use in human rated critical systems in a cost-effective manner.

• Innovative approaches to effective utilization of health information from NASA spacecraft and launch vehicles with seamless integration to ground based systems using commercial health information from programmable logic controller systems and commercial Reliability, Availability and Serviceability (RAS) systems.

Sensors for Autonomous Systems Topic X2

The Sensors for Autonomous Systems topic is defined to include sensors, sensor components or sensor systems that provide relative information between a spacecraft and another body, independent of Earth-based assets or personnel. The scope of this topic encompasses relative navigation for rendezvous, proximity operations and docking (RPOD) between a spacecraft and a target vehicle, such as the International Space Station or lunar module, and also precision landing and hazard detection for landing on a lunar or planetary surface. Technology
development is needed to create robust sensor capabilities that work within the required environments and meet functional and performance requirements to accomplish the defined missions.

Sub Topics:

**X2.01 Autonomous Rendezvous and Docking Sensors**

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

The Exploration Systems Architecture defines missions that require rendezvous, proximity operations, and docking (RPOD) of two spacecraft both in Low Earth Orbit (LEO) and in Low Lunar Orbit (LLO). Uncrewed spacecraft must perform automated and/or autonomous rendezvous, proximity operations and docking operations (commonly known as Automated Rendezvous and Docking, AR&D). The crewed versions may also perform AR&D, possibly with a different level of automation and/or autonomy, and must also provide the crew with reliable, fault tolerant relative navigation information for manual piloting. The capabilities of the RPOD sensors are critical to the success of the Exploration Program. The relatively low technology readiness of existing relative navigation sensors for AR&D has been carried as one of the Crew Exploration Vehicle (CEV) Project's top risks.

This subtopic seeks innovative technologies that can provide relative navigation capabilities for rendezvous, proximity operations and docking of two spacecraft. Long-range rendezvous sensors should provide bearing from beyond 200 km to 5 km distance between spacecraft, but range and range-rate are also desirable. Proximity operations sensors should provide range, range-rate, and bearing from approximately 5 km to 100 m. Docking sensors should provide relative position and relative attitude from approximately 100 m to docking; relative attitude may only be needed from 30 m in to docking but longer ranges are desirable. Ideal solutions would combine multiple relative navigation sensing capabilities into a single system in order to reduce mass, volume, and power. Solutions should be designed to operate in Low Earth Orbit, Low Lunar Orbit, or both. Solutions can include a relative navigation sensor "suite" that consists of multiple sensor types but covers the full range; the sensor suite should allow RPOD under any lighting conditions. Solutions should also include a robust and fault tolerant capability that is suitable for a human-rated space vehicle. In addition, the relative navigation technologies should be designed so that existing infrastructure on the International Space Station (reflectors, communications systems, etc.) does not interfere with the relative navigation capability of the maneuvering vehicle.

Some specific technology focus areas of interest include: (1) use of relative navigation sensors that do not require special retro-reflectors or targets on the target spacecraft but can make use of natural features or existing infrastructure; this focus area may make use of Light-Imaging Detection and Ranging (LIDAR) components in order to get range and range-rate to the objects in the field of view, or may use video-based technology; (2) fault tolerant sensor systems; and (3) other technology areas for long-range rendezvous sensors that may include star trackers, infrared sensors, and radio frequency-based sensors; these types of sensors may have an extended range well beyond 200 km.

**X2.02 Autonomous Precision Landing and Hazard Detection and Avoidance**

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

NASA seeks innovative sensor system technologies to support autonomous precision landing with hazard detection and avoidance for landing spacecraft on the lunar surface with extensibility to Mars. Sensor systems that can characterize and identify spacecraft landing surface hazards for purposes of avoidance and surface relative
navigation with high precision and accuracy are of interest. The emphasis of this solicitation is for sensor systems or sensor components that can be utilized in current sensor systems to go beyond current technology capability. These systems or components must be compatible with the environmental conditions of spaceflight and the rigors of landing on the planetary surface. Proposals for development of certain aspects of these technology systems including sensor components that include partnering with other vendors developing this kind of technology are encouraged.

Candidate items include but are not limited to the following:

- Innovative lidar sensor systems and component technologies that directly address autonomous precision landing and hazard avoidance needs
  - 3D imaging lidar systems capable of generating elevation maps covering terrain areas 10k to 100k square meters from 1-2 km altitude with a resolution of the order of 20 cm
  - High efficiency focal plane arrays with over 16k pixels capable of detecting laser pulses shorter than a few nanoseconds (wavelengths of interest are 1 to 1.5 microns)
  - Reliable Readout Integrated Circuit (ROIC) with high frame rate capability greater than 20 hertz and capable of resolving target depth to a few centimeters
  - Novel real-time lidar image reconstruction and processing technologies;

- Passive or active detector systems which operate in certain ranges between 100 km to 2 km for utilization in terrain relative navigation systems;

- Sensor systems which provide very high accuracy and precision for determining velocities and altitudes relative to the surface with 0.1% accuracy;

- Robust and reliable sensor system or sensor system components which significantly reduce the impact of incorporating such sensors or components on the spacecraft in terms of volume, mass, power, thermal dissipation, placement or cost;

- Semiconductor or solid-state-controlled mirror systems capable of rapidly moving a lidar FOV over a defined areas;

- Innovative systems that significantly improve current precision landing and hazard detection capability for lunar descent and landing.

Proposals should describe the expected improvements and advantages of proposed deliverables over existing technologies and should estimate the effects of these improvements on the state-of-the-art navigation and hazard detection capabilities. Attributes of interest include reliability, precision, lighting requirements, accuracy, thermal sensitivity, heat dissipation capability and performance degradation due to rocket plumes and lunar dust.
Environmental Control and Life Support (ECLS) Topic X3

Environmental Control and Life Support (ECLS) encompasses the process technologies and equipment necessary to provide and maintain a livable environment within a crewed spacecraft or surface habitat cabin. Functional areas of interest to this solicitation include atmospheric resource management; airborne particulate matter removal and disposal; water recovery systems; waste management; 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 and long duration lunar outpost missions. Vehicles of interest include the Lunar Lander and Lunar Outpost (LO). Requirements include operation in micro- and/or partial-gravity as well as ambient and reduced-pressure cabin environments. Special emphasis is placed on developing 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 Resource Management and Particulate Matter Removal

Lead Center: JSC

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

Atmospheric resource management and particulate matter removal 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. Systems must be innovative and extremely efficient with respect to volume, mass, energy and thermal requirements.

Atmospheric Resource Management

Atmospheric resource management encompasses process technologies and equipment to supply, store, and condition atmospheric gases; provide gaseous oxygen at pressures at or above 3,000 psia; and achieve mass closure by recycling resources and using in situ resources. Typical process technologies employed for achieving these needs may include reduction of carbon dioxide to carbon, sub-critical gas storage, and electrolytic oxygen production with compression. Techniques for enhancing NASA’s present capabilities and filling technology gaps are sought. The ability to provide early computer-based process technology predictive performance models for application scale-up and scale-down is desirable. Areas of emphasis include:

- Carbon Dioxide Removal and Reduction for Recovery of Oxygen: 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 sought. Technologies to reduce carbon dioxide to a carbon product with high efficiency that yields a high percentage mass balance closure are also of interest.
• Gas Supply and Storage: 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. Further, process technologies leading to a ready, in-flight renewable source of 3,000-psia gaseous oxygen are of interest.

Particulate Matter Removal and Disposal

Dust and particulate matter contamination are challenges that must be overcome for lunar surface exploration. Particulate contamination originating from the external surface environment or from internal sources are both of concern. Development of process technologies and equipment to minimize the impacts of surface dust on crew health and equipment inside the habitable volume are sought, including novel approaches to remove dust from spacecraft cabin atmosphere and isolate habitable volumes from surface dust. Candidate technology solutions should provide high efficiency and long-lived removal capacity. Technologies must be tolerant to the abrasive effects of dust particles. Performance should be demonstrated with appropriate lunar dust analogs or simulants. Areas of emphasis include:

• Removal of Fine Atmospheric Dust Particulates: Fine airborne lunar dust will be detrimental to crew health. Filtration technologies are sought that will provide significantly improved capture efficiency of both fines (10 nm to 2 microns) and ultra-fines.

• Regenerative Processes and Filters: Regeneration techniques and regenerable filters are sought that effectively handle a broad particulate size range from larger-sized particles down to fine particle sizes. These techniques must be able to separate and dispose of lunar dust to the lunar surface, and/or dispose of and collect all other particulate matter to highly compacted units/states. Salient features for this application include capability for regeneration in place, long-lived and large bulk removal capacity, and high efficiency. Operational modes of continuous regeneration or long interval regeneration cycles using either single or multi-stage regeneration processes will be considered. Methods for determining and annunciating the loading and unloading status of the regenerative unit and for automated regeneration are of interest.

• 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.

X3.02 Water Processing and Waste Management Systems

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

Water processing and waste management systems supporting critical needs for lunar mission architectures are requested. Improved technologies for recovery of water and other resources as well as safe long term stabilization and storage of residuals inside and outside the habitat are needed. Water processes collect, store, recycle, and disinfect water for reuse as both drinking water and hygiene water. Waste processes collect, process, recover resources, stabilize, and store residuals. Although this solicitation is directed at technologies for lunar missions, crosscutting technologies that are also applicable to human missions to Mars are of interest. Proposals should explicitly describe the weight, power, and volume advantages of the proposed technology.
**Water Reclamation**

Efficient treatment of wastewater from a variety of sources is critical to long-term exploration missions. Sources of water to be recovered may include urine, wash water, humidity condensate, and/or water derived from in situ planetary resources. Treatment processes should produce potable and hygiene water supplies. Treatment methods for long duration missions should seek high levels of mass closure. Systems targeted for planetary surface applications must be designed to function in hypogravity environments but need not be microgravity compatible. Areas of emphasis include:

- Disinfection and residual disinfectant technologies that are compatible with both biological and physicochemical wastewater processing systems;
- Techniques to minimize or eliminate biofilms, microbial contamination and/or solids precipitation from potable water, wastewater and water treatment system components;
- Post-treatment methods to reduce total organic carbon from 100 mg/L to less than 1 mg/L in the presence of 50 mg/L bicarbonate ions, 25 mg/L ammonium ions and 25 ppm other inorganic ions.

**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:

- Solid waste stabilization including water removal and recovery of water from wet wastes (including human fecal wastes, food packaging, brines, etc.);
- Solid waste storage and odor control (e.g., catalytic and adsorptive systems);
- Energy efficient/internal heat recycling waste pyrolysis systems for mineralization of wastes.

**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.

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**X3.03 Spacecraft Cabin Environmental Monitoring and Control**

Lead Center: JPL

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

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. A desire is for an immersible water quality sensor that is reversible; i.e., it tracks analyte changes in water without having to replace any sensor chemistry element.

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.
X3.04 Spacecraft Fire Protection
Lead Center: GRC
Participating Center(s): ARC, JPL, JSC, KSC, MSFC

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 and detector systems 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.

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Extra Vehicular Activity (EVA) Topic X4

Advanced extravehicular activity (EVA) systems are necessary for the successful support of future human space exploration missions. Advanced EVA systems include the space suit pressure garment, the portable life support system, tools and equipment, and mobility aids, such as rovers. Complex missions require innovative approaches for maximizing human productivity and for providing the capability to perform useful work tasks. Top level requirements include reduction of system hardware weight and volume; increased hardware reliability, durability, and operating lifetime (before resupply, recharge and maintenance, or replacement is necessary); reduced hardware and software costs; increased human comfort; and less-restrictive work performance capability in the
space environment, in hazardous ground-level contaminated atmospheres, or in extreme ambient thermal environments. Environmental protection, such as space suit radiation protection and dust mitigation technologies, are of particular interest. Innovative and highly reliable EVA communications, avionics and informatics are also of interest. All proposed Phase 1 research must lead to specific Phase 2 experimental development that could be integrated into a functional EVA system.

**Sub Topics:**

**X4.01 Space Suit Pressure Garment and Airlock Technologies**

**Lead Center:** JSC  
**Participating Center(s):** GRC

Innovative technologies are needed to meet the challenging requirements for the exploration space suit pressure garment and surface systems airlock. These technologies should be able to be developed further for application to the lunar missions.

Specifically, the space suit pressure garment requires radiation protection technologies that protect the suited crew member from radiation particles, puncture protection technologies that provide self-sealing capabilities when a puncture occurs and minimizes punctures and cuts from sharp objects, dust and abrasion protection materials to exclude dust and withstand abrasion and prevent dust adhesion, flexible thermal insulation suitable for use in vacuum and low ambient pressure, and space suit low profile bearings that maximize rotation which is necessary for partial gravity mobility requirements, and is also lightweight and low cost.

Due to the expected large number of space walks that will be performed on the lunar surface, innovative technologies and designs for surface airlocks will also be needed. Technology development is needed for minimum gas loss airlocks providing quick exit and entry that can accommodate an incapacitated crew member, suit port/suit lock systems for docking a space suit to a dust mitigating entry/hatch in order for the space suit to remain in the airlock and prevent dust from entering the habitable environment, and active and passive space suit and equipment dust removal technologies inside and outside the airlock.

**X4.02 Space Suit Life Support Systems**

**Lead Center:** JSC  
**Participating Center(s):** GRC

Exploration missions will require a robust, lightweight, and maintainable portable life support system. Technology development is needed for long-life and high-capacity chemical oxygen storage systems for an emergency supply of oxygen for breathing; low-venting or non-venting regenerable individual life support subsystem(s) concepts for crew member cooling, heat rejection, and removal of expired water vapor and CO$_2$; convection and freezable radiators that will be low cost and lightweight for thermal control; innovative garments that provide direct thermal control to crew member; high reliability pumps and fans that will provide flow for a space suit but can be stacked to give greater flow for a vehicle; CO$_2$ and humidity control devices that, while minimizing expendables, function in a CO$_2$ environment; and a non-toxic, non-flammable, super cooled below 32°F phase change material that can absorb metabolic heat for an 8 hour duration.

Also for removing metabolic heat from the astronaut, research is needed for a variable conductance flexible suit...
garment that can function as a radiator for high metabolic loads and as an insulator for low metabolic loads.

X4.03 Space Suit Displays, Cameras, Controls, and Integrated Systems

Lead Center: GRC
Participating Center(s): JSC

Future exploration space suits will require innovative technologies for displaying various types of information. Technology development is needed for space suit mounted displays for use both inside and outside the space suit; outside mounted displays must be compatible with the space radiation, thermal, and vacuum environment. Examples include internally or externally mounted helmet displays and lightweight wrist or arm mounted displays.

The spacesuit will also require research for lightweight CO$_2$, biomedical, and core temperature sensors with reduced size, increased reliability, and greater packaging flexibility; and camera systems that are lightweight, low power draw, and integrate with the spacesuit. The camera system should allow both motion and still imagery providing compressed digital data output suitable for transmission over IP networks. This camera must provide excellent situational awareness for crew members and quality imagery for remote viewing and public relations.

Research is also needed for lightweight, low power consuming general purpose computing platforms that are tolerant to the space radiation environment. Such platforms could be processor or FPGA based to allow the use of on-suit software applications such as biomedical advisory algorithms, procedure displays, navigation displays, and voice recognition. Technology development is needed for low computational overhead voice recognition processing systems capable of performing on lightweight radiation tolerant embedded computing platforms.

Lunar In-Situ Resource Utilization (ISRU) Topic X5

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

Sub Topics:

X5.01 Oxygen Production from Lunar Regolith

Lead Center: JSC

Participating Center(s): GRC, KSC, MSFC

Oxygen production from lunar regolith processing consists of receiving regolith from the excavation subsystem into a hopper, transferring that regolith into a reactor where it is reduced using chemical or an electrochemical process, potentially intermediate reactions to reach oxygen, purification of the oxygen, and transfer of the oxygen to the liquefaction and storage subsystem. After oxygen has been extracted from the regolith, the spent regolith must be removed from the reactor and returned to the excavation subsystem for disposal. Depending on the process used, the reactor may contain reduced metals that can be extracted in their pure form for use as a manufacturing feedstock.

To maximize the benefits of In Situ Resource Utilization (ISRU) for the Lunar Exploration Architecture, oxygen production systems must minimize the mass and power consumption of ISRU systems. ISRU systems must be able to produce many times their own mass in oxygen and other products to provide a benefit to the architecture. ISRU systems must be able to autonomously operate in a harsh environment that has wide temperature swings, high radiation and abrasive dust. Depending on the outpost location, the systems must be able to sustain many startup and shutdown sequences when solar power is not available. Some of these shutdown periods may exceed several hundred hours.

The next phase of ISRU research and development will focus on the design and testing of a regolith reduction system that can produce roughly 1000 kilograms of oxygen in a year. The operation assumption is that the production plant will operate off of solar power which is estimated to be available about 70% of the time and will operate at a lunar pole with highlands soils. The current oxygen production approaches being developed into prototypes are: Hydrogen Reduction, Carbothermal and Molten Oxide Electrolysis. The basic description of these approaches can be found in the NASA funded report by Eagle Engineering, entitled "Conceptual Design of a Lunar Oxygen Pilot Plant (1988)". The report can be found on the web at [http://www.isruinfo.com/index.php](http://www.isruinfo.com/index.php). [1]

NASA is seeking subsystem component technologies rather than full system proposals. We would like to encourage the development of subsystem components that could be inserted into our Exploration Technology Development Program funded oxygen production systems to improve the mass, power and efficiency of the system. Technology areas of particular interest are:
• Heat exchangers to recover energy from heated regolith;
• Low/No maintenance system filtration technologies for removing dust from gas lines;
• Water condensers that would use the cooling potential of the space environment to water condensation with minimal energy usage;
• Solar Concentrators that are lightweight and able to deliver concentrated solar thermal energy to reactors generating regolith temperatures from 900°C up to 1600°C;
• Gas Separators that provide low pressure drop separation of the system and product gas streams from impurities (e.g., H₂S, SO₂);
• Microchannel methanation reactors that convert a mixture of carbon monoxide, carbon dioxide, and hydrogen to methane and water vapor with carbon monoxide and carbon dioxide consumed to the maximum extent possible;
• O₂ Purification technologies that perform the removal (and reclamation) of all contaminants prior to liquefaction of the oxygen;
• Feed systems to introduce regolith to the reactors and remove the regolith, slag or molten products from the reactor post processing. The systems must minimize the possibility of dust contaminating the reactor seals;
• Reactor Seals: The sealing of reactors includes sealing gas interfaces from the reactor to the remainder of the system and also the regolith feed/exit to the reactor. Valves proposed for use for gas interfaces must be capable of 1000s of operations and able to operate when lunar dust is present in the gas stream. Reactor regolith feed/exit seals proposed for use must either be kept clean, can be automatically cleaned, or seal even with a coating of lunar dust. Interested companies should keep in mind that each reactor system operates at significantly different temperatures so the gas and regolith sealing methods could see a wide range of thermal conditions.

X5.02 Lunar Regolith Excavation and Material Handling
Lead Center: JSC
Participating Center(s): GRC, JPL, KSC

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

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

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

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

- Specific technologies for flow of regolith in the lunar environment related to excavation, handling and transportation.

- Modeling of granular material physics in partial gravity related to regolith excavation, handling and transportation.

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**X5.03 Lunar Volatile Resource Prospecting and Collection**

_Lead Center: JSC_  
_Participating Center(s): GRC, JPL, KSC_

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

- Excavation techniques for soil-like to rock-like regolith (70MPa), depending on water content, and very
cold (40K to 100K) regolith and local environment conditions;

- Excavation technology or systems for collecting regolith while preserving the loosely held volatile species that may be present;

- Regolith handling, processing, and heating techniques that minimize the amount of time and energy required to evolve volatiles (either solar wind implanted or in permanently shadowed craters);

- Gas separation and collection techniques for a product stream containing various concentrations of hydrogen, carbon dioxide, nitrogen, helium, water, ammonia, and methane;

- Demonstration of sealing technology for repetitive (less than 50 times) use at a wide range of temperatures (40K - 500K nominal and up to 1500K maximum) in abrasive, electrostatic, high vacuum environment; and

- Specific technologies or recipes for implanting volatile species in terrestrial samples of lunar regolith simulant to support volatile species collection and extraction technology development.

Structures, Materials and Mechanisms Topic X6

The SBIR topic area of Structures, Materials and Mechanisms centers on (1) developing lightweight structures and advance materials technologies to support Lunar Landers and Lunar Habitats and (2) low-temperature mechanisms to improve and or allow for reliable and efficient mechanism operation for long duration in the cold polar and crater regions of the lunar surface. Lightweight structures and advanced materials 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 structures and materials program utilizes and combines multi-center R&D teams into focused activities for developing lightweight structure technology for the primary load bearing structure of the pressurized elements of the Vision for Space Exploration (VSE) program. 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. Three subtopics represent the structures and materials area: (1) Lightweight Structures; (2) Low Temperature Mechanisms; and (3) Advanced Radiation Shielding Materials. In missions to the lunar surface, permanently shadowed regions of the Moon, e.g., the bottoms of craters in the Polar Regions, are high interest to science and exploration. These areas appear to remain at temperatures of 50 to 80K (-223°C to -193°C). Current surface exploration hardware has demonstrated capability to operate in the range of -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) improve mechanism performance (torque out put, 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), for lunar surface operations. This topic area is responsible for mid-level technology research, development, and testing through experimental and/or analytical validation. There is one subtopic in this area, Low Temperature Mechanisms.
Sub Topics:

**X6.01 Lightweight Structures**

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

This subtopic solicits innovative structural concepts that support the development of lightweight structures technologies that could be applicable to lunar surface landers and habitats. The targeted innovative lightweight structures are for primary pressurized structures such as 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:

- Lightweight multifunctional and/or integrated structural systems that include radiation shielding, impact shielding, thermal management, damage tolerance and durability, and/or integral diagnostics/health monitoring, and novel inspection/nondestructive evaluation 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 impact 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. Research should be conducted to demonstrate technical feasibility during Phase 1 and show a path toward a Phase 2 hardware demonstration, and when possible, deliver a demonstration unit for functional and environmental testing at the completion of the Phase 2 contract.

**X6.02 Low Temperature Mechanisms**

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

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 380K (-190°C to +107°C). 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.

Research should be conducted to demonstrate technical feasibility during Phase 1 and show a path toward a Phase 2 hardware demonstration, and when possible, deliver a demonstration unit for functional and environmental testing at the completion of the Phase 2 contract.

### X6.03 Advanced Radiation Shielding Materials

**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 particulate radiation species are considered, including electrons, protons, neutrons, alpha particles, light ions, heavy ions, etc. All space radiation environments in which humans may travel in the near future are considered, including low-Earth orbit, geosynchronous orbit, Moon, etc. The primary area of interest for this 2007 solicitation is radiation shielding materials systems for long duration lunar surface protection for humans. Lightweight radiation shielding materials systems for short-term in-space operations for humans are also of interest. The materials emphasis is on multifunctional materials, where two of the functions are, but not exclusively, radiation shielding efficiency and structural integrity. Radiation shielding design software to optimize multifunctional materials usage in specific designs is also of interest. Radiation shielding augmentation materials are part of this solicitation, along with associated software tools to minimize augmentation requirements. Research should be conducted to demonstrate technical feasibility during Phase 1 and to show a path toward a Phase 2 technology demonstration. 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:

- Innovative lightweight radiation shielding materials and structures to shield humans in crew exploration vehicles, large space structures such as space stations, orbiters, landers, rovers, rigid habitats, inflatable habitats, spacesuits, etc.;

- 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 phases of the design process;

• Radiation shielding software, compatible with Multi-Disciplinary Optimization (MDO) analysis, for optimization of specific vehicle designs;

• 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;

• Innovative fabrication techniques to fabricate advanced radiation shielding materials into useful products and structural components;

• 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;

• 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;

• Innovative concepts to reuse, recycle, and reprocess materials and structures in space for use as radiation shielding materials and structures.

**X6.04 Advanced Composite Materials**

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

This subtopic solicits innovative research for advanced composite materials, processing and characterization 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. Reduction in structural mass translates directly to additional up-and-down mass capability that would facilitate logistics and increase science return for future missions. Advanced composites are targeted that could be implemented into vehicle and propulsion systems for launch vehicles, lunar landers, and habitats. Innovations in technology are needed to increase specific strength and stiffness, provide radiation shielding, enhance thermal management, reduce Micrometeoroid/Orbital Debris (MMOD) damage potential, and provide effective nondestructive verification and characterization, while maintaining safety, reliability, and reducing costs.

Advanced composite material systems and their corresponding manufacturing, processing and verification techniques are desired. Examples would include, but are not limited to, material systems and mature applications of nano-structured materials. Processing examples would include, but are not limited to, automated composite fiber/tape placement, non-autoclave curing, processing innovations for multifunctionality, ceramic processing, nano materials processing, freeform fabrication, and bonding of composites.

Development of concepts can include material system characterization, proof-of-concept demonstrations for integrated lightweight structures, innovative multifunctional concepts, enabling performance and affordability (including life cycle costs) enhancement, damage tolerance/control techniques, 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. Preferred processing and verification techniques would include non-contact, high-resolution nondestructive evaluation 2D and 3D imaging and characterization approaches using electromagnetic techniques such as Terahertz and millimeter waves with resolutions of 1-5 mm. Research should be conducted to demonstrate technical feasibility during Phase 1 and show a path toward a Phase 2 prototype demonstration.

Lunar Operations 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 lunar exploration missions, providing systems that interact with humans, handle surface equipment and move people and their payloads at, and away from, a lunar outpost. The objective is to produce new technology that will reduce crew extra-vehicular activity (EVA) and intra-vehicular activity (IVA) workloads, lunar operations and reduce the total mass and volume of equipment and materials required to support missions. The proposals should focus on component technologies to improve the operations of exploration equipment, allowing for less expensive, more productive and less risky missions. This research will focus on technology development 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. This work will include supporting the crew in IVA and in EVA tasks. The third phase of surface exploration will include long-term maintenance of the facility, as well as supporting activities performed between crews.

Sub Topics:

X7.01 Supportability

Lead Center: JSC

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

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:
- 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.

Rapid manufacturing processes have advanced rapidly in recent decades. The technology has gone from a means of quickly producing models to a means of quickly producing usable hardware. NASA seeks technology improvements which extend the efficiency of rapid manufacturing and improve the properties of resulting components. NASA also seeks to identify different applications that will highlight the capabilities of rapid manufacturing in support of the Vision of Space Exploration and potential commercial applications. NASA also seeks technology focused on integration of rapid manufacturing, computer numerical control, coordinate measuring machines, Robotics and Digital Manufacturing and Simulations technologies. This technology should be focused on an autonomous system where the parts fabricated in rapid manufacturing can be positioned for machining on critical surfaces, then positioned for measurements and inspections and ultimate delivery (independently and remotely). The results should be an autonomous system where these technologies are integrated as modules to produce the end result.

X7.02 Human Systems Interaction

Lead Center: JSC

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

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 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 site operations, both at an outpost and at remote lunar surface locations. Site operations support focuses on two types of activities: (1) tedious, highly repetitive, long-duration tasks that cannot be performed by EVA crew and (2) rapid response for addressing emergency, time-critical situations. Candidate tasks include: mobile camera platform control, systematic site survey (engineering and/or science), inspection, emergency response, site preparation (clearing, leveling, etc.), and instrument deployment. 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) line-of-sight remote, and lunar. Particular interest is given to systems that flexibly support human-robot operations in the presence of time-delays of up to 10 seconds.

- Adaptive user interfaces including perception, speech recognition, context awareness, computational cognitive models, and 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.

- Geospatial tools for situational awareness including content generation tools for geospatial information, particularly for supporting planetary surface missions; software libraries for generating, parsing, and importing heterogeneous mission data (orbital imagery, navigation information, sensor and instrument readings, etc.); and terrain modeling (Digital Elevation Map).

- Vehicle control components 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 Mobility and Transportation

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

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 mobility systems to provide the power train for site clearing, pad construction, and regolith manipulation (note that the power train attachments for this activity will be provided by the in situ resource utilization (ISRU) area); 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:

- 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.

- Low-mass, high-strength, long-life wheels capable of spreading supported load over an extended contact patch area and moving over surface terrain similar to loose beach sand. Range, Life, Mass, Mean-time-to-repair, and Mean-time-between-failure are key performance parameters being sought.

- Reliable navigation sensors to support surface mobility by a range of vehicles (ranging from MER-class to LRV-class). For example, a range finder with dynamically-operated foveal aperture could support wide field-of-view scanning and three-dimensional object tracking.

- Navigation and communication infrastructure technologies for use on the Lunar surface to support surface mobility and communication between lunar base, EVA astronaut and mobile rover/robotic assistant.

X7.04 Surface System Dust Mitigation

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

The general objective of the subtopic is to provide knowledge and technologies (to Technology Readiness Level (TRL) 6 development level) required to address adverse dust effects to exploration surface systems and equipment, which will reduce life cycle cost and risk, and will increase the probability of sustainable and successful lunar missions. The subtopic will help to develop a balance of near- and long-term knowledge and technology development, driven by Exploration Systems Mission Directorate needs and schedule requirements, aligned with existing technology investments where possible. The technical scope of the subtopic includes the evaluation of lunar dust effects and development of mitigation strategies and technologies related to Exploration Surface Systems, such as: Rovers and Robotic Systems, In Situ Resource Utilization (ISRU) Systems, Power Systems, Communication Systems, Airlock Systems and Seals, Habitats, and Science Experiments.

The subtopic specifically requests technologies addressing dynamic mechanical systems used for lunar surface
missions with potential to mitigate effects of lunar dust. For lubricated mechanisms, such as drives and pointing mechanisms, the sealing element must be durable enough to maintain a hermetic seal to prevent lubricant outgassing and dust contamination for at least 5 years. Also, the bearings, gears, etc. of the mechanism must be robust enough to survive and provide nominal operation with lunar dust contamination and possible lubrication starvation.

The subtopic also requests proposals for advanced materials, coatings, and related technologies with the proper combination of physical, mechanical, and electrical properties, and lunar environmental durability, suitable for use in dust mitigation applications on the lunar surface.

Energy Generation and Storage Topic X8

This topic includes the development of power capabilities that are on the critical path to enabling the Exploration Vision including human and robotic exploration missions from Earth orbit to the Moon and ultimately, Mars. Areas of primary interest are: orbital and planetary surface energy storage and non-solar power generation. Flight elements of the Exploration Vision initially include the Orion and ARES crew and launch vehicles, respectively. For lunar capability, additional elements include the Lunar Lander or Lunar Surface Access Module (LSAM), robotic missions, and surface systems. Surface systems include human habitats, Extravehicular Activities (EVA), science measurements, and the utilization of in situ resources. These flight systems require energy storage capabilities up to and greater than 10 kW-hr. Effective solutions require high-capacity, high-energy density, and long-life energy storage systems. Rechargeable lithium-based batteries (e.g., ion, sulphur) that provide energy storage for Exploration missions are required to be human-rated. For the lunar environment, batteries must operate over a greater range of temperatures than current state-of-the-art systems. The Exploration architecture calls for advanced fuel cells to meet the LSAM and surface system power requirements. Fuel cell systems provide power largely independent of environment (solar incidence), which allows greater mission flexibility and provide more power than other energy storage systems. Regenerative fuel cell systems, which combine a fuel cell with a water electrolyzer, will be required to meet long duration surface power energy storage needs. Prior architecture studies have identified nuclear power technology to effectively satisfy high power requirements for extended duration lunar surface missions. Nuclear power generation is especially attractive for missions with significant solar eclipse periods, including non-polar locations and inside lunar craters. Likewise, nuclear power has been identified as a critical power technology for Mars exploration and a lunar deployment is proposed to reduce risk through demonstration and validation of capabilities.

Sub Topics:

X8.01 Fuel Cells for Surface Systems

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

Energy storage devices are required to enable future robotic and human exploration missions. Advanced regenerative fuel cell (RFC) energy storage systems are sought for use in a wide range of Exploration mission
applications including portable power for landers and rovers, and stationary power for surface bases. Technology advances that will reduce the weight and volume, improve the efficiency, life, safety, system simplicity and reliability of RFC systems are desired. The specific advancements of interest are outlined below.

Regenerative Fuel Cell (RFC) Systems: Primary fuel cells and water electrolyzers are the two major constituent subsystems of RFC systems. Of these two subsystems, water electrolyzers are at a lower level of technology readiness than primary fuel cells.

Specifically, technological advances are sought in the area of highly efficient, high-pressure proton-exchange-membrane (PEM) water electrolyzers. Highly efficient operation reduces the total quantity of reactants required, thereby minimizing weight. The efficiency of electrolysis stacks increases by operating at lower current densities. High-pressure electrolysis eliminates or reduces the need for external gas compression prior to reactant storage. The draw-back of high-pressure operation, however, is the increased diffusion of reactants across the proton exchange membrane of the cell, which effectively decreases the efficiency. This efficiency loss is magnified at lower current densities. The challenge, therefore, is to minimize this diffusion at higher operating pressures and low current densities, making efficient electrolysis operation possible.

High-pressure electrolysis systems capable of oxygen and hydrogen gas production at pressures less than 2000 psi are of special interest.

Research should be conducted to demonstrate technical feasibility during Phase 1 and show a path toward a Phase 2 hardware demonstration, and when possible, deliver a demonstration unit for functional and environmental testing at the completion of the Phase 2 contract.

X8.02 Advanced Space Rated Batteries

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

Advanced human-rated energy rechargeable batteries are required for future robotic and human exploration missions. Advanced Li-based battery systems are sought for use in a wide range of Exploration mission applications including portable power for landers, rovers, Extravehicular activities (EVA), and astronaut equipment; storage systems for crew exploration vehicles and spacecraft; and stationary energy storage applications such as base power or peaking power applications. Areas of emphasis include advanced component materials with the potential to achieve weight and volume performance improvements and safety advancements in human-rated systems.

Rechargeable lithium-based batteries with advanced non-toxic anode and cathode materials are of particular interest. Technology advancements that contribute to the following performance goals are sought: specific energy greater than 180 Wh/kg, energy density greater than 400 Wh/l, calendar life less than 5 years, cycle life at 100% Depth of Discharge (DOD) greater than 2000 cycles, and fast recharge capability (100% recharge in less than 15
minutes. Systems that combine all of the above characteristics and demonstrate a high degree of safety and reliability are desired.

Proposals are sought which address advanced cathodes with specific capacities in excess of 240 mAh/g at C/2 rate discharge and 25°C and/or advanced anodes with specific capacities in excess of 400 mAh/g at 25°C with minimal irreversible capacity loss.

Research should be conducted to demonstrate technical feasibility during Phase 1 and show a path toward a Phase 2 hardware demonstration, and when possible, deliver a demonstration unit for functional and environmental testing at the completion of the Phase 2 contract.

**X8.03 Nuclear Surface Power**

**Lead Center:** GRC

**Participating Center(s):** MSFC

NASA is interested in the development of highly advanced systems, subsystems and components for use with fission and isotopic power systems for future lunar and Mars robotic and manned missions. Proposals are sought for critical technologies for fission and isotopic power systems to meet the following anticipated missions and applications.

The current Vision for Space Exploration identifies the first human lunar landing in 2017 with subsequent longer duration stays of approximately 6 months in 2021. Fission-based systems are anticipated to enable the long duration stay over the lunar night and for "global access" Mars missions. Initial planetary outpost power levels are anticipated to be between 30-50 kWe with anticipated growth to 100's kWe, accommodating resource production and advanced life support habitation, which require additional power.

Planetary surface human base applications include: habitats, propellant production/liquefaction/maintenance, surface mobility for both robotic and piloted rovers, excavating and mining equipment and science applications such as: deep drilling, resource production demos, weather stations, etc. Isotopic technologies are needed for unique space environments that improve the utilization of a limited fuel supply and have extensibility to fission systems.

Specific technology topics of interest are:

- Advanced, high efficiency, high temperature power conversion less than 20%;
- Electrical power management, control and distribution (1000-5000 V);
- High temperature, low mass thermal management/heat rejection less than 6kg/m²;
- 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 (greater than 10 years), autonomous control and operation, including sensor and control technologies;
- Radiation tolerant systems and materials enabling 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 will be used on robotic and human missions and it is to NASA's advantage to develop those technologies that satisfy both robotic and human mission requirements.

Propulsion and Cryogenic Systems Topic X9

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

Sub Topics:

X9.01 Cryogenic Propellant Storage and Distribution for Space Exploration Applications

Lead Center: GRC

Participating Center(s): ARC, GSFC, JSC, KSC, MSFC
This subtopic includes technologies for long term cryogenic propellant storage and distribution 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 (less than 20\(\text{m}^3\) for supercritical air and payload cooling) to very large (greater than 3400\(\text{m}^3\) 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: passive and active thermal control, pressure control, and propellant feed line conditioning. 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:

1) Thermal Control

**Passive Thermal Control:**

Successful passive thermal control is enabling for all aspects of Cryogenic Fuel Management. The propellant boil-off losses attributable to the passive thermal control subsystem are influenced by Multi-Layer Insulation (MLI) design, MLI to tank attachment techniques and materials, tank to vehicle support structure and attachments, tank size and configuration, tank and insulation penetrations, insulation venting provisions for launch and ascent, flight and surface environments, vehicle orientation in those environments, and thermal control surface coatings and materials.

Applications/Technology Maturity: The Earth Departure Stage (EDS) and the Lunar Surface Access Module (LSAM) descent stage require LH\(_2\) and LO\(_2\) storage durations of 5 to 95 days in Low Earth Orbit (LEO).

The LSAM ascent stage requires LO\(_2\) and LCH\(_4\) storage durations of up to 95 days in LEO and up to an additional six months on the lunar surface.
Development Needs: Passive thermal control development needs include; integration of MLI with micro-meteoroid protection, tank support structure, and other insulation penetrations. Other development needs include; characterization of the potential advantages of subcooled propellants, investigation of options such as shading, advanced materials, mechanisms and other techniques for passive thermal control on the lunar surface.

Active Thermal Control:

Active thermal control combines the passive thermal control technology element with active refrigeration (cryocoolers) to allow storage periods from a few months to years with reduced boil-off losses.

Applications/Technology Maturity: Flight-type 20K (LH₂) cryocoolers of sufficient cooling capacity (20 watts) to eliminate LH₂ boil-off do not exist, and thus the development of 20K cryocoolers is a long-lead technology item. State-of-the-art cryocoolers in the 80K range (LO₂/LCH₄ temperatures) have been developed for cooling sensors and have flown on numerous satellites. However, the integration of these cryocoolers into an active thermal control system for propellant storage of LO₂ and LCH₄ and LH₂ is a technology issue.

Development Needs: Flight cryocooler to propellant tank integration techniques for large space-based storage systems, distributed cooling shields integrated with MLI and development and testing of active cooling techniques for tank penetrations and supports is required. Development of flight-type 20K, 20 watt capacity cryocoolers designed for integration into large space-based LH₂ storage systems is also required for application to Mars missions.

2) Pressure Control

Controlling cryogenic propellant tank pressure in low gravity with minimum boil-off losses without settling the propellants can be accomplished with a thermodynamic vent system (TVS). A TVS subsystem typically consists of a pump for circulation and mixing, a Joule Thompson expansion device/heat exchanger for heat removal, valves and a vent line.

Applications/Technology Maturity: A TVS will be required for the EDS, LSAM and the LO₂/LCH₄ version of the Orbital Maneuvering Systems (OMS) and Reaction Control Systems (RCS) for the CEV.

Development Needs: EDS, LSAM and CEV development needs include innovative TVS configurations and
applications, system integration and control and modeling of low-gravity fluid dynamics and heat transfer for specific TVS designs. EDS, LSAM and CEV vehicle advanced development needs include integrated system testing with LH$_2$, LO$_2$ and LCH$_4$ to determine the effect of internal tank hardware configuration on fluid mixing.

3) Propellant Feed Line Conditioning:

Maintaining vapor-free liquid propellant between the tank outlet and the OMS/RCS engine inlet is a significant technology challenge. For lunar in situ cryogenic applications, systems are needed to store and transfer to warm tanks in the dusty lunar surface environment.

Applications/Technology Maturity: Propellant feed line conditioning will be required for all vehicles with a cryogenic OMS/RCS. Specific feed line configuration, routing and heat loads for each vehicle must be addressed.

Development Needs: CEV, EDS and LSAM vehicle development needs include integrated system testing with LH$_2$, LO$_2$ and LCH$_4$ to address vehicle specific feed line routing and heat loads, and couplings for lunar in situ propellant systems.

X9.02 Cryogenic Propellant Mass Gauging and Liquid Acquisition for Low Gravity Applications

Lead Center: GRC
Participating Center(s): MSFC

This subtopic includes technologies for applications related to cryogenic propellant management in low gravity. Liquid Acquisition Device (LAD) and Mass Gauging (MG) technologies will principally impact cryogenic systems for Orbital Maneuvering Systems (OMS) and Reaction Control Systems (RCS) for orbit transfer vehicles for in-space transportation applications, and are critical to successful liquid propellant delivery to Orbital Maneuvering Systems (OMS) and Reaction Control Systems (RCS) propulsion system and allowance of smaller propellant tank residuals to assure mission success. 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: liquid acquisition devices and mass gauging/advanced
instrumentation. Innovative concepts are requested for devices that interface with the tank and provide vapor-free liquids for on-orbit propulsion systems, low-gravity mass gauging technologies to enable accurate and reliable measurements of cryogenic liquid mass in low-gravity storage tanks without propellant settling or undue constraints on mission, and cryogen leak detection technologies. 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:

1) Liquid Acquisition:

Providing vapor free cryogenic propellants to in-space propulsion systems at expulsion efficiencies less than 98% without settling the propellants is the objective of the liquid acquisition technology element. Capillary liquid acquisition devices (LADs) are state-of-the-art for toxic propellants, but have not yet been developed for cryogens. Existing cryogenic upper stage main engine restarts use auxiliary thrusters to settle the propellants.

Applications/Technology Maturity: Cryogenic LADs will be required for the LO$_2$/LCH$_4$ version of the OMS/RCS for the CEV and LSAM and possibly the EDS. LH$_2$ LAD performance represents the primary challenge while LO$_2$ and LCH$_4$ performance risk is substantially less if the liquids are sub-cooled relative to the propellant tank ullage pressure.

Development Needs: Liquid acquisition technology needs include investigation of helium solubility and heat entrapment effects, propellant tank LAD integration, LAD materials selection, analytical performance model development, and techniques to minimize vaporization inside the LAD channel caused by incident heating through tank wall/lines and/or changes in tank pressure. CEV, LSAM and possibly the EDS vehicle advanced development needs include integrated system testing with LH$_2$, LO$_2$ and LCH$_4$ to determine the effect of internal tank hardware configuration on LAD performance.

2) Mass Gauging/Advanced Instrumentation:

The need for a reliable, accurate method for measuring cryogenic propellant mass without settling the propellants is the principal objective of the mass gauging technology element.

Applications/Technology Maturity: Applications for cryogenic mass gauging include the EDS, LSAM and the CEV OMS/RCS. A measurement uncertainty metric of less than 3% of full-tank mass has been established for the propellant mass measurements for these vehicles.
Development Needs: 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 cryogenic fluid leak detectors.

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

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

This solicitation intends to examine a range of key technology options associated with cryogenic and non-toxic storable propellant space engines. Non-toxic engine technology is desired for use in lieu of the toxic but currently operational nitrogen tetroxide and monomethylhydrazine engine technology. Safety concerns with toxic propellants drive mission planners to the use of more costly propulsion modules that are fueled and sealed on the ground. There are also concerns with exhaust residue from toxic systems, which may be carried into habitats for lunar and Mars systems.

The primary mission will be to support lunar ascent/descent reaction control engines and lunar ascent engines. These engines can be compatible with the future use of in situ propellants such as oxygen, methane, and methanol. Key performance parameters:

- Reaction control thruster development is in the 100-500-lbf thrust class with a target vacuum specific impulse of 325-sec. These RCS engines would operate cryogenic liquid-liquid for applications requiring integration with main engine propellants; or would operate gas-gas or gas-storable liquid for small total impulse type applications.

- Ascent engine development is projected to be in the 3,500-6,000-lbf thrust class with a target vacuum specific impulse of 355-sec. The engine shall achieve 90% rated thrust within 0.5 second of the issuance of the Engine ON Command.

Specific technologies of interest to meet proposed engine requirements include:
• Low-mass propellant injectors that provide stable, uniform combustion over a wide range of propellant inlet conditions;

• Combustion chamber designs using high temperature materials, coatings and/or ablative for combustion chambers, nozzles and nozzle extensions;

• Combustion chamber thermal control technologies such as regenerative, transpiration, swirl or other cooling methods which offer improved performance and adequate chamber life;

• Highly-reliable, long-life, fast-acting cryogenic valves that tolerate high thermal loading due to heat soak-back in low-thrust, pulsing propulsion systems (Thermal Isolation less than 1 Btu/hr) with reduced volume and size is also desirable;

• Highly-reliable, long-life, fast-acting propellant valves for gaseous propellants with reduced power, volume and size.

A key risk related to the use of cryogenic and gaseous propellants such as oxygen and methane are the ability to reliably ignite the propellants in a timely manner. This is of particular importance on ascent engines during abort operations. Recently NASA has been conducting a number of investigations into the ignition characteristics for oxygen and methane, primarily for spark torch systems. NASA continues to be interested in new and innovative methods which may be used as primary or back-up systems. Proposals are also solicited for igniter exciter technologies. In particular, for reaction control systems involving multiple engines that are not all co-located, issues between distributed vs. centralized exciter architectures must be balanced when selecting an exciter design. A "distributed" system refers to an integral exciter at each spark plug, whereas a "centralized" arrangement has at least some exciter components (e.g., DC-DC converter, control electronics, etc.) remotely located (e.g., with other avionics) and shared by multiple engines/spark plugs. Specific technologies of interest include:

• Reliable ignition systems such as spark torch, catalytic, microwave, combustion wave, laser, etc.;

• Exciters to support either capacitive (CDI) or inductive (IDI) discharge ignition types;

• High cycle spark plugs for use with cryogenic and/or gaseous propellants;

• Cryogenic instrumentation such as pressure and temperature sensors that will operate for months/years instead of hours.

X9.04 Launch Vehicle Propulsion and Pyrotechnic Technologies

Lead Center: MSFC
Participating Center(s): GRC

The goal of this subtopic is the development of innovative components, manufacturing techniques, health management systems, and design and analysis tools for launch vehicle propulsion and pyrotechnic systems. Performance, reliability, and cost of operations improvements to existing and planned Constellation launch vehicle propulsion and pyrotechnic systems are needed. Technologies that would contribute to decreased sensitivity to manufacturing and handling effects, that will lead to reduction in development and qualification testing, and that will
lead to reduction in touch labor during ground operations and vehicle turnaround are particularly welcomed. Also solicited are proposals that would reduce the time, cost, and complexity associated with designing and analyzing launch vehicle propulsion and pyrotechnic systems. While solid or hybrid rocket propulsion is specifically emphasized, compelling proposals related to liquid engine boost propulsion are also invited.

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; technology that supports applicability of these systems for in-space primary propulsion is also of interest.
- 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 improvements that allow for reductions in the cost and schedule required to fabricate and test solid or hybrid rockets.
- 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 encouraged.
- Retrofitable technologies to existing boost liquid engines that address the goals of performance enhancement and/or lower operations cost.
- Improvements in explosive bolt technology, both for traction as well as ejector bolts, to improve handling safety and increasing robustness of installation.
- Improvement to detonators to reduce the required initiation power, or to provide integrated safe-and-arm functions within detonator.
- Wireless or optical approaches for initiation of explosive bolts and frangible nuts for reduced system weight and improved safety.
- Improvements to explosive cutters, cutting chords, and specialty cutting charges to reduce installation labor, check-out labor, and sensitivity to environmental, handling, and ageing effects without reducing reliability.
- Analysis tools that support development and operation of launch vehicle propulsion systems (liquid, solid, or hybrid) by allowing for a more accurate definition of the environment internal to the propulsion system. Test data that provides for validation of existing design and analysis tools is also sought.
- Improvement to the design and analysis tools that support pyrotechnic devices development and integration into the launch vehicle system, especially those tools that define the induced environments created during and immediately after the action time of the pyrotechnic device; Test data to validate and quantify uncertainty in launch vehicle pyrotechnic devices design and induced environments.
Proposals that address more than one of these items are highly encouraged.

Protection Systems 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 Detachable, Human-rated, Ablative Environmentally Compliant TPS

Lead Center: ARC

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

The Crew Exploration Vehicle (CEV) will first be used for transporting crew and cargo to the International Space Station and later for the human exploration of the Moon and Mars. The TPS for the CEV will have to protect the
crew and cargo from entry heating at entry velocities of approximately 8 km/s for International 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 thermal protection system (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.

**Shape Optimization/Entry System Architectures**

The design of a reentry craft must encompass not only aerothermodynamic heating concerns but also the conflicting constraints of aerodynamic stability, mass, and cross-range performance. Therefore, the TPS cannot be designed in isolation but must be viewed as a part of a whole. Advances are sought in multidisciplinary design optimization (MDO) methods such as gradient methods and genetic algorithms.

**Instrumentation**

Thermal Protection System (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 bond line 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. Advances are sought in material development to address survivability in the severe convective and radiative heating environment and to address mass constraints and technological developments to address flow stability concerns and control authority in the face of atmospheric uncertainties and targeting errors. Advances and innovative concepts in integrated TPS design for multi-mission modes (aerocapture followed by entry requiring multi-use ablators vs. multi-layered ablators) are sought.
Future spacecraft will be in low Earth orbit, travel to the Moon, and travel to Mars, Jupiter, Venus, and their moons. Innovative thermal management technologies are needed to manage the waste heat from these spacecraft as efficiently as possible.

Sub Topics:

X11.01 Thermal Control for Surface Systems and Spacecraft

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

Advanced technologies are sought for thermal management of Earth-orbiting spacecraft, the human lunar habitat, landers, and rovers, for Martian transit spacecraft, as well as planetary expeditions to Jupiter, Venus, and their moons. Future spacecraft will require more sophisticated thermal control systems that can dissipate or reject greater heat loads at higher input heat fluxes while using fewer of the limited spacecraft mass, volume and power resources. The thermal control designs also must accommodate the harsh environments associated with these missions including dust and high sink temperatures. Modular, reconfigurable designs could limit the number of required spares.

Earth-orbiting spacecraft contain instruments, such as LIDAR lasers and electronics systems and/or components, which can generate high thermal dissipation loads at high heat flux rates. Spacecraft instruments can have tight temperature control requirements and/or thermal gradient requirements (micro-Kelvin requirements). Spacecraft instruments operate in temperature regimes ranging from cryogenic to above ambient (-180ºC to +100ºC). Radioisotope thermoelectric generators (RTGs) generate relatively large amounts of heat. Design plans for Earth-orbiting spacecraft seek smaller (down to MEMS level components or instruments) and reconfigurable designs.

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 polar lunar bases that are foreseen in 15 years will see extremely cold thermal environments, as will the radiators for Martian transit spacecraft. Long sojourns 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. Radiators on the Moon's poles and on a Martian transit vehicle are required that will operate and survive in very cold environments. Variable emissivity coatings, clever working fluid selection, or robust design could be used to prevent radiator damage from freezing at times of low heat load. Also, the dusty environment of an active lunar base may require dust mitigation and removal techniques to maintain radiator performance over the long term.

The lunar base and Martian transit spacecraft active thermal control systems will include high efficiency, long life mechanical pumps. 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. Small heat pumps could be used to provide cold fluid to the heat exchanger, increasing the average heat rejection temperature and reducing the size of the radiators.

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.

Exploration Crew Health Capabilities Topic X12

Human exploration capabilities must keep the crew healthy so they can adequately perform their mission and return safely to Earth. These subtopics seek innovative technologies 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.

Sub Topics:

X12.01 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.

Non-invasive Pharmacotherapy and Monitoring

Development of innovative technologies resulting in non-invasive 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.
Non-invasive 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-aged crew. Novel technology for non-invasive assessments of "bone quality" indices such as microarchitecture, macroarchitecture and trabecular Bone mineral density (BMD).

Technologies to Detect Biomarkers

Develop technologies to detect products of bone demineralization in urine during Flight and the biomarkers of bone degradation include N-telopeptide (NTX), C-telopeptide (CTX), pyridinoline and deoxypyridinoline collagen cross-links, and calcium ion. Develop technologies to monitor bone specific alkaline phosphatase and osteocalcin in serum samples.

Portable Motion Simulator

Develop a portable research platform to investigate the influence of spatial disorientation on manual control tasks during lunar-type landings. A 6-DOF motion simulator with full visual motion display will be developed to simulate landing tasks with and with visual motion (brownout) conditions. The simulator should be portable, and fit within standard (8 ft) room heights. The power requirements should be limited to 240VAC 30A. The subject restraint should accommodate both standing and seated positions. The control system should allow the user to import motion profiles, and provide the capability to evaluate various pilot-induced filter (PIO) options from a hand-held controller.

X12.02 Crew Exercise Systems

Lead Center: JSC
Participating Center(s): GRC

1) Identify compact, multi-function exercise devices to protect muscle and cardiovascular health during lunar sortie missions (missions with total duration less than 30 days). This device must be 10kg or less including all accessories, require no vehicle power to operate, include materials/components that can be flight certified and do not pose risk to the crew vehicle/habitat, and be stowed within 1 cubic foot of space aboard the Crew Exploration Vehicle/Orion and/or Lunar Surface Access Module. The device must be require no crew calibration or maintenance (for missions less than 30 days), require minimal deployment/setup time (easily portable between vehicles), and include instrumentation to document exercise session parameters using portable electronic media. The device must be capable of providing whole body and individual joint resistive loading that ideally simulates free weights. The load must be adjustable in increments no greater than 2.5 kgs and provide adequate loading to protect muscle strength to levels specified per the NASA Space Flight Human System Standards, Volume 1. The same device must be capable of providing whole-body aerobic exercise levels necessary to maintain aerobic fitness per the NASA Space Flight Human System Standards, Volume 1.
2) Identify compact, reliable multi-function exercise devices/systems to protect bone, muscle, and cardiovascular health during lunar outpost missions (missions with total duration less than 6 months). This device should be easily configured and stowed, require minimal power to operate, include instrumentation to document exercise session parameters including portable electronic media, and require minimum periodic calibration (no more than 2X/year). The device must be capable of providing whole body axial loading and individual joint resistive loading that ideally simulates free weights. If unable to match the inertial properties of free weights, then the device must provide near constant loading at any given load setting and achieve an eccentric to concentric load ratio greater than 90%. The load must be adjustable in increments no greater than 2.5 kgs and provide adequate loading to protect muscle strength and bone health to levels specified per the NASA Space Flight Human System Standards, Volume 1. The same device must be capable of providing whole-body aerobic exercise levels necessary to maintain aerobic fitness per the NASA Space Flight Human System Standards, Volume 1. Finally, the ideal device should also stimulate the sensory-motor system which controls balance and coordination.

3) Identify small, lightweight, sensor-based exercise monitoring systems that can be used to assess periodic fitness during lunar outpost missions and transit to Mars. Devices should be small, employ re-usable elements (versus requiring consumables), and be minimally invasive to measure heart rate and rhythm, oxygen consumption and lactic acid threshold. The ideal system would also include other medical monitoring capabilities such that it could be utilized to assess other crew health variables (e.g., imaging capabilities, respiration rate, blood parameters, etc.).

X12.03 Exploration Medical Capability

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

On-board clinical diagnostics to monitor crew member physiology must be available for both mid-term lunar and long-term Mars exploration missions. As in terrestrial medicine, devices with which to measure multiple constituents of small volume samples of bodily fluids are crucial components in assessing astronaut health. Nevertheless, mass, space, and power requirements of such devices are an obvious concern in an environment with scarce resources. Miniaturized laboratory analysis sensors represent a potential solution, given that these devices and supporting hardware are designed to be small, lightweight, and require little power. However, current sensor cartridges are typically single-use with limited shelf life. In order to satisfy the needs of longer duration exploration missions, reusable laboratory analysis sensors with increased shelf life must be designed without compromising accuracy or sensitivity. NASA seeks proposals for developing such reusable laboratory analysis sensors for measuring complete blood count with differential. Both the actual chips and associated electronics should minimize the use of electrical power and be as small as possible. Research should be conducted to demonstrate technical feasibility during Phase 1 and show a path toward a Phase 2 breadboard demonstration.
Space Human Factors and Food Systems Topic X13

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. This Topic seeks methods for monitoring, modeling, and predicting human performance in the spaceflight environment. These methods and tools are needed for accurate and valid human system integration into vehicle design and operations. Additionally, significant advancements in food technologies will be needed for long-duration Lunar and Mars missions. This Topic 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.

Sub Topics:

X13.01 Space Human Factors Assessment Tools

Lead Center: JSC
Participating Center(s): ARC

The Human Research Program (HRP) and the Behavioral Health and Performance Research Program (BHP) are among NASA's major Space Human Factors research programs. In collaboration with these two programs, the SBIR program is looking for research proposals that address the following two research areas: (1) an Automated Human Factors Incident Reporting Tool (AHFIRT) and (2) a Cognitive Assessment Tool (CAT).

Automated Human Factors Incident Reporting Tool (AHFIRT)

The HRP provides human health and performance countermeasures, knowledge, technologies, and tools to enable safe, reliable, and productive long-duration human space exploration. Objectives of the HRP include developing capabilities and technologies to support and mitigate risks to crew health and performance, reducing human systems resource requirements (mass, volume, power, data, etc.), and ensuring effective human-system integration across exploration systems.

To support these objectives, the HRP determines that obtaining timely and context-specific Human Factors (HF) incidents data is a technology gap the program wants to address. Currently, space HF data come from crew debriefs. Such debriefs rely on retrospective recall, which could suffer delays of up to six months. Furthermore, opportunities to discuss HF issues in detail during these debriefs are limited. Consequently, the HRP sees the need to develop an Automated Human Factors Incident Reporting Tool (AHFIRT).

Objective: Development of an AHFIRT that assists the gathering and reporting HF incidents for long-duration space missions.
Requirements: In general, the AHFIRT will be used to help detect areas where HF can contribute to mission success, access the effects of operational and hardware changes, and complement existing HF data sources for operations including crew debriefs. Specifically, the AHFIRT shall meet the following requirements:

- The crew shall have easy access to the tool at any time to eliminate the need for the crew to recall information retrospectively.
- An easy-to-use data gathering protocol with the following functionalities:
  - Allow data to be entered either as text, audio, and/or video inputs
  - It is desirable for AHFIRT to detect system anomaly automatically and immediately record system status. At the minimum, however, the tools should provide an easily accessible event marker for the crew to mark the context and take a snapshot of the system and operator system status.
  - Provide a user-friendly automated data search engine for extracting meaningful incident information from the raw data. Examples of desirable search schemes include natural language, spatial, temporal searches, etc.

Phase 1 Requirements: Technology Evaluation

The technical merit of the AHFIRT will be explored to evaluate feasibility. This process shall include:

- Evaluating/researching/developing automated data mining technologies
- Defining optimal data gathering protocol
- Determining optimal hardware/software design
- Developing hardware and software algorithms

Phase 2 Requirements: Prototype Development

The process shall include:
Developing a working AHFIRT prototype
Evaluate and test the functionality and usability of the prototype device

Cognitive Assessment Tool (CAT)

The NASA Behavioral Health and Performance Research Program (BHP) identifies and characterizes the behavioral health and performance risks associated with training, living and working in Space, and return to Earth. The BHP Research Element develops strategies, tools, and technologies to mitigate these risks. Currently, the BHP has the need for a Cognitive Assessment Tool (CAT).

Due to the high-intensity workload, disturbed sleep conditions, and other stressors of spaceflight, some astronauts have reported experiences of disturbed cognitive processes and fatigue.

Presently, a tool is utilized on the International Space Station (ISS) to detect neurocognitive deficits as a result of physical changes to the brain, which can occur from an injury to the head or exposure to a toxin. However, this assessment is designed as a programmed test that is not sensitive to crewmember fatigue. Consequently, there has been increased interest for a validated tool that can:

- Detect cognitive decrements as a result of fatigue or other stressors of spaceflight
- Support the Astronauts with an entertaining assessment activity(s)
- Support crew autonomy by providing objective feedback directly to the crewmember regarding their behavioral health

Objective: Design, develop, and fabricate a handheld, CAT that is in the form of a video game.

Requirements: The CAT game may include a suite of games as opposed to one single game. Ideally, the game would determine whether the player's deficit is a result of fatigue, stress, or neurocognitive impairment. Specifically, the CAT shall be as follows:

- In a hand-held video game format
- Portable hand-held unit
- Enjoyable and entertaining
• Flexible enough for increasing levels of difficulty
• Able to detect and identify cognitive decrements catalysts such as fatigue, stress, and/or neurocognitive deficits
• Able to provide immediate feedback to crewmembers, especially flight surgeons, with recommended countermeasure(s) based on his/her cognitive performance to support crew autonomy

Potential means for the CAT to assess performance may include measures of:

• Reaction times
• Accuracies
• Memory recall
• Complex decision making
• Physiological measures, such as heat rate via thumbs
• Speech acoustic analysis
• Facial monitoring
• Eye analysis

Note that the aforementioned methods are provided as examples of current research developments and are not intended as an all-inclusive or restrictive mandate for the development of the CAT.

Phase 1 Requirements: CAT Start-Up

The technical merit of the CAT will be explored to evaluate feasibility. This process will include:

• Defining predictors of cognitive decrements
• Determining which aspects of cognition should be assessed
• Determining optimal hardware design
• Hardware and software algorithms development

Phase 2 Requirements: CAT Research and Development
Content development of the CAT games should be determined based upon results of a qualitative study conducted with sample population (similar to Astronauts) to ensure corroboration and interest prior to the following stages:

- Develop software for gaming, data analysis, feedback, and recommended countermeasures
- Develop prototype hardware
- Develop manual and trouble shooting guide
- Evaluate and test the functionality of the prototype device.

**X13.02 Advanced Food Technologies**

**Lead Center: JSC**

The purpose of the Advanced Food Technology Project is to develop, evaluate and deliver food technologies for human centered spacecraft that will support crews on missions to the Moon, Mars, and beyond. 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. Concurrently, the food system must efficiently balance appropriate vehicle resources such as mass, volume, water, air, waste, power, and crew time. One of the objectives during the lunar outpost missions is to test technologies that can be used during the Mars missions.

This subtopic will concentrate on two specific areas; food packaging and lunar outpost food preparation and food processing.

**Non-Foil High Barrier Materials**

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. New food packaging technologies are needed that have adequate oxygen and water barrier properties to maintain the foods' quality over a 3 - 5 year shelf life. The packaging must also minimize waste by using high barrier packaging with less mass and volume.

The current flexible pouch packaging used for the thermostabilized and irradiated food items contains a layer of foil. Although the foil provides excellent oxygen and water barrier properties, it also contributes to added waste. Food
packaging will be a major contributor to the trash on the lunar or Mars surface. One of the proposed methods to dispose of trash on the lunar or Mars surface is incineration. However, the foil layer will not incinerate completely and there will be ash formed.

Two emerging food preservation technologies, high pressure processing and microwave processing, are being considered for future NASA missions. However the current high barrier packaging material cannot be used for these processes. The material delaminates during high pressure processing and cannot be used in microwave processing. Hence, any food packaging material developed in response to this subtopic should be compatible with one or more of the following food preservation technologies - retort processing, microwave processing, and/or high pressure processing. In addition, the material should have an oxygen transmission rate that shall not exceed 0.06 cc/m2/24 hrs/atm and a water vapor transmission rate that shall not exceed 0.01 gm/m2/24 hrs as stated in the MIL-PRF 33073F specification.

**Effect of Partial Gravity and Reduced Atmospheric Pressure**

It will require approximately 10,000 kg of packaged food for a 6-crew, 1000 day mission to Mars. For that reason, it has been proposed to use a food system which incorporates processing of raw ingredients into edible ingredients and uses these edible ingredients in recipes in the galley to produce meals. This type of food system will require food processing and food preparation equipment. The equipment should be miniaturized, multipurpose and efficiently use vehicle resources such as mass, volume, water, and power. Food preparation may include gourmet kitchen appliances such as food processors or bread makers in addition to the standard stove and oven. Proposed food processing equipment may include a mill to produce wheat and soy flour, a soy milk/tofu processor, and a concentrator.

The Moon's gravity is 1/6 of Earth's gravity. In addition, it is being proposed that the habitat will have a reduced atmospheric pressure of 8 psia which is equivalent to a 16,000 foot mountain top. These two factors will affect the heat and mass transfer during food processing and food preparation of the food. Heat transfer is required for proper microbial kill and to produce the desired texture and appearance of the food prior to consumption. At this pressure, the boiling temperature of water will be 181°F which has significant implications for preventing microbial contamination and to acceptable food quality.

Prior to any design of food processing or preparation equipment, the effects of partial gravity and partial atmospheric pressure as it relates to fluid management, heat and mass transfer and chemical reactions must be determined. Once the effects are determined, countermeasures must be developed. All of this needs to happen prior to any fabrication of actual food processing or food preparation equipment that can be used in the Lunar Habitat.

The response to this subtopic should (1) develop food packaging technologies that respond the above
requirements, (2) develop a technology which will aid in determining the effects of reduced cabin pressure and reduced gravity and/or (3) develop a technology that will enable safe and timely food processing and food preparation in reduced cabin pressure and reduced gravity.

Space Radiation Topic X14

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 different from forms of radiation encountered on Earth. Radiation in space consists of high-energy protons, heavy ions and secondary products created when the protons and heavy ions pass through spacecraft shielding and human tissue. The Space Radiation Program Element uses the NASA Research Announcement as a primary means of soliciting research to understand the health risks and reduce the uncertainties in risk projections. Reliable radiation monitoring for manned and unmanned spaceflight is a specific area where the SBIR technologies can potentially contribute to NASA’s overall goal. Three particular areas of interest are: Small Personal Dosimetry; Charged Particle Spectroscopy; Neutron Spectroscopy.

Sub Topics:

X14.01 Small Personal Dosimetry

Lead Center: JSC

Participating Center(s): ARC, GSFC

Background:

As astronauts return to the Moon, and this time, work for extended periods, there will be a critical need for crew personnel radiation monitoring as they perform a myriad of extravehicular activities (EVAs). Increased ISS crew size and mission duration are also driving the need for during-mission evaluation of crew specific radiation exposures.

The components of the radiation field, both primary and secondary particles, can vary significantly in charge, energy, and intensity between galactic cosmic rays and solar particle events (SPEs). This dynamic and complex radiation environment requires the development of suitable detection systems that can meet the requirements of each component of the field.

Of particular concern is the need for active monitoring capabilities that provide relevant radiation personal dosimetry information for long term galactic cosmic ray exposure (including neutron secondary radiation) and for
short term high dose rate SPEs. In addition to a complex Lunar radiation environment, which must be detected
while electronics are protected by radiation hardening, there are restrictions on size, weight, power availability, and
data transmission, as well as challenges presented by the Lunar surface environment, such as dust, temperature,
and UV radiation. If mounted on or in the EVA suit, suit constraints must be addressed and crew safety ensured.
For daily mission use, the requirements on size, data storage, and battery life/operation are particularly challenging.

Requirements/Needs:

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. New software needs to be fault
tolerant and compatible with current operating systems, new hardware and software must be fully documented
(schematics, etc.).

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.

For EVA and Mission Needs

- The dosimeter should be an omnidirectional detector system that can continuously measure and record
  the absorbed dose from charged particles with linear energy transfer 0.2 to 300 keV/micrometer, as a
  function of time, at two shielding depths: 0.5 g/cm² and 3 g/cm².

- The dosimeter should measure cumulative absorbed dose and dose equivalent once per minute and report
data with latency less than five minutes.

- The dosimeter should produce and alarm whenever the absorbed dose rate exceeds a programmable
  threshold in the range 0.05 mGy/min to 10 mGy/min for 3 consecutive 1 minute readings.

- The dosimeter dimensions should be no larger than 8.5 cm x 4.5 cm x 2 cm.

- The dosimeter should weigh no more than 150 g.

Additional Mission Only Needs

- The dosimeter should be able to be battery (re-chargeable) powered and operate for 14 days without re-
  charge.

- The dosimeter shall be able to measure dose rates in the range 0.005 mGy/hour (0.0075 mSv/hour) to 1
cGy/hour (1.5 cSv/hour).

- The dosimeter should able to measure neutron exposure (personal dose equivalent) in the energy rage 0.5
  MeV to 10 MeV, with dose equivalent sensitivity of 0.2 mSv to 0.1 Sv in a 1 hour measurement, delivered at
  0.02 mSv/hour to 1 mSv/hour.
Additional EVA Only Needs

- For suit based versions, the dosimeter would interface to the EVA suit with TBR power available. No battery is allowed for suit versions.

- The dosimeter shall be able to measure dose rates in the range 0.005 mGy/hour (0.0075 mGy-Eq/hour for proton fields in the energy 10 MeV to 300 MeV) to 70 cGy/hour (105 cGy-Eq/hour for proton fields in the energy range 10 MeV to 300 MeV).

- Software and algorithms must interface with the suit data system, but do not necessarily need to be integrated into suit control algorithms.

X14.02 Charged Particle Spectroscopy

Lead Center: ARC

Participating Center(s): GSFC, JSC

Charged particles (protons and heavy ions) contribute most of the dose-equivalent received by astronauts. Current instruments at NASA, and those under development, can provide the total (combined) dose and dose-equivalent for protons, heavy ions, gamma rays, and neutrons. At present NASA has active detectors for ISS that measure energy fluence of charged particles; however, more compact detection systems that measures energy fluence and spectrum for Exploration class missions are needed. Advanced technologies (up to technology readiness level (TRL) level 4) are requested.

Subtopic Requirements/Needs:

Of particular interest are compact real-time detection systems that can measure energy fluence and spectrum of protons and other ions (Z = 2 to 26) and be sensitive to charged particles with LET of 0.2 to 1000 keV/µm. For Z less than 3, the spectrometer should detect energies in the range 20 MeV/n to 400 MeV/n. For Z = 3 to 26, the spectrometer should detect energies in the range 50 MeV/n to 1 GeV/n.

The monitor should be able to measure charged particles at both ambient conditions in space (0.005 mGy/hr) and during a large solar particle event (1000 mGy/hr).

The time resolution should be less than or equal to 1 minute.

The dosimeter shall be able to perform data reduction internally and provide processed data out to ISS, CEV, and future lunar outpost data systems. New software needs to be fault tolerant and updated to current operating
systems, new hardware and software must be fully documented (schematics, etc.).

X14.03 Neutron Spectroscopy

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

Neutrons can contribute a significant fraction to the total dose-equivalent received by astronauts. Current instruments at NASA, and those under development, can provide the total (combined) dose and dose-equivalent for protons, heavy ions, gamma rays, and neutrons. At present, neutrons are included as integral measurements of NASA space flights; however compact active detection systems that can measure neutrons only are needed. Advanced technologies (up to technology readiness level (TRL) level 4) are requested.

Subtopic Requirements/Needs:

Systems are needed specifically to measure the neutron component of the dose and provide the neutron dose-equivalent in real time. Of interest also would be compact active monitoring devices that could measure neutron energy spectra.

The principal energies of interest are neutrons from 0.5 MeV to 150 MeV.

The monitor should be able to measure neutrons at ambient conditions such that proton/ion veto capability should be approaching 100% at solar minimum GCR rates.

During solar particle events, neutrons will be present at increased levels and should also be measured.

The device should be able to measure ambient dose equivalent of 0.02 mSv in a 1 hour measurement period, using ICRP 74 (1997) conversion factors.

The instrument shall be able to perform data reduction internally and provide processed data out to ISS, CEV, and or future lunar outpost data systems. New software needs to be fault tolerant and updated to current operating systems, new hardware and software must be fully documented (schematics, etc.).
Automation and autonomy are key elements in realizing the vision for space exploration. Constellation systems that would benefit from automation and autonomy include crewed vehicle systems, surface robots, habitats, and infrastructure (in situ resource utilization, power systems, etc.). Needed capabilities range from decision support systems in Mission Control to autonomous robotic operations for the Moon and Mars. These capabilities will be instrumental for decreasing workload, reducing dependence on Earth-based support staff, enhancing response time, and releasing crew and operators from routine tasks to focus on those requiring human judgment. In addition, significant reductions in Mission Risk can be achieved through the use of automated checking and enforcing of flight rules and constraints.

The NASA Exploration Technology Development Program (ETDP) has been developing a set of core autonomy capabilities that can adjust the level of human interaction from fully supervised to fully autonomous. To further the application of adjustable automation and autonomy, development is needed in three broad areas:

- Execution tools;
- Decision support systems;
- Trustable systems.

### Execution Tools

Executives are a key autonomy capability. However, support tools are needed to facilitate the authoring and validation of execution scripts. Tools that are not tied specifically to one executive would provide NASA the most flexibility in applying such tools across projects. Examples of needed capabilities include:

- Graphical tool for monitoring and debugging plan execution;
- Graphical tool for creating and editing execution scripts;
- Tools for authoring and validating execution plans;
- User friendly abstraction of low-level execution languages by adding syntactic enhancements.

### Decision Support Systems

Decision support systems amplify the efficiency of operators by providing the information they need when and where they need it. As the complexity of the constellation system increases, so must the capabilities of decision support systems. Decision support tools are needed that:
• Command and supervise complex tasks while projecting the outcome of actions and identify potential problems;
• Understand system state, including visualization and summarization;
• Allow the system to interact with a user when generating the plan and allow evaluation of alternate courses of action;
• Integration of a planning and scheduling system as part of an on-board, closed loop controller;
• Scale up existing techniques to larger problem applications.

Trustable Systems

Systems that support or interact with crew require a very high level of reliability. Tools are needed that improve the reliability and trustworthiness of autonomous systems. These include:

• Ability to predict what the system will do;
• Guarantees of behavioral properties;
• Other properties that increase the operator’s trust;
• Verifiability (e.g., restricted executive languages that facilitate model-based verification).

To enable the application of intelligent automation and autonomy techniques, the technologies need to address two significant challenges: configuration management and software validation.

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 address the definition of autonomy and automation software architectures that facilitate adaptation and ensure correctness.
Reliable Software for Exploration Systems Topic X1.02

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. It will be challenging, but critical to NASA's exploration objectives to ensure that these capabilities are reliable and can be developed and maintained affordably. 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 Integrated Systems Health Management (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).

Radiation Hardened/Tolerant and Low temperature Electronics and Processors Topic X1.03
Electronic technologies that are to be used in near-term exploration activities must be capable of operating on the lunar and/or Martian surfaces. Systems will need to operate across a wide temperature range and must survive frequent (and often rapid) thermal-cycling. For example, the Moon’s equatorial regions experience 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. Likewise, the diurnal temperature on Mars spans from about -120°C to +20°C. While many types of devices can operate down to very low temperatures (e.g., SiGe HBT’s), there are significant circuit design challenges that need to be addressed.

Thermal cycling present in lunar and Martian environments introduces reliability concerns associated with mechanical stress and fatigue of components and integrated circuits. For example, thermal cycling may result in mechanical or packaging related fractures. The selection of appropriate materials is therefore critical to developing suitable electronic products.

In addition, electronic systems and/or components must be radiation tolerant, operating reliably after receiving a total ionizing dose (TID) greater than but not equal to 50 krads (Si) and providing single-event latchup immunity (SEL) greater than but not equal to 100 MeV cm$^2$/mg.

Proposals are sought in the following specific areas:

- Wide temperature (-180°C to +130°C) and low-temperature (-230°C), radiation-tolerant, low-power 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, and drive electronics for sensors, actuators, and communications transponders.

- Packaging capable of surviving numerous thermal cycles and tolerant of the extreme temperatures on the Moon and Mars. This includes the use of appropriate materials including substrates, die-attach, encapsulants, thermal compounds, etc.

- Tightly-integrated electronic sensor and actuator modules that include power, command and control, and processing. Such modules should be capable of operating at the lunar and/or Martian temperature extremes.

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


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

- Circuit design and layout methodologies/techniques that facilitate improved low-temperature (-230°C) analog and mixed-signal circuit performance.

- Radiation-tolerant processors with significantly improved throughput and processing efficiencies. Chip-level (not board-level) technologies optimized for numerically intensive algorithms and applications with the following minimum performance metrics are sought:
- Sustained throughput - 2 GMACS (16-bit operations);
- Power efficiency - 1 GMACS/W (16-bit operations);
- Total ionizing dose - 100 krads;
- Single event upset rate - 10-10 errors / bit-day;
- Single event latchup - greater than 75 MeV/cm²/mg;
- Operational temperature range - -55°C to +125°C.

Proposals should demonstrate a working knowledge of temperature concerns, whether they be mechanical (material transition points, thermal stress, fatigue, fracture, etc.) or electrical (carrier freezeout, base-emitter injection efficiency, leakage, threshold voltage dependency, Johnson noise, charge trapping, kink effect, etc.).

Research should be conducted in two phases. During Phase 1, research should demonstrate the technical feasibility and show a path towards a hardware/software demonstration. During Phase 2, emphasis should be placed on developing and demonstrating the technology under relevant test conditions. Additionally, a path should be outlined that shows how the technology could be commercialized or further developed into space-worthy systems. When applicable, researchers should deliver a demonstration unit for functional and environmental testing at the completion of the Phase 2 contract.

Sub Topics:
- Integrated System Health Management Topic X1.04

Innovative health management technologies are needed throughout NASA's Constellation architecture in order to increase the safety and mission-effectiveness of future spacecraft and launch vehicles. In human space flight, a significant concern for NASA is the safety of ground and flight crews under off-nominal or failure conditions. The new Ares Crew Launch Vehicle will provide the means to abort the crew using a launch abort system. In case of a catastrophic failure during launch or ascent, the decision to abort the crew needs to be made within a very brief timeframe and with high certainty: either false positive or false negative crew abort indications carry a large safety and cost burden. Furthermore, the Constellation architecture allows for fully-automated crew abort under certain circumstances, increasing the accuracy and sensitivity requirements on the system health management function for the Ares launch vehicle and the Orion crew capsule.

There are other health and status requirements beyond launch and ascent. Traditional means of verifying space system health and status, such as caution and warning systems that are triggered by off-nominal sensor values are rather limited in their utility. In addition to issues such as sensor failures and false alarms, redline-triggered caution and warning events are difficult to interpret, often requiring involvement of large numbers of mission support staff to isolate a failure and initiate a recovery procedure. Health and status methods that depend on support from the ground are likely to become a safety liability as communication delays or bottlenecks increase (e.g., lunar trips). 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. For deployment on human missions, health management systems must be treated as Class A human-rated systems as defined by NASA procedural requirements (NPR 7150.2) and must undergo formal verification and validation.

Future ground operations will require quick and efficient turnaround and processing of spacecraft for launch. In
addition, new operations concepts must be developed to provide a high level of safety and mission assurance while reducing ground processing and mission support staff. New methods driven by health management innovation may be used to curtail system lifecycle costs through more cost-effective inspection and certification of flight systems, as well as more cost-effective management of ground and mission operations.

Proposals should be responsive to the overall goals and objectives of NASA's Constellation and Lunar Precursors and Robotics 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 solid rocket motors, liquid propulsion systems, structures and mechanisms, thermal protection systems, power, avionics, life support, and communications. Proposals that involve the use of existing testbeds or facilities at one of the participating NASA centers (ARC, MSFC, KSC, or JPL) for technology validation and maturation are strongly encouraged.

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

- Methods and tools to enable early-stage design of health management functionality during the development of space 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.

- Innovative methods for sensor validation and robust state estimation in the presence of inherently unreliable sensors. Proposals should focus on data analysis and interpretation using legacy sensors rather than development of new sensors or sensor systems.

- Model-based methods for fault detection and isolation in rocket propulsion systems based on existing sensor suites during pre-launch propellant loading and during mission operations.

- Concepts for advanced built-in-tests for spacecraft avionics that reduce or eliminate the need for extensive functional verification and to predict remaining life of avionics systems based on usage history.

- Methods for robust control of critical components, subsystems, and systems and robust execution of critical sequences during launch operations or 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.

- Innovative human-system integration methods that can convey a wealth of health and status information to flight crews, ground and mission support staff quickly and effectively, especially under off-nominal and emergency conditions.

- Verification and validation techniques for advanced fault detection and prognostic capabilities leading to certification for use in human rated critical systems in a cost-effective manner.

- Innovative approaches to effective utilization of health information from NASA spacecraft and launch vehicles with seamless integration to ground based systems using commercial health information from programmable logic controller systems and commercial Reliability, Availability and Serviceability (RAS) systems.
Sub Topics: Autonomous Rendezvous and Docking Sensors Topic X2.01

The Exploration Systems Architecture defines missions that require rendezvous, proximity operations, and docking (RPOD) of two spacecraft both in Low Earth Orbit (LEO) and in Low Lunar Orbit (LLO). Uncrewed spacecraft must perform automated and/or autonomous rendezvous, proximity operations and docking operations (commonly known as Automated Rendezvous and Docking, AR&D). The crewed versions may also perform AR&D, possibly with a different level of automation and/or autonomy, and must also provide the crew with reliable, fault tolerant relative navigation information for manual piloting. The capabilities of the RPOD sensors are critical to the success of the Exploration Program. The relatively low technology readiness of existing relative navigation sensors for AR&D has been carried as one of the Crew Exploration Vehicle (CEV) Project's top risks.

This subtopic seeks innovative technologies that can provide relative navigation capabilities for rendezvous, proximity operations and docking of two spacecraft. Long-range rendezvous sensors should provide bearing from beyond 200 km to 5 km distance between spacecraft, but range and range-rate are also desirable. Proximity operations sensors should provide range, range-rate, and bearing from approximately 5 km to 100 m. Docking sensors should provide relative position and relative attitude from approximately 100 m to docking; relative attitude may only be needed from 30 m in to docking but longer ranges are desirable. Ideal solutions would combine multiple relative navigation sensing capabilities into a single system in order to reduce mass, volume, and power. Solutions should be designed to operate in Low Earth Orbit, Low Lunar Orbit, or both. Solutions can include a relative navigation sensor "suite" that consists of multiple sensor types but covers the full range; the sensor suite should allow RPOD under any lighting conditions. Solutions should also include a robust and fault tolerant capability that is suitable for a human-rated space vehicle. In addition, the relative navigation technologies should be designed so that existing infrastructure on the International Space Station (reflectors, communications systems, etc.) does not interfere with the relative navigation capability of the maneuvering vehicle.

Some specific technology focus areas of interest include: (1) use of relative navigation sensors that do not require special retro-reflectors or targets on the target spacecraft but can make use of natural features or existing infrastructure; this focus area may make use of Light-Imaging Detection and Ranging (LIDAR) components in order to get range and range-rate to the objects in the field of view, or may use video-based technology; (2) fault tolerant sensor systems; and (3) other technology areas for long-range rendezvous sensors that may include star trackers, infrared sensors, and radio frequency-based sensors; these types of sensors may have an extended range well beyond 200 km.

Sub Topics: Autonomous Precision Landing and Hazard Detection and Avoidance Topic X2.02

NASA seeks innovative sensor system technologies to support autonomous precision landing with hazard detection and avoidance for landing spacecraft on the lunar surface with extensibility to Mars. Sensor systems that can characterize and identify spacecraft landing surface hazards for purposes of avoidance and surface relative navigation with high precision and accuracy are of interest. The emphasis of this solicitation is for sensor systems or sensor components that can be utilized in current sensor systems to go beyond current technology capability. These systems or components must be compatible with the environmental conditions of spaceflight and the rigorous
of landing on the planetary surface. Proposals for development of certain aspects of these technology systems including sensor components that include partnering with other vendors developing this kind of technology are encouraged.

Candidate items include but are not limited to the following:

- Innovative lidar sensor systems and component technologies that directly address autonomous precision landing and hazard avoidance needs
  - 3D imaging lidar systems capable of generating elevation maps covering terrain areas 10k to 100k square meters from 1-2 km altitude with a resolution of the order of 20 cm
  - High efficiency focal plane arrays with over 16k pixels capable of detecting laser pulses shorter than a few nanoseconds (wavelengths of interest are 1 to 1.5 microns)
  - Reliable Readout Integrated Circuit (ROIC) with high frame rate capability greater than 20 hertz and capable of resolving target depth to a few centimeters
  - Novel real-time lidar image reconstruction and processing technologies;
- Passive or active detector systems which operate in certain ranges between 100 km to 2 km for utilization in terrain relative navigation systems;
- Sensor systems which provide very high accuracy and precision for determining velocities and altitudes relative to the surface with 0.1% accuracy;
- Robust and reliable sensor system or sensor system components which significantly reduce the impact of incorporating such sensors or components on the spacecraft in terms of volume, mass, power, thermal dissipation, placement or cost;
- Semiconductor or solid-state-controlled mirror systems capable of rapidly moving a lidar FOV over a defined areas;
- Innovative systems that significantly improve current precision landing and hazard detection capability for lunar descent and landing.

Proposals should describe the expected improvements and advantages of proposed deliverables over existing technologies and should estimate the effects of these improvements on the state-of-the-art navigation and hazard detection capabilities. Attributes of interest include reliability, precision, lighting requirements, accuracy, thermal sensitivity, heat dissipation capability and performance degradation due to rocket plumes and lunar dust.
Atmospheric resource management encompasses process technologies and equipment to supply, store, and condition atmospheric gases; provide gaseous oxygen at pressures at or above 3,000 psia; and achieve mass closure by recycling resources and using in situ resources. Typical process technologies employed for achieving these needs may include reduction of carbon dioxide to carbon, sub-critical gas storage, and electrolytic oxygen production with compression. Techniques for enhancing NASA's present capabilities and filling technology gaps are sought. The ability to provide early computer-based process technology predictive performance models for application scale-up and scale-down is desirable. Areas of emphasis include:

- **Carbon Dioxide Removal and Reduction for Recovery of Oxygen**: 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 sought. Technologies to reduce carbon dioxide to a carbon product with high efficiency that yields a high percentage mass balance closure are also of interest.

- **Gas Supply and Storage**: 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. Further, process technologies leading to a ready, in-flight renewable source of 3,000-psia gaseous oxygen are of interest.

**Particulate Matter Removal and Disposal**

Dust and particulate matter contamination are challenges that must be overcome for lunar surface exploration. Particulate contamination originating from the external surface environment or from internal sources are both of concern. Development of process technologies and equipment to minimize the impacts of surface dust on crew health and equipment inside the habitable volume are sought, including novel approaches to remove dust from spacecraft cabin atmosphere and isolate habitable volumes from surface dust. Candidate technology solutions should provide high efficiency and long-lived removal capacity. Technologies must be tolerant to the abrasive effects of dust particles. Performance should be demonstrated with appropriate lunar dust analogs or simulants. Areas of emphasis include:

- **Removal of Fine Atmospheric Dust Particulates**: Fine airborne lunar dust will be detrimental to crew health.
Filtration technologies are sought that will provide significantly improved capture efficiency of both fines (10 nm to 2 microns) and ultra-fines.

- **Regenerative Processes and Filters:** Regeneration techniques and regenerable filters are sought that effectively handle a broad particulate size range from larger-sized particles down to fine particle sizes. These techniques must be able to separate and dispose of lunar dust to the lunar surface, and/or dispose of and collect all other particulate matter to highly compacted units/states. Salient features for this application include capability for regeneration in place, long-lived and large bulk removal capacity, and high efficiency. Operational modes of continuous regeneration or long interval regeneration cycles using either single or multi-stage regeneration processes will be considered. Methods for determining and annunciating the loading and unloading status of the regenerative unit and for automated regeneration are of interest.

- **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.

**Sub Topics:**

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

Water processing and waste management systems supporting critical needs for lunar mission architectures are requested. Improved technologies for recovery of water and other resources as well as safe long term stabilization and storage of residuals inside and outside the habitat are needed. Water processes collect, store, recycle, and disinfect water for reuse as both drinking water and hygiene water. Waste processes collect, process, recover resources, stabilize, and store residuals. Although this solicitation is directed at technologies for lunar missions, crosscutting technologies that are also applicable to human missions to Mars are of interest. Proposals should explicitly describe the weight, power, and volume advantages of the proposed technology.

**Water Reclamation**

Efficient treatment of wastewater from a variety of sources is critical to long-term exploration missions. Sources of water to be recovered may include urine, wash water, humidity condensate, and/or water derived from in situ planetary resources. Treatment processes should produce potable and hygiene water supplies. Treatment methods for long duration missions should seek high levels of mass closure. Systems targeted for planetary surface applications must be designed to function in hypogravity environments but need not be microgravity compatible. Areas of emphasis include:

- Disinfection and residual disinfectant technologies that are compatible with both biological and physicochemical wastewater processing systems;
- Techniques to minimize or eliminate biofilms, microbial contamination and/or solids precipitation from potable water, wastewater and water treatment system components;
- Post-treatment methods to reduce total organic carbon from 100 mg/L to less than 1 mg/L in the presence of 50 mg/L bicarbonate ions, 25 mg/L ammonium ions and 25 ppm other inorganic ions.

**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:
- Solid waste stabilization including water removal and recovery of water from wet wastes (including human fecal wastes, food packaging, brines, etc.);
- Solid waste storage and odor control (e.g., catalytic and adsorptive systems);
- Energy efficient/internal heat recycling waste pyrolysis systems for mineralization of wastes.

**Clothing Systems**

Low mass reusable or long usage clothing options that meet flammability, outgassing, 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:

**Spacecraft Cabin Environmental Monitoring and Control Topic X3.03**

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. A desire is for an immersible water quality sensor that is reversible; i.e., it tracks analyte changes in water without having to replace any sensor chemistry element.

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.

Sub Topics:
Spacecraft Fire Protection Topic X3.04
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 and detector systems 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:
Space Suit Pressure Garment and Airlock Technologies Topic X4.01
Innovative technologies are needed to meet the challenging requirements for the exploration space suit pressure garment and surface systems airlock. These technologies should be able to be developed further for application to the lunar missions.

Specifically, the space suit pressure garment requires radiation protection technologies that protect the suited crew member from radiation particles, puncture protection technologies that provide self-sealing capabilities when a puncture occurs and minimizes punctures and cuts from sharp objects, dust and abrasion protection materials to exclude dust and withstand abrasion and prevent dust adhesion, flexible thermal insulation suitable for use in vacuum and low ambient pressure, and space suit low profile bearings that maximize rotation which is necessary for partial gravity mobility requirements, and is also lightweight and low cost.

Due to the expected large number of space walks that will be performed on the lunar surface, innovative technologies and designs for surface airlocks will also be needed. Technology development is needed for minimum gas loss airlocks providing quick exit and entry that can accommodate an incapacitated crew member, suit port/suit lock systems for docking a space suit to a dust mitigating entry/hatch in order for the space suit to remain in the airlock and prevent dust from entering the habitable environment, and active and passive space suit and equipment dust removal technologies inside and outside the airlock.

Sub Topics:
Space Suit Life Support Systems Topic X4.02
Exploration missions will require a robust, lightweight, and maintainable portable life support system. Technology development is needed for long-life and high-capacity chemical oxygen storage systems for an emergency supply of oxygen for breathing; low-venting or non-venting regenerative individual life support subsystem(s) concepts for crew member cooling, heat rejection, and removal of expired water vapor and CO$_2$; convection and freezable radiators that will be low cost and lightweight for thermal control; innovative garments that provide direct thermal control to crew member; high reliability pumps and fans that will provide flow for a space suit but can be stacked to give greater flow for a vehicle; CO$_2$ and humidity control devices that, while minimizing expendables, function in a CO$_2$ environment; and a non-toxic, non-flammable, super cooled below 32°F phase change material that can absorb metabolic heat for an 8 hour duration.

Also for removing metabolic heat from the astronaut, research is needed for a variable conductance flexible suit garment that can function as a radiator for high metabolic loads and as an insulator for low metabolic loads.

Sub Topics:
Space Suit Displays, Cameras, Controls, and Integrated Systems Topic X4.03
Future exploration space suits will require innovative technologies for displaying various types of information.
Technology development is needed for space suit mounted displays for use both inside and outside the space suit; outside mounted displays must be compatible with the space radiation, thermal, and vacuum environment. Examples include internally or externally mounted helmet displays and lightweight wrist or arm mounted displays.

The spacesuit will also require research for lightweight CO\textsubscript{2}, biomedical, and core temperature sensors with reduced size, increased reliability, and greater packaging flexibility; and camera systems that are lightweight, low power draw, and integrate with the spacesuit. The camera system should allow both motion and still imagery providing compressed digital data output suitable for transmission over IP networks. This camera must provide excellent situational awareness for crew members and quality imagery for remote viewing and public relations.

Research is also needed for lightweight, low power consuming general purpose computing platforms that are tolerant to the space radiation environment. Such platforms could be processor or FPGA based to allow the use of on-suit software applications such as biomedical advisory algorithms, procedure displays, navigation displays, and voice recognition. Technology development is needed for low computational overhead voice recognition processing systems capable of performing on lightweight radiation tolerant embedded computing platforms.

Sub Topics:

Oxygen Production from Lunar Regolith Topic X5.01
Oxygen production from lunar regolith processing consists of receiving regolith from the excavation subsystem into a hopper, transferring that regolith into a reactor where it is reduced using chemical or an electrochemical process, potentially intermediate reactions to reach oxygen, purification of the oxygen, and transfer of the oxygen to the liquefaction and storage subsystem. After oxygen has been extracted from the regolith, the spent regolith must be removed from the reactor and returned to the excavation subsystem for disposal. Depending on the process used, the reactor may contain reduced metals that can be extracted in their pure form for use as a manufacturing feedstock.

To maximize the benefits of In Situ Resource Utilization (ISRU) for the Lunar Exploration Architecture, oxygen production systems must minimize the mass and power consumption of ISRU systems. ISRU systems must be able to produce many times their own mass in oxygen and other products to provide a benefit to the architecture. ISRU systems must be able to autonomously operate in a harsh environment that has wide temperature swings, high radiation and abrasive dust. Depending on the outpost location, the systems must be able to sustain many startup and shutdown sequences when solar power is not available. Some of these shutdown periods may exceed several hundred hours.
The next phase of ISRU research and development will focus on the design and testing of a regolith reduction system that can produce roughly 1000 kilograms of oxygen in a year. The operation assumption is that the production plant will operate off of solar power which is estimated to be available about 70% of the time and will operate at a lunar pole with highlands soils. The current oxygen production approaches being developed into prototypes are: Hydrogen Reduction, Carbothermal and Molten Oxide Electrolysis. The basic description of these approaches can be found in the NASA funded report by Eagle Engineering, entitled "Conceptual Design of a Lunar Oxygen Pilot Plant (1988)". The report can be found on the web at [http://www.isrufil.com/index.php](http://www.isruinfo.com/index.php) [1].

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

- Heat exchangers to recover energy from heated regolith;
- Low/No maintenance system filtration technologies for removing dust from gas lines;
- Water condensers that would use the cooling potential of the space environment to water condensation with minimal energy usage;
- Solar Concentrators that are lightweight and able to deliver concentrated solar thermal energy to reactors generating regolith temperatures from 900°C up to 1600°C;
- Gas Separators that provide low pressure drop separation of the system and product gas streams from impurities (e.g., H₂S, SO₂);
- Microchannel methanation reactors that convert a mixture of carbon monoxide, carbon dioxide, and hydrogen to methane and water vapor with carbon monoxide and carbon dioxide consumed to the maximum extent possible;
- O₂ Purification technologies that perform the removal (and reclamation) of all contaminants prior to liquefaction of the oxygen;
- Feed systems to introduce regolith to the reactors and remove the regolith, slag or molten products from the reactor post processing. The systems must minimize the possibility of dust contaminating the reactor seals;
- Reactor Seals: The sealing of reactors includes sealing gas interfaces from the reactor to the remainder of the system and also the regolith feed/exit to the reactor. Valves proposed for use for gas interfaces must be capable of 1000s of operations and able to operate when lunar dust is present in the gas stream. Reactor regolith feed/exit seals proposed for use must either be kept clean, can be automatically cleaned, or seal even with a coating of lunar dust. Interested companies should keep in mind that each reactor system operates at significantly different temperatures so the gas and regolith sealing methods could see a wide range of thermal conditions.
Lunar Regolith Excavation and Material Handling Topic X5.02

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

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

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

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

- Specific technologies for flow of regolith in the lunar environment related to excavation, handling and transportation.

- Modeling of granular material physics in partial gravity related to regolith excavation, handling and transportation.

Sub Topics:

Lunar Volatile Resource Prospecting and Collection Topic X5.03

Lunar volatile extraction, separation, and collection consists of all aspects of locating and characterizing lunar volatile resources (especially polar hydrogen/water); excavating regolith in the permanently shadowed craters (-233°C and down to 2 meters); mechanical, thermal, chemical, and/or electrical processing of this regolith to release volatiles; identifying/quantifying all volatiles; and separating and collecting volatiles of interest. Metrics of interest include: excavation rate (kg/hr); excavation efficiency (power required/excavation rate); resource extraction efficiency (Watts per mass of volatiles produced per hour); collection efficiency (mass collected vs. total evolved); and collection purity (mass collected of desired product vs. total collected). Specific areas of interest include:
Excavation techniques for soil-like to rock-like regolith (70MPa), depending on water content, and very cold (40K to 100K) regolith and local environment conditions;

Excavation technology or systems for collecting regolith while preserving the loosely held volatile species that may be present;

Regolith handling, processing, and heating techniques that minimize the amount of time and energy required to evolve volatiles (either solar wind implanted or in permanently shadowed craters);

Gas separation and collection techniques for a product stream containing various concentrations of hydrogen, carbon dioxide, nitrogen, helium, water, ammonia, and methane;

Demonstration of sealing technology for repetitive (less than 50 times) use at a wide range of temperatures (40K - 500K nominal and up to 1500K maximum) in abrasive, electrostatic, high vacuum environment; and

Specific technologies or recipes for implanting volatile species in terrestrial samples of lunar regolith simulant to support volatile species collection and extraction technology development.

Sub Topics:

Lightweight Structures Topic X6.01
This subtopic solicits innovative structural concepts that support the development of lightweight structures technologies that could be applicable to lunar surface landers and habitats. The targeted innovative lightweight structures are for primary pressurized structures such as 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:

- Lightweight multifunctional and/or integrated structural systems that include radiation shielding, impact shielding, thermal management, damage tolerance and durability, and/or integral diagnostics/health monitoring, and novel inspection/nondestructive evaluation 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 impact 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. Research should be conducted to demonstrate technical feasibility during Phase 1 and show a path toward a Phase 2 hardware demonstration, and when possible, deliver a demonstration unit for functional and environmental testing at the completion of the Phase 2 contract.

Sub Topics:

Low Temperature Mechanisms Topic X6.02
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 380K (-190°C to +107°C). 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.

Research should be conducted to demonstrate technical feasibility during Phase 1 and show a path toward a Phase 2 hardware demonstration, and when possible, deliver a demonstration unit for functional and environmental testing at the completion of the Phase 2 contract.

Sub Topics:

Advanced Radiation Shielding Materials Topic X6.03
Revolutionary advances in radiation shielding materials and structures technologies are needed to protect humans from the hazards of space radiation during NASA missions. All particulate radiation species are considered, including electrons, protons, neutrons, alpha particles, light ions, heavy ions, etc. All space radiation environments in which humans may travel in the near future are considered, including low-Earth orbit, geosynchronous orbit, Moon, etc. The primary area of interest for this 2007 solicitation is radiation shielding materials systems for long duration lunar surface protection for humans. Lightweight radiation shielding materials systems for short-term in-space operations for humans are also of interest. The materials emphasis is on multifunctional materials, where two of the functions are, but not exclusively, radiation shielding efficiency and structural integrity. Radiation shielding design software to optimize multifunctional materials usage in specific designs is also of interest.

Radiation shielding augmentation materials are part of this solicitation, along with associated software tools to minimize augmentation requirements. Research should be conducted to demonstrate technical feasibility during Phase 1 and to show a path toward a Phase 2 technology demonstration. 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:
• Innovative lightweight radiation shielding materials and structures to shield humans in crew exploration vehicles, large space structures such as space stations, orbiters, landers, rovers, rigid habitats, inflatable habitats, spacesuits, etc.;

• 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 phases of the design process;

• Radiation shielding software, compatible with Multi-Disciplinary Optimization (MDO) analysis, for optimization of specific vehicle designs;

• 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;

• Innovative fabrication techniques to fabricate advanced radiation shielding materials into useful products and structural components;

• 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;

• 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;

• Innovative concepts to reuse, recycle, and reprocess materials and structures in space for use as radiation shielding materials and structures.

Sub Topics:
Advanced Composite Materials Topic X6.04
This subtopic solicits innovative research for advanced composite materials, processing and characterization 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. Reduction in structural mass translates directly to additional up-and-down mass capability that would facilitate logistics and increase science return for future missions. Advanced composites are targeted that could be implemented into vehicle and propulsion systems for launch vehicles, lunar landers, and habitats. Innovations in technology are needed to increase specific strength and stiffness, provide radiation shielding, enhance thermal management, reduce Micrometeoroid/Orbital Debris (MMOD) damage potential, and provide effective nondestructive verification and characterization, while maintaining safety, reliability, and reducing costs.

Advanced composite material systems and their corresponding manufacturing, processing and verification techniques are desired. Examples would include, but are not limited to, material systems and mature applications of nano-structured materials. Processing examples would include, but are not limited to, automated composite
fiber/tape placement, non-autoclave curing, processing innovations for multifunctionality, ceramic processing, nanomaterials processing, freeform fabrication, and bonding of composites.

Development of concepts can include material system characterization, proof-of-concept demonstrations for integrated lightweight structures, innovative multifunctional concepts, enabling performance and affordability (including life cycle costs) enhancement, damage tolerance/control techniques, 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. Preferred processing and verification techniques would include non-contact, high-resolution nondestructive evaluation 2D and 3D imaging and characterization approaches using electromagnetic techniques such as Terahertz and millimeter waves with resolutions of 1-5 mm. Research should be conducted to demonstrate technical feasibility during Phase 1 and show a path toward a Phase 2 prototype demonstration.

Sub Topics:

Supportability 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:

- 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.

Rapid manufacturing processes have advanced rapidly in recent decades. The technology has gone from a means of quickly producing models to a means of quickly producing usable hardware. NASA seeks technology improvements which extend the efficiency of rapid manufacturing and improve the properties of resulting components. NASA also seeks to identify different applications that will highlight the capabilities of rapid manufacturing in support of the Vision of Space Exploration and potential commercial applications. NASA also seeks technology focused on integration of rapid manufacturing, computer numerical control, coordinate measuring machines, Robotics and Digital Manufacturing and Simulations technologies. This technology should be focused on an autonomous system where the parts fabricated in rapid manufacturing can be positioned for machining on critical surfaces, then positioned for measurements and inspections and ultimate delivery (independently and remotely). The results should be an autonomous system where these technologies are integrated as modules to produce the end result.

Sub Topics:

**Human Systems 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 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 site operations, both at an outpost and at remote lunar surface locations. Site operations support focuses on two types of activities: (1) tedious, highly repetitive, long-duration tasks that cannot be performed by EVA crew and (2) rapid response for addressing emergency, time-critical situations. Candidate tasks include: mobile camera platform control, systematic site survey (engineering and/or science), inspection, emergency response, site preparation (clearing, leveling, etc.), and instrument deployment. 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) line-of-sight remote, and lunar. Particular interest is given to systems that flexibly support human-robot operations in the presence of time-delays of up to 10 seconds.

- Adaptive user interfaces including perception, speech recognition, context awareness, computational cognitive models, and 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.

- Geospatial tools for situational awareness including content generation tools for geospatial information,
  particularly for supporting planetary surface missions; software libraries for generating, parsing, and
  importing heterogeneous mission data (orbital imagery, navigation information, sensor and instrument
  readings, etc.); and terrain modeling (Digital Elevation Map).

- Vehicle control components 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 Mobility and Transportation 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 mobility systems to provide the power train for site clearing, pad
construction, and regolith manipulation (note that the power train attachments for this activity will be provided by the
in situ resource utilization (ISRU) area); 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:

- 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.

- Low-mass, high-strength, long-life wheels capable of spreading supported load over an extended contact
  patch area and moving over surface terrain similar to loose beach sand. Range, Life, Mass, Mean-time-to-
  repair, and Mean-time-between-failure are key performance parameters being sought.
- Reliable navigation sensors to support surface mobility by a range of vehicles (ranging from MER-class to LRV-class). For example, a range finder with dynamically-operated foveal aperture could support wide field-of-view scanning and three-dimensional object tracking.

- Navigation and communication infrastructure technologies for use on the Lunar surface to support surface mobility and communication between lunar base, EVA astronaut and mobile rover/robotic assistant.

Sub Topics:
Surface System Dust Mitigation Topic X7.04
The general objective of the subtopic is to provide knowledge and technologies (to Technology Readiness Level (TRL) 6 development level) required to address adverse dust effects to exploration surface systems and equipment, which will reduce life cycle cost and risk, and will increase the probability of sustainable and successful lunar missions. The subtopic will help to develop a balance of near- and long-term knowledge and technology development, driven by Exploration Systems Mission Directorate needs and schedule requirements, aligned with existing technology investments where possible. The technical scope of the subtopic includes the evaluation of lunar dust effects and development of mitigation strategies and technologies related to Exploration Surface Systems, such as: Rovers and Robotic Systems, In Situ Resource Utilization (ISRU) Systems, Power Systems, Communication Systems, Airlock Systems and Seals, Habitats, and Science Experiments.

The subtopic specifically requests technologies addressing dynamic mechanical systems used for lunar surface missions with potential to mitigate effects of lunar dust. For lubricated mechanisms, such as drives and pointing mechanisms, the sealing element must be durable enough to maintain a hermetic seal to prevent lubricant outgassing and dust contamination for at least 5 years. Also, the bearings, gears, etc. of the mechanism must be robust enough to survive and provide nominal operation with lunar dust contamination and possible lubrication starvation.

The subtopic also requests proposals for advanced materials, coatings, and related technologies with the proper combination of physical, mechanical, and electrical properties, and lunar environmental durability, suitable for use in dust mitigation applications on the lunar surface.

Sub Topics:
Fuel Cells for Surface Systems Topic X8.01
Energy storage devices are required to enable future robotic and human exploration missions. Advanced regenerative fuel cell (RFC) energy storage systems are sought for use in a wide range of Exploration mission applications including portable power for landers and rovers, and stationary power for surface bases. Technology advances that will reduce the weight and volume, improve the efficiency, life, safety, system simplicity and reliability of RFC systems are desired. The specific advancements of interest are outlined below.
Regenerative Fuel Cell (RFC) Systems: Primary fuel cells and water electrolyzers are the two major constituent subsystems of RFC systems. Of these two subsystems, water electrolyzers are at a lower level of technology readiness than primary fuel cells.

Specifically, technological advances are sought in the area of highly efficient, high-pressure proton-exchange-membrane (PEM) water electrolyzers. Highly efficient operation reduces the total quantity of reactants required, thereby minimizing weight. The efficiency of electrolysis stacks increases by operating at lower current densities. High-pressure electrolysis eliminates or reduces the need for external gas compression prior to reactant storage. The draw-back of high-pressure operation, however, is the increased diffusion of reactants across the proton exchange membrane of the cell, which effectively decreases the efficiency. This efficiency loss is magnified at lower current densities. The challenge, therefore, is to minimize this diffusion at higher operating pressures and low current densities, making efficient electrolysis operation possible.

High-pressure electrolysis systems capable of oxygen and hydrogen gas production at pressures less than 2000 psi are of special interest.

Research should be conducted to demonstrate technical feasibility during Phase 1 and show a path toward a Phase 2 hardware demonstration, and when possible, deliver a demonstration unit for functional and environmental testing at the completion of the Phase 2 contract.

Sub Topics:
Advanced Space Rated Batteries Topic X8.02
Advanced human-rated energy rechargeable batteries are required for future robotic and human exploration missions. Advanced Li-based battery systems are sought for use in a wide range of Exploration mission applications including portable power for landers, rovers, Extravehicular activities (EVA), and astronaut equipment; storage systems for crew exploration vehicles and spacecraft; and stationary energy storage applications such as base power or peaking power applications. Areas of emphasis include advanced component materials with the potential to achieve weight and volume performance improvements and safety advancements in human-rated systems.

Rechargeable lithium-based batteries with advanced non-toxic anode and cathode materials are of particular interest. Technology advancements that contribute to the following performance goals are sought: specific energy greater than 180 Wh/kg, energy density greater than 400 Wh/l, calendar life less than 5 years, cycle life at 100% Depth of Discharge (DOD) greater than 2000 cycles, and fast recharge capability (100% recharge in less than 15 minutes). Systems that combine all of the above characteristics and demonstrate a high degree of safety and reliability are desired.

Proposals are sought which address advanced cathodes with specific capacities in excess of 240 mAh/g at C/2 rate discharge and 25°C and/or advanced anodes with specific capacities in excess of 400 mAh/g at 25°C with minimal irreversible capacity loss.
Research should be conducted to demonstrate technical feasibility during Phase 1 and show a path toward a Phase 2 hardware demonstration, and when possible, deliver a demonstration unit for functional and environmental testing at the completion of the Phase 2 contract.

Sub Topics:
Nuclear Surface Power Topic X8.03
NASA is interested in the development of highly advanced systems, subsystems and components for use with fission and isotopic power systems for future lunar and Mars robotic and manned missions. Proposals are sought for critical technologies for fission and isotopic power systems to meet the following anticipated missions and applications.

The current Vision for Space Exploration identifies the first human lunar landing in 2017 with subsequent longer duration stays of approximately 6 months in 2021. Fission-based systems are anticipated to enable the long duration stay over the lunar night and for "global access" Mars missions. Initial planetary outpost power levels are anticipated to be between 30-50 kWe with anticipated growth to 100's kWe, accommodating resource production and advanced life support habitation, which require additional power.

Planetary surface human base applications include: habitats, propellant production/liquefaction/maintenance, surface mobility for both robotic and piloted rovers, excavating and mining equipment and science applications such as: deep drilling, resource production demos, weather stations, etc. Isotopic technologies are needed for unique space environments that improve the utilization of a limited fuel supply and have extensibility to fission systems.

Specific technology topics of interest are:

- Advanced, high efficiency, high temperature power conversion less than 20%;
- Electrical power management, control and distribution (1000-5000 V);
- High temperature, low mass thermal management/heat rejection less than 6kg/m^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_2, corrosive soils, etc.);
- Power system design considerations for long life (greater than 10 years), autonomous control and operation, including sensor and control technologies;
- Radiation tolerant systems and materials enabling 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 will be used on robotic and human missions and it is to NASA’s advantage to develop those technologies that satisfy both robotic and human mission requirements.

Sub Topics:

Cryogenic Propellant Storage and Distribution for Space Exploration Applications Topic X9.01
This subtopic includes technologies for long term cryogenic propellant storage and distribution 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 (less than 20m$^3$ for supercritical air and payload cooling) to very large (greater than 3400m$^3$ 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: passive and active thermal control, pressure control, and propellant feed line conditioning. 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:

1) Thermal Control

**Passive Thermal Control:**

Successful passive thermal control is enabling for all aspects of Cryogenic Fuel Management. The propellant boil-off losses attributable to the passive thermal control subsystem are influenced by Multi-Layer Insulation (MLI)
design, MLI to tank attachment techniques and materials, tank to vehicle support structure and attachments, tank size and configuration, tank and insulation penetrations, insulation venting provisions for launch and ascent, flight and surface environments, vehicle orientation in those environments, and thermal control surface coatings and materials.

Applications/Technology Maturity: The Earth Departure Stage (EDS) and the Lunar Surface Access Module (LSAM) descent stage require LH$_2$ and LO$_2$ storage durations of 5 to 95 days in Low Earth Orbit (LEO).

The LSAM ascent stage requires LO$_2$ and LCH$_4$ storage durations of up to 95 days in LEO and up to an additional six months on the lunar surface.

Development Needs: Passive thermal control development needs include; integration of MLI with micro-meteoroid protection, tank support structure, and other insulation penetrations. Other development needs include; characterization of the potential advantages of subcooled propellants, investigation of options such as shading, advanced materials, mechanisms and other techniques for passive thermal control on the lunar surface.

Active Thermal Control:

Active thermal control combines the passive thermal control technology element with active refrigeration (cryocoolers) to allow storage periods from a few months to years with reduced boil-off losses.

Applications/Technology Maturity: Flight-type 20K (LH$_2$) cryocoolers of sufficient cooling capacity (20 watts) to eliminate LH$_2$ boil-off do not exist, and thus the development of 20K cryocoolers is a long-lead technology item. State-of-the-art cryocoolers in the 80K range (LO$_2$/LCH$_4$ temperatures) have been developed for cooling sensors and have flown on numerous satellites. However, the integration of these cryocoolers into an active thermal control system for propellant storage of LO$_2$ and LCH$_4$ and LH$_2$ is a technology issue.

Development Needs: Flight cryocooler to propellant tank integration techniques for large space-based storage systems, distributed cooling shields integrated with MLI and development and testing of active cooling techniques for tank penetrations and supports is required. Development of flight-type 20K, 20 watt capacity cryocoolers designed for integration into large space-based LH$_2$ storage systems is also required for application to Mars missions.
2) Pressure Control

Controlling cryogenic propellant tank pressure in low gravity with minimum boil-off losses without settling the propellants can be accomplished with a thermodynamic vent system (TVS). A TVS subsystem typically consists of a pump for circulation and mixing, a Joule Thompson expansion device/heat exchanger for heat removal, valves and a vent line.

Applications/Technology Maturity: A TVS will be required for the EDS, LSAM and the LO₂/LCH₄ version of the Orbital Maneuvering Systems (OMS) and Reaction Control Systems (RCS) for the CEV.

Development Needs: EDS, LSAM and CEV development needs include innovative TVS configurations and applications, system integration and control and modeling of low-gravity fluid dynamics and heat transfer for specific TVS designs. EDS, LSAM and CEV vehicle advanced development needs include integrated system testing with LH₂, LO₂ and LCH₄ to determine the effect of internal tank hardware configuration on fluid mixing.

3) Propellant Feed Line Conditioning:

Maintaining vapor-free liquid propellant between the tank outlet and the OMS/RCS engine inlet is a significant technology challenge. For lunar in situ cryogenic applications, systems are needed to store and transfer to warm tanks in the dusty lunar surface environment.

Applications/Technology Maturity: Propellant feed line conditioning will be required for all vehicles with a cryogenic OMS/RCS. Specific feed line configuration, routing and heat loads for each vehicle must be addressed.

Development Needs: CEV, EDS and LSAM vehicle development needs includes integrated system testing with LH₂, LO₂ and LCH₄ to address vehicle specific feed line routing and heat loads, and couplings for lunar in situ propellant systems.
Sub Topics:

Cryogenic Propellant Mass Gauging and Liquid Acquisition for Low Gravity Applications Topic X9.02

This subtopic includes technologies for applications related to cryogenic propellant management in low gravity. Liquid Acquisition Device (LAD) and Mass Gauging (MG) technologies will principally impact cryogenic systems for Orbital Maneuvering Systems (OMS) and Reaction Control Systems (RCS) for orbit transfer vehicles for in-space transportation applications, and are critical to successful liquid propellant delivery to Orbital Maneuvering Systems (OMS) and Reaction Control Systems (RCS) propulsion system and allowance of smaller propellant tank residuals to assure mission success. 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: liquid acquisition devices and mass gauging/advanced instrumentation. Innovative concepts are requested for devices that interface with the tank and provide vapor-free liquids for on-orbit propulsion systems, low-gravity mass gauging technologies to enable accurate and reliable measurements of cryogenic liquid mass in low-gravity storage tanks without propellant settling or undue constraints on mission, and cryogen leak detection technologies. 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:

1) Liquid Acquisition:

Providing vapor free cryogenic propellants to in-space propulsion systems at expulsion efficiencies less than 98% without settling the propellants is the objective of the liquid acquisition technology element. Capillary liquid acquisition devices (LADs) are state-of-the-art for toxic propellants, but have not yet been developed for cryogens. Existing cryogenic upper stage main engine restarts use auxiliary thrusters to settle the propellants.

Applications/Technology Maturity: Cryogenic LADs will be required for the LO$_2$/LCH$_4$ version of the OMS/RCS for the CEV and LSAM and possibly the EDS. LH$_2$ LAD performance represents the primary challenge while LO$_2$ and LCH$_4$ performance risk is substantially less if the liquids are sub-cooled relative to the propellant tank ullage pressure.

Development Needs: Liquid acquisition technology needs include investigation of helium solubility and heat entrapment effects, propellant tank LAD integration, LAD materials selection, analytical performance model development, and techniques to minimize vaporization inside the LAD channel caused by incident heating through tank wall/lines and/or changes in tank pressure. CEV, LSAM and possibly the EDS vehicle advanced development needs include integrated system testing with LH$_2$, LO$_2$ and LCH$_4$ to determine the effect of internal tank hardware configuration on LAD performance.
2) Mass Gauging/Advanced Instrumentation:

The need for a reliable, accurate method for measuring cryogenic propellant mass without settling the propellants is the principal objective of the mass gauging technology element.

Applications/Technology Maturity: Applications for cryogenic mass gauging include the EDS, LSAM and the CEV OMS/RCS. A measurement uncertainty metric of less than 3% of full-tank mass has been established for the propellant mass measurements for these vehicles.

Development Needs: 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 cryogenic fluid leak detectors.

Sub Topics:
   Cryogenic and Non-Toxic Storable Propellant Space Engines Topic X9.03
This solicitation intends to examine a range of key technology options associated with cryogenic and non-toxic storable propellant space engines. Non-toxic engine technology is desired for use in lieu of the toxic but currently operational nitrogen tetroxide and monomethylhydrazine engine technology. Safety concerns with toxic propellants drive mission planners to the use of more costly propulsion modules that are fueled and sealed on the ground. There are also concerns with exhaust residue from toxic systems, which may be carried into habitats for lunar and Mars systems.

The primary mission will be to support lunar ascent/descent reaction control engines and lunar ascent engines. These engines can be compatible with the future use of in situ propellants such as oxygen, methane, and methanol. Key performance parameters:

- Reaction control thruster development is in the 100-500-lbf thrust class with a target vacuum specific impulse of 325-sec. These RCS engines would operate cryogenic liquid-liquid for applications requiring integration with main engine propellants; or would operate gas-gas or gas-storable liquid for small total impulse type applications.

- Ascent engine development is projected to be in the 3,500-6,000-lbf thrust class with a target vacuum
specific impulse of 355-sec. The engine shall achieve 90% rated thrust within 0.5 second of the issuance of the Engine ON Command.

Specific technologies of interest to meet proposed engine requirements include:

- Low-mass propellant injectors that provide stable, uniform combustion over a wide range of propellant inlet conditions;
- Combustion chamber designs using high temperature materials, coatings and/or ablatives for combustion chambers, nozzles and nozzle extensions;
- Combustion chamber thermal control technologies such as regenerative, transpiration, swirl or other cooling methods which offer improved performance and adequate chamber life;
- Highly-reliable, long-life, fast-acting cryogenic valves that tolerate high thermal loading due to heat soak-back in low-thrust, pulsing propulsion systems (Thermal Isolation less than 1 Btu/hr) with reduced volume and size is also desirable;
- Highly-reliable, long-life, fast-acting propellant valves for gaseous propellants with reduced power, volume and size.

A key risk related to the use of cryogenic and gaseous propellants such as oxygen and methane are the ability to reliably ignite the propellants in a timely manner. This is of particular importance on ascent engines during abort operations. Recently NASA has been conducting a number of investigations into the ignition characteristics for oxygen and methane, primarily for spark torch systems. NASA continues to be interested in new and innovative methods which may be used as primary or back-up systems. Proposals are also solicited for igniter exciter technologies. In particular, for reaction control systems involving multiple engines that are not all co-located, issues between distributed vs. centralized exciter architectures must be balanced when selecting an exciter design. A "distributed" system refers to an integral exciter at each spark plug, whereas a "centralized" arrangement has at least some exciter components (e.g., DC-DC converter, control electronics, etc.) remotely located (e.g., with other avionics) and shared by multiple engines/spark plugs. Specific technologies of interest include:

- Reliable ignition systems such as spark torch, catalytic, microwave, combustion wave, laser, etc.;
- Exciters to support either capacitive (CDI) or inductive (IDI) discharge ignition types;
- High cycle spark plugs for use with cryogenic and/or gaseous propellants;
- Cryogenic instrumentation such as pressure and temperature sensors that will operate for months/years instead of hours.

Sub Topics:
Launch Vehicle Propulsion and Pyrotechnic Technologies Topic X9.04
The goal of this subtopic is the development of innovative components, manufacturing techniques, health management systems, and design and analysis tools for launch vehicle propulsion and pyrotechnic systems. Performance, reliability, and cost of operations improvements to existing and planned Constellation launch vehicle propulsion and pyrotechnic systems are needed. Technologies that would contribute to decreased sensitivity to manufacturing and handling effects, that will lead to reduction in development and qualification testing, and that will lead to reduction in touch labor during ground operations and vehicle turnaround are particularly welcomed. Also solicited are proposals that would reduce the time, cost, and complexity associated with designing and analyzing launch vehicle propulsion and pyrotechnic systems. While solid or hybrid rocket propulsion is specifically emphasized, compelling proposals related to liquid engine boost propulsion are also invited.

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; technology that supports applicability of these systems for in-space primary propulsion is also of interest.
- 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 improvements that allow for reductions in the cost and schedule required to fabricate and test solid or hybrid rockets.
- 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 encouraged.
- Retrofitable technologies to existing boost liquid engines that address the goals of performance enhancement and/or lower operations cost.
- Improvements in explosive bolt technology, both for traction as well as ejector bolts, to improve handling safety and increasing robustness of installation.
- Improvement to detonators to reduce the required initiation power, or to provide integrated safe-and-arm functions within detonator.
- Wireless or optical approaches for initiation of explosive bolts and frangible nuts for reduced system weight and improved safety.
- Improvements to explosive cutters, cutting chords, and specialty cutting charges to reduce installation labor, check-out labor, and sensitivity to environmental, handling, and ageing effects without reducing reliability.
- Analysis tools that support development and operation of launch vehicle propulsion systems (liquid, solid, or hybrid) by allowing for a more accurate definition of the environment internal to the propulsion system. Test data that provides for validation of existing design and analysis tools is also sought.
• Improvement to the design and analysis tools that support pyrotechnic devices development and integration into the launch vehicle system, especially those tools that define the induced environments created during and immediately after the action time of the pyrotechnic device; Test data to validate and quantify uncertainty in launch vehicle pyrotechnic devices design and induced environments.

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

Sub Topics:
Detachable, Human-rated, Ablative Environmentally Compliant TPS Topic X10.01
The Crew Exploration Vehicle (CEV) will first be used for transporting crew and cargo to the International Space Station and later for the human exploration of the Moon and Mars. The TPS for the CEV will have to protect the crew and cargo from entry heating at entry velocities of approximately 8 km/s for International 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 thermal protection system (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.

Shape Optimization/Entry System Architectures

The design of a reentry craft must encompass not only aerothermodynamic heating concerns but also the conflicting constraints of aerodynamic stability, mass, and cross-range performance. Therefore, the TPS cannot be
designed in isolation but must be viewed as a part of a whole. Advances are sought in multidisciplinary design
optimization (MDO) methods such as gradient methods and genetic algorithms.

**Instrumentation**

Thermal Protection System (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 bond line 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. Advances are sought in material development to address survivability in the severe convective and radiative heating environment and to address mass constraints and technological developments to address flow stability concerns and control authority in the face of atmospheric uncertainties and targeting errors. Advances and innovative concepts in integrated TPS design for multi-mission modes (aerocapture followed by entry requiring multi-use ablators vs. multi-layered ablators) are sought.

Sub Topics:
Thermal Control for Surface Systems and Spacecraft Topic X11.01
Advanced technologies are sought for thermal management of Earth-orbiting spacecraft, the human lunar habitat, landers, and rovers, for Martian transit spacecraft, as well as planetary expeditions to Jupiter, Venus, and their moons. Future spacecraft will require more sophisticated thermal control systems that can dissipate or reject greater heat loads at higher input heat fluxes while using fewer of the limited spacecraft mass, volume and power resources. The thermal control designs also must accommodate the harsh environments associated with these missions including dust and high sink temperatures. Modular, reconfigurable designs could limit the number of required spares.

Earth-orbiting spacecraft contain instruments, such as LIDAR lasers and electronics systems and/or components, which can generate high thermal dissipation loads at high heat flux rates. Spacecraft instruments can have tight temperature control requirements and/or thermal gradient requirements (micro-Kelvin requirements). Spacecraft instruments operate in temperature regimes ranging from cryogenic to above ambient (-180ºC to +100ºC). Radioisotope thermoelectric generators (RTGs) generate relatively large amounts of heat. Design plans for Earth-orbiting spacecraft seek smaller (down to MEMS level components or instruments) and reconfigurable designs.

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 polar lunar bases that are foreseen in 15 years will see extremely cold thermal environments, as will the radiators for Martian transit spacecraft. Long sojourns 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. Radiators on the Moon's poles and on a Martian transit vehicle are required that will operate and survive in very cold environments. Variable emissivity coatings, clever working fluid selection, or robust design could be used to prevent radiator damage from freezing at times of low heat load. Also, the dusty environment of an active lunar base may require dust mitigation and removal techniques to maintain radiator performance over the long term.
The lunar base and Martian transit spacecraft active thermal control systems will include high efficiency, long life mechanical pumps. 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. Small heat pumps could be used to provide cold fluid to the heat exchanger, increasing the average heat rejection temperature and reducing the size of the radiators.

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.

Sub Topics:

Health Preservation in the Space Environment Topic X12.01
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.

Non-invasive Pharmacotherapy and Monitoring
Development of innovative technologies resulting in non-invasive 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.

Non-invasive 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-aged crew. Novel technology for non-invasive assessments of "bone quality" indices such as microarchitecture, macroarchitecture and trabecular Bone mineral density (BMD).

Technologies to Detect Biomarkers

Develop technologies to detect products of bone demineralization in urine during Flight and the biomarkers of bone degradation include N-telopeptide (NTX), C-telopeptide (CTX), pyridinoline and deoxypyridinoline collagen cross-links, and calcium ion. Develop technologies to monitor bone specific alkaline phosphatase and osteocalcin in serum samples.

Portable Motion Simulator

Develop a portable research platform to investigate the influence of spatial disorientation on manual control tasks during lunar-type landings. A 6-DOF motion simulator with full visual motion display will be developed to simulate landing tasks with and with visual motion (brownout) conditions. The simulator should be portable, and fit within standard (8 ft) room heights. The power requirements should be limited to 240VAC 30A. The subject restraint should accommodate both standing and seated positions. The control system should allow the user to import motion profiles, and provide the capability to evaluate various pilot-induced filter (PIO) options from a hand-held controller.

Sub Topics:
Crew Exercise Systems Topic X12.02
1) Identify compact, multi-function exercise devices to protect muscle and cardiovascular health during lunar sortie missions (missions with total duration less than 30 days). This device must be 10kg or less including all accessories, require no vehicle power to operate, include materials/components that can be flight certified and do not pose risk to the crew vehicle/habitat, and be stowed within 1 cubic foot of space aboard the Crew Exploration Vehicle/Orion and/or Lunar Surface Access Module. The device must be capable of providing whole body and individual joint resistive loading that ideally simulates free weights. The load must be adjustable in increments no greater than 2.5 kgs and provide adequate loading to protect muscle strength to levels specified per the NASA Space Flight Human System Standards, Volume 1. The same device must be capable of providing whole-body aerobic exercise levels necessary to maintain aerobic fitness per the NASA Space Flight Human System Standards, Volume 1.

2) Identify compact, reliable multi-function exercise devices/systems to protect bone, muscle, and cardiovascular health during lunar outpost missions (missions with total duration less than 6 months). This device should be easily configured and stowed, require minimal power to operate, include instrumentation to document exercise session parameters using portable electronic media. The device must be capable of providing whole body axial loading and individual joint resistive loading that ideally
simulates free weights. If unable to match the inertial properties of free weights, then the device must provide near constant loading at any given load setting and achieve an eccentric to concentric load ratio greater than 90%. The load must be adjustable in increments no greater than 2.5 kgs and provide adequate loading to protect muscle strength and bone health to levels specified per the NASA Space Flight Human System Standards, Volume 1. The same device must be capable of providing whole-body aerobic exercise levels necessary to maintain aerobic fitness per the NASA Space Flight Human System Standards, Volume 1. Finally, the ideal device should also stimulate the sensory-motor system which controls balance and coordination.

3) Identify small, lightweight, sensor-based exercise monitoring systems that can be used to assess periodic fitness during lunar outpost missions and transit to Mars. Devices should be small, employ re-usable elements (versus requiring consumables), and be minimally invasive to measure heart rate and rhythm, oxygen consumption and lactic acid threshold. The ideal system would also include other medical monitoring capabilities such that it could be utilized to assess other crew health variables (e.g., imaging capabilities, respiration rate, blood parameters, etc.).

Sub Topics:  
Exploration Medical Capability Topic X12.03  
On-board clinical diagnostics to monitor crew member physiology must be available for both mid-term lunar and long-term Mars exploration missions. As in terrestrial medicine, devices with which to measure multiple constituents of small volume samples of bodily fluids are crucial components in assessing astronaut health. Nevertheless, mass, space, and power requirements of such devices are an obvious concern in an environment with scarce resources. Miniaturized laboratory analysis sensors represent a potential solution, given that these devices and supporting hardware are designed to be small, lightweight, and require little power. However, current sensor cartridges are typically single-use with limited shelf life. In order to satisfy the needs of longer duration exploration missions, reusable laboratory analysis sensors with increased shelf life must be designed without compromising accuracy or sensitivity. NASA seeks proposals for developing such reusable laboratory analysis sensors for measuring complete blood count with differential. Both the actual chips and associated electronics should minimize the use of electrical power and be as small as possible. Research should be conducted to demonstrate technical feasibility during Phase 1 and show a path toward a Phase 2 breadboard demonstration.

Sub Topics:  
Space Human Factors Assessment Tools Topic X13.01  
The Human Research Program (HRP) and the Behavioral Health and Performance Research Program (BHP) are among NASA’s major Space Human Factors research programs. In collaboration with these two programs, the SBIR program is looking for research proposals that address the following two research areas: (1) an Automated Human Factors Incident Reporting Tool (AHFIRT) and (2) a Cognitive Assessment Tool (CAT).
Automated Human Factors Incident Reporting Tool (AHFIRT)

The HRP provides human health and performance countermeasures, knowledge, technologies, and tools to enable safe, reliable, and productive long-duration human space exploration. Objectives of the HRP include developing capabilities and technologies to support and mitigate risks to crew health and performance, reducing human systems resource requirements (mass, volume, power, data, etc.), and ensuring effective human-system integration across exploration systems.

To support these objectives, the HRP determines that obtaining timely and context-specific Human Factors (HF) incidents data is a technology gap the program wants to address. Currently, space HF data come from crew debriefs. Such debriefs rely on retrospective recall, which could suffer delays of up to six months. Furthermore, opportunities to discuss HF issues in detail during these debriefs are limited. Consequently, the HRP sees the need to develop an Automated Human Factors Incident Reporting Tool (AHFIRT).

Objective: Development of an AHFIRT that assists the gathering and reporting HF incidents for long-duration space missions.

Requirements: In general, the AHFIRT will be used to help detect areas where HF can contribute to mission success, access the effects of operational and hardware changes, and complement existing HF data sources for operations including crew debriefs. Specifically, the AHFIRT shall meet the following requirements:

- The crew shall have easy access to the tool at any time to eliminate the need for the crew to recall information retrospectively.
- An easy-to-use data gathering protocol with the following functionalities:
  - Allow data to be entered either as text, audio, and/or video inputs
  - It is desirable for AHFIRT to detect system anomaly automatically and immediately record system status. At the minimum, however, the tools should provide an easily accessible event marker for the crew to mark the context and take a snapshot of the system and operator system status.
- Provide a user-friendly automated data search engine for extracting meaningful incident information from the raw data. Examples of desirable search schemes include natural language, spatial, temporal searches, etc.
Phase 1 Requirements: Technology Evaluation

The technical merit of the AHFIRT will be explored to evaluate feasibility. This process shall include:

- Evaluating/researching/developing automated data mining technologies
- Defining optimal data gathering protocol
- Determining optimal hardware/software design
- Developing hardware and software algorithms

Phase 2 Requirements: Prototype Development

The process shall include:

- Developing a working AHFIRT prototype
- Evaluate and test the functionality and usability of the prototype device

Cognitive Assessment Tool (CAT)

The NASA Behavioral Health and Performance Research Program (BHP) identifies and characterizes the behavioral health and performance risks associated with training, living and working in Space, and return to Earth. The BHP Research Element develops strategies, tools, and technologies to mitigate these risks. Currently, the BHP has the need for a Cognitive Assessment Tool (CAT).

Due to the high-intensity workload, disturbed sleep conditions, and other stressors of spaceflight, some astronauts have reported experiences of disturbed cognitive processes and fatigue.

Presently, a tool is utilized on the International Space Station (ISS) to detect neurocognitive deficits as a result of physical changes to the brain, which can occur from an injury to the head or exposure to a toxin. However, this assessment is designed as a programmed test that is not sensitive to crewmember fatigue. Consequently, there has been increased interest for a validated tool that can:
Detect cognitive decrements as a result of fatigue or other stressors of spaceflight

Support the Astronauts with an entertaining assessment activity(s)

Support crew autonomy by providing objective feedback directly to the crewmember regarding their behavioral health

Objective: Design, develop, and fabricate a handheld, CAT that is in the form of a video game.

Requirements: The CAT game may include a suite of games as opposed to one single game. Ideally, the game would determine whether the player's deficit is a result of fatigue, stress, or neurocognitive impairment. Specifically, the CAT shall be as follows:

- In a hand-held video game format
- Portable hand-held unit
- Enjoyable and entertaining
- Flexible enough for increasing levels of difficulty
- Able to detect and identify cognitive decrements catalysts such as fatigue, stress, and/or neurocognitive deficits
- Able to provide immediate feedback to crewmembers, especially flight surgeons, with recommended countermeasure(s) based on his/her cognitive performance to support crew autonomy

Potential means for the CAT to assess performance may include measures of:

- Reaction times
- Accuracies
- Memory recall
- Complex decision making
- Physiological measures, such as heat rate via thumbs
- Speech acoustic analysis
- Facial monitoring
- Eye analysis
Note that the aforementioned methods are provided as examples of current research developments and are not intended as an all-inclusive or restrictive mandate for the development of the CAT.

Phase 1 Requirements: CAT Start-Up

The technical merit of the CAT will be explored to evaluate feasibility. This process will include:

- Defining predictors of cognitive decrements
- Determining which aspects of cognition should be assessed
- Determining optimal hardware design
- Hardware and software algorithms development

Phase 2 Requirements: CAT Research and Development

Content development of the CAT games should be determined based upon results of a qualitative study conducted with sample population (similar to Astronauts) to ensure corroboration and interest prior to the following stages:

- Develop software for gaming, data analysis, feedback, and recommended countermeasures
- Develop prototype hardware
- Develop manual and trouble shooting guide
- Evaluate and test the functionality of the prototype device.

Sub Topics:
Advanced Food Technologies Topic X13.02
The purpose of the Advanced Food Technology Project is to develop, evaluate and deliver food technologies for human centered spacecraft that will support crews on missions to the Moon, Mars, and beyond. 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. Concurrently, the food system must efficiently balance appropriate vehicle resources such as mass, volume, water, air, waste, power, and crew time. One of the objectives during the lunar outpost missions is to test technologies that can be used during the Mars missions.
This subtopic will concentrate on two specific areas; food packaging and lunar outpost food preparation and food processing.

**Non-Foil High Barrier Materials**

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. New food packaging technologies are needed that have adequate oxygen and water barrier properties to maintain the foods' quality over a 3 - 5 year shelf life. The packaging must also minimize waste by using high barrier packaging with less mass and volume.

The current flexible pouch packaging used for the thermostabilized and irradiated food items contains a layer of foil. Although the foil provides excellent oxygen and water barrier properties, it also contributes to added waste. Food packaging will be a major contributor to the trash on the lunar or Mars surface. One of the proposed methods to dispose of trash on the lunar or Mars surface is incineration. However, the foil layer will not incinerate completely and there will be ash formed.

Two emerging food preservation technologies, high pressure processing and microwave processing, are being considered for future NASA missions. However the current high barrier packaging material cannot be used for these processes. The material delaminates during high pressure processing and cannot be used in microwave processing. Hence, any food packaging material developed in response to this subtopic should be compatible with one or more of the following food preservation technologies - retort processing, microwave processing, and/or high pressure processing. In addition, the material should have an oxygen transmission rate that shall not exceed 0.06 cc/m2/24 hrs/atm and a water vapor transmission rate that shall not exceed 0.01 gm/m2/24 hrs as stated in the MIL-PRF 33073F specification.

**Effect of Partial Gravity and Reduced Atmospheric Pressure**

It will require approximately 10,000 kg of packaged food for a 6-crew, 1000 day mission to Mars. For that reason, it has been proposed to use a food system which incorporates processing of raw ingredients into edible ingredients and uses these edible ingredients in recipes in the galley to produce meals. This type of food system will require food processing and food preparation equipment. The equipment should be miniaturized, multipurpose and efficiently use vehicle resources such as mass, volume, water, and power. Food preparation may include gourmet kitchen appliances such as food processors or bread makers in addition to the standard stove and oven. Proposed food processing equipment may include a mill to produce wheat and soy flour, a soy milk/tofu processor, and a concentrator.
The Moon's gravity is 1/6 of Earth's gravity. In addition, it is being proposed that the habitat will have a reduced atmospheric pressure of 8 psia which is equivalent to a 16,000 foot mountain top. These two factors will affect the heat and mass transfer during food processing and food preparation of the food. Heat transfer is required for proper microbial kill and to produce the desired texture and appearance of the food prior to consumption. At this pressure, the boiling temperature of water will be 181°F which has significant implications for preventing microbial contamination and to acceptable food quality.

Prior to any design of food processing or preparation equipment, the effects of partial gravity and partial atmospheric pressure as it relates to fluid management, heat and mass transfer and chemical reactions must be determined. Once the effects are determined, countermeasures must be developed. All of this needs to happen prior to any fabrication of actual food processing or food preparation equipment that can be used in the Lunar Habitat.

The response to this subtopic should (1) develop food packaging technologies that respond the above requirements, (2) develop a technology which will aid in determining the effects of reduced cabin pressure and reduced gravity and/or (3) develop a technology that will enable safe and timely food processing and food preparation in reduced cabin pressure and reduced gravity.

Sub Topics:
Small Personal Dosimetry Topic X14.01

Background:
As astronauts return to the Moon, and this time, work for extended periods, there will be a critical need for crew personnel radiation monitoring as they perform a myriad of extravehicular activities (EVAs). Increased ISS crew size and mission duration are also driving the need for during-mission evaluation of crew specific radiation exposures.

The components of the radiation field, both primary and secondary particles, can vary significantly in charge, energy, and intensity between galactic cosmic rays and solar particle events (SPEs). This dynamic and complex radiation environment requires the development of suitable detection systems that can meet the requirements of each component of the field.
Of particular concern is the need for active monitoring capabilities that provide relevant radiation personal dosimetry information for long term galactic cosmic ray exposure (including neutron secondary radiation) and for short term high dose rate SPEs. In addition to a complex Lunar radiation environment, which must be detected while electronics are protected by radiation hardening, there are restrictions on size, weight, power availability, and data transmission, as well as challenges presented by the Lunar surface environment, such as dust, temperature, and UV radiation. If mounted on or in the EVA suit, suit constraints must be addressed and crew safety ensured. For daily mission use, the requirements on size, data storage, and battery life/operation are particularly challenging.

Requirements/Needs:

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. New software needs to be fault tolerant and compatible with current operating systems, new hardware and software must be fully documented (schematics, etc.).

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.

For EVA and Mission Needs

- The dosimeter should be an omnidirectional detector system that can continuously measure and record the absorbed dose from charged particles with linear energy transfer 0.2 to 300 keV/micrometer, as a function of time, at two shielding depths: 0.5 g/cm² and 3 g/cm².
- The dosimeter should measure cumulative absorbed dose and dose equivalent once per minute and report data with latency less than five minutes.
- The dosimeter should produce and alarm whenever the absorbed dose rate exceeds a programmable threshold in the range 0.05 mGy/min to 10 mGy/min for 3 consecutive 1 minute readings.
- The dosimeter dimensions should be no larger than 8.5 cm x 4.5 cm x 2 cm.
- The dosimeter should weigh no more than 150 g.

Additional Mission Only Needs

- The dosimeter should be able to be battery (re-chargeable) powered and operate for 14 days without re-charge.
- The dosimeter shall be able to measure dose rates in the range 0.005 mGy/hour (0.0075 mSv/hour) to 1 cGy/hour (1.5 cSv/hour)
The dosimeter should be able to measure neutron exposure (personal dose equivalent) in the energy range 0.5 MeV to 10 MeV, with dose equivalent sensitivity of 0.2 mSv to 0.1 Sv in a 1 hour measurement, delivered at 0.02 mSv/hour to 1 mSv/hour.

Additional EVA Only Needs

- For suit-based versions, the dosimeter would interface to the EVA suit with TBR power available. No battery is allowed for suit versions.
- The dosimeter shall be able to measure dose rates in the range 0.005 mGy/hour (0.0075 mGy-Eq/hour for proton fields in the energy 10 MeV to 300 MeV) to 70 cGy/hour (105 cGy-Eq/hour for proton fields in the energy range 10 MeV to 300 MeV).
- Software and algorithms must interface with the suit data system, but do not necessarily need to be integrated into suit control algorithms.

Sub Topics:
- Charged Particle Spectroscopy Topic X14.02
  Charged particles (protons and heavy ions) contribute most of the dose-equivalent received by astronauts. Current instruments at NASA, and those under development, can provide the total (combined) dose and dose-equivalent for protons, heavy ions, gamma rays, and neutrons. At present NASA has active detectors for ISS that measure energy fluence of charged particles; however, more compact detection systems that measures energy fluence and spectrum for Exploration class missions are needed. Advanced technologies (up to technology readiness level (TRL) level 4) are requested.

Subtopic Requirements/Needs:

Of particular interest are compact real-time detection systems that can measure energy fluence and spectrum of protons and other ions ($Z = 2$ to 26) and be sensitive to charged particles with LET of 0.2 to 1000 keV/µm. For $Z$ less than 3, the spectrometer should detect energies in the range 20 MeV/n to 400 MeV/n. For $Z = 3$ to 26, the spectrometer should detect energies in the range 50 MeV/n to 1 GeV/n.

The monitor should be able to measure charged particles at both ambient conditions in space (0.005 mGy/hr) and during a large solar particle event (1000 mGy/hr).

The time resolution should be less than or equal to 1 minute.

The dosimeter shall be able to perform data reduction internally and provide processed data out to ISS, CEV, and future lunar outpost data systems. New software needs to be fault tolerant and updated to current operating systems, new hardware and software must be fully documented (schematics, etc.).
Neutron Spectroscopy Topic X14.03

Neutrons can contribute a significant fraction to the total dose-equivalent received by astronauts. Current instruments at NASA, and those under development, can provide the total (combined) dose and dose-equivalent for protons, heavy ions, gamma rays, and neutrons. At present, neutrons are included as integral measurements of NASA space flights; however compact active detection systems that can measure neutrons only are needed. Advanced technologies (up to technology readiness level (TRL) level 4) are requested.

Subtopic Requirements/Needs:

Systems are needed specifically to measure the neutron component of the dose and provide the neutron dose-equivalent in real time. Of interest also would be compact active monitoring devices that could measure neutron energy spectra.

The principal energies of interest are neutrons from 0.5 MeV to 150 MeV.

The monitor should be able to measure neutrons at ambient conditions such that proton/ion veto capability should be approaching 100% at solar minimum GCR rates.

During solar particle events, neutrons will be present at increased levels and should also be measured.

The device should be able to measure ambient dose equivalent of 0.02 mSv in a 1 hour measurement period, using ICRP 74 (1997) conversion factors.

The instrument shall be able to perform data reduction internally and provide processed data out to ISS, CEV, and or future lunar outpost data systems. New software needs to be fault tolerant and updated to current operating systems, new hardware and software must be fully documented (schematics, etc.).