



NASA SBIR 2009 Phase I Solicitation

Exploration Systems

Avionics and Software Topic X1

The Exploration Technology Development Program (ETDP) leads the Agency in the development of advanced avionics, software and information technology capabilities and research for the Exploration Systems Mission Directorate. The Avionics and Software elements perform mission-driven research and development to enable new system functionality, reduce risk, and enhance the capability for NASA's exploration missions. NASA's focus has clarified around Exploration, and the agency's expertise and capabilities are being called upon to support these missions. The Ares Launch Vehicle, the Orion Crew Exploration Vehicle (CEV), the Altair Lunar Lander, and future lunar surface systems will each require unique advances in avionic and software technologies such as 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.

Sub Topics:

X1.01 Automation for Vehicle Habitat Operations

Lead Center: ARC

Participating Center(s): JPL, JSC

Automation 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, leading to increased efficiency and reduced mission risk. To enable the application of intelligent automation and autonomy techniques, the technologies need to address two significant challenges: adaptability and software validation. Proposals are solicited in the areas of:

- **Automation Support Tools:** Support tools are needed to facilitate the authoring and validation of plans and execution scripts. Tools that are not tied specifically to one executive would provide NASA the most flexibility. Examples include: Graphical tool for monitoring and debugging plan execution and 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. Examples: Command and supervise complex tasks while projecting the outcome 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.
- **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).

X1.02 Reliable Software for Exploration Systems

Lead Center: ARC

Participating Center(s): JPL, LaRC

This subtopic seeks to develop 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 contractors) and not specialists. 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. 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). Specific software engineering tools and methods are sought in the following areas:

- 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 against high-fidelity hardware-in-the-loop test-beds 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);
- 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, JPL, MSFC

Constellation projects that are designed to leave low-earth orbit (Orion, Ares V Earth Departure Stage, Altair, Lunar Surface Systems, EVA suits, etc.) require avionic systems, components, and controllers that are capable of operating in the extreme temperature and radiation environments of deep space, the lunar surface, and eventually the Martian surface. Spacecraft vehicle electronics will be required to operate across a wide temperature range and must be capable of enduring frequent (and often rapid) thermal-cycling. Packaging for these electronics must be able to accommodate the mechanical stress and fatigue associated with the thermal cycling. Spacecraft vehicle electronics must be radiation hardened for the target environment. They must be capable of operating through a minimum total ionizing dose (TID) of 100 krad (Si) or more and providing single-event latchup immunity (SEL) of 100 MeV cm²/mg or more.

Considering the extreme environment performance parameters for thermal and radiation extremes, proposals are sought in the following specific areas:

- Low power, high efficiency, radiation-hardened processor technologies;
- Field Programmable Gate Array (FPGA) technologies;
- Innovative radiation hardened volatile and nonvolatile memory technologies;
- Tightly-integrated electronic sensor and actuator modules that include power, command and control, and processing;
- Radiation-hardened analog application specific integrated circuits (ASICs) for spacecraft power management;
- Radiation-hardened DC-to-DC converters and point-of-load power distribution circuits;
- 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 radiation hardness and low-temperature (-230°C) analog and mixed-signal circuit performance;
- Packaging capable of surviving numerous thermal cycles and tolerant of the extreme temperatures on the Moon and Mars, which includes the use of appropriate materials including substrates, die-attach, encapsulants, thermal compounds, etc.

X1.04 Integrated System Health Management for Ground Operations

Lead Center: ARC

Participating Center(s): JPL, JSC, KSC, MSFC, SSC

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 within a very brief timeframe and with high certainty. Health management is essential for dormant periods between human habitation, and for transition of assets (such as lunar habitats) to crewed operations. In addition, the long-duration health of software systems themselves are also critical. 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, communications, and software. Proposals that involve the use of existing testbeds or facilities at NASA are strongly encouraged. Specific technical areas of interest are methods and tools for:

- Early-stage design of health management functionality during the development of space systems, including failure detection methods, sensor types and locations that enable fault detection to line replaceable units.
- Sensor validation and robust state estimation in the presence of inherently unreliable sensors. Focus on data analysis and interpretation using legacy sensors.
- Model-based fault detection and isolation in rocket propulsion systems based on existing sensor suites during pre-launch and flight mission operations that enables fault detection within time ranges to allow mission abort.
- Automatic construction of models used in model-based diagnostic strategies, limiting model construction times to 60% of the time required using manual methods.
- Advanced built-in-tests for spacecraft avionics that provide 95% functional coverage and reduce or eliminate the need for extensive functional verification and to predict remaining life of avionics systems.
- Prognostic techniques able to anticipate system degradation before loss of critical functions and enable further improvements in mission success probability, operational effectiveness, and automated recovery of function.
- Approaches for effective utilization of 100% of the health information on critical functions from spacecraft and launch vehicles with integration to ground based systems using commercial health information from programmable logic controller and RAS system.
- Techniques that address the particular constraints of maintaining long-duration systems health of structures, mechanical parts, electronics, and software systems on lunar surfaces are of special interest.

Environmental Control and Life Support (ECLS) encompasses the process technologies and equipment necessary to provide and maintain a livable environment within the pressurized cabin of crewed spacecraft and to support associated human systems such as Extra Vehicular Activity (EVA). Functional areas of interest to this Solicitation include thermal control and ventilation, atmosphere resource management and particulate control, water recovery systems, solid waste management, habitation systems, environmental monitoring and fire protection systems. Technologies must be directed at Lunar transit and surface missions, including such vehicles as Lunar landers, surface habitats and pressurized rovers.

Requirements include operation in Lunar gravity and/or microgravity and compatibility with cabin atmospheres of up to 34% O₂ by volume and pressures ranging from 1 atmosphere to as low as 7.6 psia, or for EVA, as low as 3.2 psia and 100% O₂. Systems external to the spacecraft will be at vacuum. Special emphasis is placed on developing technologies that will fill existing gaps, reduce requirements for consumables and other resources including mass, power, volume and crew time, and which will increase safety and reliability with respect to the state-of-the-art. Non-venting processes may be of interest for technologies that have dual application to Lunar and Mars missions. Results of a Phase 1 contract should show feasibility of the technology and approach. A resulting Phase 2 contract should lead to development, evaluation and delivery of prototype hardware. Specific technologies of interest to this Solicitation are addressed in each subtopic.

Additional information may be found at the following websites: <http://els.jsc.nasa.gov> [1] and <http://aemc.jpl.nasa.gov> [2].

Sub Topics:

X2.01 Spacecraft Cabin Atmosphere Revitalization and Particulate Management

Lead Center: MSFC

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

Cabin Atmosphere Revitalization

Atmosphere revitalization developmental activities target process technologies and equipment to condition and supply gaseous oxygen at pressures at or above 3,600 psia and achieve mass closure by recycling resources. As well, portable means for atmosphere revitalization that have synergy with extravehicular activity (EVA) equipment pertaining to trace contaminant control, carbon dioxide removal, humidity control are target technology areas. Durable, dust-tolerant fluid connections support the EVA and life support system infrastructure. Details on areas of emphasis are the following:

High Pressure Oxygen Gas Supply and Conditioning: Process technologies leading to an on-demand, in-flight renewable 3,600-psia oxygen supply are of interest. Process technologies and techniques must be capable of conditioning oxygen for temperature, pressure, and water content using oxygen from several sources. Source oxygen may originate directly from the cabin atmosphere or from gaseous storage, cryogenic storage, and/or on-demand production from water electrolysis or in-situ resource utilization processes.

There is specific interest in process technologies to remove water from saturated oxygen to provide a product having a dewpoint below -62°C.

Atmospheric Resource Recycling Techniques: Process technologies suitable for conditioning and converting gaseous products produced by the Sabatier CO₂ reduction reaction to useful products are of interest. Of particular interest are process technologies to recover moisture from a saturated stream of methane that contains residual CO₂ and hydrogen reactants, to convert methane to products such as low molecular weight alcohols or other compounds suitable for use in power co-generation via fuel cells or other means, and to produce a solid carbon

product via a regenerative process based on the Bosch reaction or a variant of the Bosch reaction.

Particulate Matter Management

Particulate matter suspended in the habitable cabin atmosphere is a challenge for all phases of crewed lunar surface exploration missions. Removing and disposing of particulate matter originating from sources internal to the habitable cabin and from lunar surface dust intrusion into the cabin environment is of interest. Staged techniques employing combinations of course media filtration (>50 micron size), inertial separation (2.5 micron size), and fine media filtration (

Atmosphere Revitalization for EVA

Synergy exists between cabin atmosphere revitalization and EVA suits. Common functions include trace contaminant control, CO₂ partial pressure control, and humidity control.

Trace Contaminant Control for EVA Suits: EVA suits designed for long durations with minimal maintenance will require new methods of trace contaminant control to maintain spacesuit environments below Spacecraft Maximum Allowable Concentrations for toxic or irritating chemicals. Historically this has used activated charcoal. In the case of ISS EVA, the charcoal is regenerable with heat. A need exists for a reduced power solution, such as vacuum regeneration of a sorbent, or another, innovative, low consumable solution. Consideration of on-back, real-time EVA regeneration as well as post EVA regeneration is acceptable.

Mars EVA CO₂ and Humidity Control: ISS EVA suits utilize heat regenerable CO₂ removal systems. These systems are heavy and require significant power for regeneration. Lunar EVA suits are planned to use a lightweight, vacuum regenerable amine system to remove CO₂ and humidity from the suit. It is envisioned this concept could be extensible to Mars suits with the addition of sweep gas to prevent intrusion of the Martian atmosphere. An innovative CO₂ and humidity removal system that could remove CO₂ and humidity while eliminating gas losses to the Martian atmosphere, remain lightweight, and utilize minimal power is desired. Consideration of on-back, real-time EVA regeneration as well as post EVA regeneration is acceptable.

Dust Tolerant Quick Disconnects for High and Low Pressure Fluids

Connections will need to be made between the EVA suits and lunar and Martian vehicles in environments where dust will be present. A lightweight QD that excludes dust during connections and disconnections is required.

X2.02 Spacecraft Habitation Systems, Water Recovery and Waste Management

Lead Center: ARC

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

Habitation, water recovery and waste management systems supporting critical needs for lunar mission architectures are requested. Improved technologies are needed for clothing/laundry, recovery of water, recovery of other resources, stabilization of wastes and safe long term storage of waste residuals. Proposals should explicitly

describe the weight, power, and volume advantages of the proposed technology and be compatible with the lunar and microgravity environments described in the overall X2 topic description.

Clothing/Laundry Systems

Clothing and towels are a major consumable and trash source. Advanced durable fabrics to enable multiple crew wear cycles before cleaning/disposal are required. The laundry system should remove/stabilize combined perspiration salt/organic/dander and lunar dust contaminants, preserve flame resistance properties and use cleaning agents compatible with biological water recovery technologies. Proposals using water for cleaning should use significantly less than 10 kg of water per kg of clothing cleaned.

Waste Management

Wastes (trash, food scraps, feces, water brines, clothing) must be managed to protect crew health, safety and quality of life, to avoid harm of planetary surfaces, and to recover useful resources. Areas of emphasis include: stabilization (particularly water removal and recovery) and solid waste storage and odor control (e.g., catalytic and adsorptive systems). Preferred stabilization methods will dry solids to less than 60% water activity and sterilize and/or prevent microbial growth. Waste compactors must reduce trash to less than 10% of hand compacted volume after any spring-back. Odor control technologies should reduce gaseous contaminants in air to below NASA's Space Maximum Allowable Concentration levels and below the human odor threshold. Lunar-Martian storage containers are desired that are lightweight, low in resupply stowage volume, easily deployable and capable of containing space mission wastes and residuals on Lunar or Martian surfaces without rupture for 400 years.

Water Recovery

Efficient technologies are desired for treatment to potability of wastewater including urine, brines, humidity condensate, hygiene water, and in situ lunar water. Areas of emphasis include: primary treatment reducing 1000 mg/L TOC to less than 100mg/L, post-treatment reducing 100 mg/L TOC to

X2.03 Spacecraft 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 life support system is functioning properly. The sensors may also provide data to automated control systems. All proposed technologies should have a 2 year shelf-life, including any calibration materials (liquid or gas). The technologies will need to function in low pressure environments (~8 psi) and may see unpressurized storage. Significant improvements are sought in miniaturization, accuracy, precision, and operational reliability, as well as long life, in-line operation, self-calibration, reduction of expendables, low energy consumption, and minimal operator time/maintenance for monitoring and controlling the life-support processes.

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- Microbial monitoring in water
 - 2 year shelf-life; this requirement precludes the usual antibody techniques which have lifetime limitations. Sufficient precision to resolve the following: 50 CFU/ml bacteria; coliform and fungi are required to be zero per 100 ml; zero counts of parasitic protozoa

 - Microbial control of surfaces, typically done by chemically treated wipes or ultraviolet
 - Microbial Controls should be recyclable w/reduced consumables

 - Improved Oxygen Monitor for breathing air
 - +/- 0.05%, must operate in variable pressure 8-14.7 psia and survive exposure to vacuum

 - Broad spectrum Trace Contaminant Monitor, for air, with 2 year shelf life

X2.04 Spacecraft Fire Protection

Lead Center: GRC

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

NASA's fire protection strategy consists of strict control of ignition sources and flammable materials, early detection and annunciation of fires, and effective fire suppression and response procedures. Providing effective and efficient means for conducting and monitoring post-fire cleanup and restoration of the cabin atmosphere to a habitable environment are also major concerns. While proposals for novel technologies in all of these areas are applicable, they are particularly sought in the areas of nonflammable crew clothing and advanced carbon monoxide sensors for fire detection and monitoring the progress of post-fire cleanup.

The requirements for crew clothing are balanced between appearance, comfort, wear, flammability and toxicity. Ideally, crew clothing should have durable flame resistance in a 34% O₂ (by volume) enriched environment through all end-use conditions including cleaning methods and frequency.

Fire detection strategies are being developed that combine advanced particulate detection technology with sensors that detect gaseous combustion products. Monitoring of carbon monoxide is being targeted both for fire detection and to monitor the progress of post-fire cleanup. A robust optical method is desired that has the dynamic range required to detect and monitor CO from approximately 1 to 500 ppm with resolution to 1 ppm CO. In addition to being sufficiently rugged, this sensor must have minimal mass, power, and volume requirements and exhibit high degrees of reliability, minimal maintenance, and self-calibration under varying humidity and ambient pressures.

X2.05 Spacecraft Thermal Control Systems

Lead Center: JSC

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

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 system designs also must accommodate the harsh thermal environments associated with these missions. Modular, reconfigurable designs could limit the number of required spares.

The lunar environment presents several challenges to the design and operation of active thermal control systems. During the approximately 2 hour lunar orbit, the environment can range from extremely cold to near room temperature. Polar lunar bases will see unrelenting cold thermal environments, as will the radiators for Martian transit spacecraft. In both cases the effective sink temperature will approach absolute zero.

Innovative thermal management components and systems are needed to accomplish the rejection of waste heat during these future missions. Advances are sought in the general areas of radiators, thermal control loops, thermal system equipment, and EVA thermal control.

Systems with enhanced thermal mass may be required to deal with the lunar orbital environment. Variable emissivity coatings (near unity emissivity with the ability to reduce emissivity by at least a factor of ten), clever working fluid selection (a freezing point approaching 150K), or robust design could be used to prevent radiator damage from freezing in cold environments at times of low heat load.

Part of the thermal control system in a habitable volume is likely to be a condensing heat exchanger, which should be designed to preclude microbial growth. Small, highly reliable, heat pumps could be used to provide 278 K cold fluid to the heat exchanger, allowing the loop temperatures to approach 300 K, thus reducing the size of the radiators.

Future space systems may generate waste heat in excess of 10 kW which could either be rejected or redirected to areas which require it. Novel thermal bus systems which can collect, transport (over a distance of ~30 meters), and provide heat for components are sought. The system should be highly flexible and adaptable to changes in equipment locations. Possible systems include single and two-phase pumped fluid loops, capillary-based loops, and heat pumps. Innovative design of the loops and components is needed.

Historically spacesuits have used water sublimators to provide heat rejection. Development of a low-venting or non-venting regenerable individual life support subsystem(s) concept for crewmember cooling and heat rejection is desired. Systems that integrate spacesuit thermal control systems with other life support tasks, such as removal of expired water vapor and CO₂ are highly desirable. Interests include low cost lightweight spacesuit compatible freezable radiators for thermal control and variable conductance flexible EVA spacesuit garments that can function as a radiator or as an insulator as required. Sensible heat loads average 300 W and peak at 800 W. Spacesuit cooling garments have water flow rates of approximately 100 kg/hr.

Lunar In-Situ Resource Utilization Topic X3

The purpose of In Situ Resource Utilization (ISRU) is to harness and utilize resources at the site of exploration to create products and services which can enable and significantly reduce the mass, cost, and risk of near-term and long-term space exploration. In particular, the ability to make propellants, life support consumables, fuel cell reagents, and radiation shielding can significantly reduce the cost, mass, and risk of sustained human activities beyond Earth. To perform these tasks on the lunar surface, detailed knowledge of the terrain, local minerals and potential resources, and the behavior and characteristics of lunar regolith is extremely important. Lastly, since ISRU systems and operations have never been demonstrated before in missions, it is important that ISRU concepts and technologies be evaluated under relevant conditions (1/6 g and vacuum) as well as anchored through modeling to lunar soil and environmental conditions. With this in mind, the ISRU Project within the Exploration Technology Development Program (ETDP) has initiated development and testing of hardware and systems in two main focus areas: (1) Oxygen Extraction from Regolith, including regolith feed/removal; and (2) ISRU Development & Precursor Activities to evaluate alternative resource processing and product concepts.

The purpose of the following subtopics is to develop and demonstrate hardware and software technologies that can be added to on-going analysis and ISRU capability development and demonstration activities in ETDP to meet Outpost architecture and surface manipulation objectives for near and long term human exploration of the Moon.

Sub Topics:

X3.01 Oxygen Production from Lunar Regolith

Lead Center: JSC

Participating Center(s): GRC, KSC, MSFC

Oxygen (O₂) production from lunar regolith processing consists of receiving regolith from the excavation subsystem into a hopper, transferring that regolith into a chemical or an electrochemical reactor, intermediate reactions to produce O₂ and regenerate reactants if required, purification of the O₂ produced, and removal of processed regolith from the reactor to an outlet hopper. Three O₂ production from lunar regolith reaction concepts are currently under development: Hydrogen reduction, Carbothermal reduction, and Molten Oxide Electrolysis at initial lunar Outpost production scale of 1 to 2 MT per year (70% per year operations). This subtopic is seeking hardware, subsystem, and system components and technologies for insertion and integration into on-going oxygen extraction from regolith development and demonstration efforts. Items of particular interest are:

- Move feedstock material from hopper on ground to 2 m height for reactor inlet hopper; 40 kg/hr; material size
- Inlet/outlet regolith hopper design and valve/seal concepts with no gas leakage, 1000's of operating cycles with abrasive lunar material, and minimum heat loss.

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- Removal of 5 to 10 kg of molten material from molten electrolysis cell with metal slag processing and purification into individual metals.
 - Water condensers that use the space environment for water condensation/separation with minimal energy usage.
 - Gas Separators that provide low pressure drop separation of the system and product gas streams from impurities (e.g., HCl, HF, H₂S, SO₂); the process should be regenerable and the output contaminant concentration should be less than 50ppb.
 - Removal of dissolved ions in water by methods other than de-ionization resins to meet water electrolysis purity requirements (minimum resistivity of 1M-Ohms-cm). Ions of interest are dissolved metal ions (Fe, Cr, Co, Ni, Zn) at concentration of 0.01% and dissolved anions (Cl, F, S) at concentrations of 0.01%-2%. The process should be regenerable, minimize consumables, and minimize water loss.
 - Contaminant resistant, high temperature water electrolysis concepts.
 - Advanced reactor concepts for carbothermal reduction or molten oxide electrolysis.

Phase 1 proposals should demonstrate technical feasibility of the technology or hardware concept through laboratory validation of critical aspects of the innovation proposed, as well as the design and path toward delivering hardware/subsystems in Phase 2 for incorporation into existing development activities. Interface requirements for on-going development efforts will be provided after selection. Proposers are encouraged to use the Lunar Sourcebook at a minimum for understanding lunar regolith material parameters in the design and testing of hardware proposed. It is also recommended that JSC-1a simulants be used during testing unless a more appropriate simulant can be obtained or manufactured.

X3.02 Lunar ISRU Development and Precursor Activities

Lead Center: JSC

Participating Center(s): GRC, KSC, MSFC

The incorporation of ISRU concepts is an on-going effort which requires an evaluation of the benefits and risks through computer modeling and testing under laboratory, analog field, and simulated lunar environmental conditions (1/6 g and vacuum). While excavation and oxygen extraction from regolith are included in lunar architecture plans, it is recognized that evaluating the feasibility and benefits of other technologies and concepts not ready for insertion into these efforts should be pursued. This subtopic is aimed at providing development support capabilities and hardware to advanced potentially beneficial ISRU concepts not yet ready for incorporation into current ISRU system laboratory and field test activities. Proposals aimed at the following are of particular interest:

- Mineral beneficiation concepts to separate iron oxide-bearing material from bulk regolith; up to 20 kg/hr based on hydrogen reduction. Hardware/concepts need to be designed for compatibility with both 1/6 g flight experiments and ground vacuum experiments.
- Lunar regolith storage and granular flow computer models, devices, and instruments to evaluate regolith flow and manipulation under 1/6 g flight and ground vacuum experimental conditions.

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- Granular materials mixing and separation for reactor feedstock conditioning: remove material > 0.5 cm diameter before dumping into storage bin during excavation operation for oxygen extraction from regolith.
 - Processing concepts for production of carbon monoxide, carbon dioxide, and/or water from plastic trash and dried crew solid waste using solar thermal or electrical/heat energy. In-situ produced oxygen or other reagents/consumables must be identified and quantified; recycling schemes for reagents to minimize consumables should be evaluated.
 - Thermal energy storage and utilization using bulk or processed regolith.

Phase 1 proposals should demonstrate technical feasibility of the technology and/or subsystem through laboratory validation of critical aspects of the innovation proposed, as well as the design and path toward delivering hardware/subsystems in Phase 2.

Structures, Materials and Mechanisms Topic X4

The SBIR topic area of Structures, Materials and Mechanisms centers on developing lightweight structures, advanced materials technologies, and low-temperature mechanisms for enabling Exploration Vehicles and Lunar Surface Systems.

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 major technology drivers of the lightweight structure technology development are to significantly enhance structural systems 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. The targeted applications of the lightweight structures and materials technologies are Orion Crew Module, the Ares launch vehicles, Lunar Lander, and Lunar Surface Systems. For this Solicitation, the desired area of focus is Lunar Surface Systems, particularly for Lunar habitats.

Low-temperature mechanism technology is being developed for reliable and efficient operation of mechanisms in lunar temperatures including operations in lunar shadows at -230°C and sustained surface operations thru varying lunar temperatures of -230°C to +120°C for lunar surface rovers, robotics, and mechanized operations. The technology drivers of the low temperature mechanism technology development are to significantly enhance operation of mechanized parts by 1) lowering the operating temperature for life of the component and 2) improving mechanism performance (torque output, actuation performance, lubrication state) at the lunar environment conditions of cold and vacuum over the required life of the mechanism. 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 to enhance and fill gaps in technology development programs in the Exploration Technology Exploration Program's Structures, Materials, and Mechanisms (SMM) Project. Areas of development included in the SMM project include: low temperature drive system, motor, and gearbox system, personal kit radiation shielding materials, low density parachute material systems, expandable structural systems, and friction stir welded spindomes. This topic area is responsible for mid-level technology research, development, and testing through experimental and/or analytical validation.

Sub Topics:

X4.01 Advanced Radiation Shielding Materials and Structures

Lead Center: LaRC

Participating Center(s): ARC, MSFC

Advances in radiation shielding materials and structures technologies are needed to protect humans from the hazards of space radiation during NASA missions. The primary area of interest for this 2009 solicitation is radiation shielding materials systems for long-duration lunar surface galactic cosmic radiation (GCR) protection. The innovative materials systems should have radiation shielding effectiveness approaching that of polyethylene, for an equivalent areal density (grams per square centimeter). This can be determined either by radiation transport calculations or by radiation exposure measurements. 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 include the following:

- Innovative lightweight radiation shielding materials and structures to shield humans in crew exploration vehicles, landers, habitats, and rovers;
- Physical, mechanical, structural, and other relevant characterization data to validate and qualify multifunctional radiation shielding materials and structures;
- Innovative processing methods to produce quality-controlled advanced radiation shielding materials of all forms.

X4.02 Expandable Structures

Lead Center: LaRC

Participating Center(s): JSC, MSFC

This subtopic solicits innovative structural concepts that support the development of lightweight structures technologies that could be applicable to lunar surface system habitats. The targeted innovative lightweight structures are for primary pressurized volumes and secondary structures that must be deployed during or after expansion of the primary volume such as the floor and work surfaces. Innovations in technology are needed to minimize launch mass, size and costs, while increasing operational volume and maintaining the required structural performance for loads and environments.

Of particular interest are inflatable structures which are considered to be viable solutions for increasing the volume in habitats, airlocks, and potentially other crewed vessels. However, areas of risk need to be mitigated to build confidence in the use of these structures, in particular: consistent and reproducible mechanical behavior, durability in the presence of micrometeoroid impact, crew-induced and ground handling damage, and repair techniques for long term survivability. Other interests include preintegration solutions, launching pressurized volume in an expandable, and addressing lunar surface deployment concerns.

Also of interest are innovative deployable secondary structures that have minimal mass and high packaging efficiency. These secondary multi-functional structures provide highly robust, stiff and mass efficient surfaces that enable the useful outfitting and pre-integration of subsystems within the primary structural volume.

Development of concepts can include structural components, 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.

X4.03 Low Temperature Mechanisms

Lead Center: GSFC

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

This subtopic focuses on the development of high power and high specific torque density actuators (e.g., motors and gear boxes) that will operate on the lunar surface exposed to the day/night cycle. They will need to operate over a temperature range of approximately 40 K to 403 K. A five year lifetime is desired. The component technologies developed in this effort will be utilized for rovers, cranes, 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 with partial gravity, abrasive dust, and full solar and cosmic 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 innovative long life, light weight, wide temperature range motors (in the range of one to five kWatts), gear boxes, lubricants, and closely related components that are suitable for the environments discussed above.

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.

Advanced Composite Technology Topic X5

The SBIR Topic area of Advanced Composites Technologies (ACT) focuses on technologies to mature the use of composite structures and materials for launch vehicles and/or the lunar lander.

Organic matrix composite materials have the potential for a significant mass reduction compared to metallic materials by optimizing the structural architecture of applications including the Ares V Core Stage intertank, the Ares V Core-Stage-to-Earth-Departure-Stage interstage, the Ares V Payload Shroud, and the Altair lunar lander support struts. The major technology drivers for these applications of advanced composites technologies include large scale composites manufacturing, composite damage tolerance and detection, and primary structure durability in a lunar environment. Successful composites technologies will demonstrate concepts with reduced weight and cost with no loss in performance when compared to technologies for metallic concepts.

This Topic is to enhance and fill gaps in technology development activities in the Exploration Technology Development Program Advanced Composites Technologies Project. Areas of development in the ACT project include: materials; manufacturing; nondestructive evaluation/structural health monitoring; and structural concepts. This Topic is responsible for mid-level technology research, development, and testing through experimental and/or analytical validation.

Sub Topics:

X5.01 Composite Structures - Practical Monitoring and NDE for Composite Structures

Lead Center: JSC

Participating Center(s): ARC, LaRC

Orion backshell, Aries Payload fairing, and Lander struts and composite pressure vessel option, COPV and composite tankage and Habitat modules are only a few of the many weight-reducing applications for composites that need efficient and modular systems to accomplish monitoring and NDE for them to be practical.

This subtopic seeks the development of technologies to detect, locate and characterize indications of a failure far enough ahead that routine actions can be taken to rectify the situation. Perform monitoring such that models can be built of event behaviors and structural response condition can be determined. Monitoring and/or NDE changes can be made with minimum cost/operations.

Performance Goals/Metrics:

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- Provide impending system failure indications with sufficient time to take action to reduce the risk of catastrophic failure;
 - Increase the number of sensor locations per pound of monitoring weight by 50%;
 - Decrease the system monitoring electronics weight by 50%;
 - Decrease total wiring required for monitoring by 50%;
 - Decrease the time to plan and install monitoring by 50%;
 - Decrease the overall life-cycle cost per sensor by 50%;
 - Decrease total data rate required from the sensor data acquisition location by 50%;
 - Decrease time to perform NDE inspections by 50%;
 - Decrease the expected cost of instrumentation changes/upgrades by 50%.

Technologies sought include: smart sensors, wireless passive sensors, flexible sensors for highly curved surfaces, direct-write film sensors, real-time compact NDE imagers for damage inspection, highly accurate defect and tool position determination.

Applications include: Advanced composite structures such as cryo-tanks, large area composites such as launch vehicle fairings, habitable volumes, hard to access/inspect composite members, as well as metallic pressurized structures of all kinds. Interior as well as exterior measurements of the pressure vessel are needed.

This subtopic is also a subtopic for the "Low-Cost and Reliable Access to Space (LCRATS)" topic. Proposals to this subtopic may gain additional consideration to the extent that they effectively address the LCRATS topic (See topic O5 under the Space Operations Mission Directorate).

X5.02 Composite Structures - Cryotanks

Lead Center: LaRC

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

The use of composite materials for smaller cryotanks offers the potential of significant weight savings. Composite cryotank technology would be applicable to EDS propellant tanks, Altair propellant tanks, lunar cryogenic storage tanks and Ares V tanks. A material system (resin+fiber) which displays high resistance to microcracking at cryogenic temperatures is necessary for linerless cryotanks, which provide the most weight-saving potential.

This subtopic will focus on development of toughened, high strength composite materials, because the literature

indicates that they have the highest microcrack resistance at cryogenic temperatures. Greatest interest is in novel approaches to increase resin strength and/or reduce resin CTE, thereby increasing resistance to microcracking at cryogenic temperature.

Performance would be evaluated by a characterization program, which would ideally generate temperature-dependent material properties including strength, modulus, and CTE as functions of temperature. Additionally, notch sensitivity, plain strain fracture toughness, and microcracking fracture toughness as functions of temperature are desirable. Tests will need to be performed at temperatures between -273°C and 180°C to fully characterize any nonlinearity in material properties with changes in temperature.

Initial property characterization would be done at the coupon level in Phase 1. Generation of design allowables, characterization of long-term material durability, and fabrication of larger panels would be part of follow-on efforts.

X5.03 Composite Structures - Manufacturing

Lead Center: MSFC

Participating Center(s): GRC, LaRC

The SBIR subtopic area of Composites Materials and Manufacturing centers on developing lightweight structures using advanced materials technologies, and new manufacturing processes. The objective of the subtopic is to advance technology readiness levels of composite materials and manufacturing for Ares launch vehicle applications resulting in structures having consistent, predictable response.

Areas of interest include: polymer matrix composites (PMCs), large-scale manufacturing; innovative automated processes (e.g., fiber placement); advanced non-autoclave curing; bonding of composite joints; and damage-tolerant/repairable structures.

Performance metrics include: achieving adequate structural and weight performance; analysis supported by test approach; manufacturing and life-cycle affordability; ability to demonstrate capabilities at the laboratory scale and confidence for scale-up; validation of confidence in design, materials performance, and manufacturing processes; quantitative risk reduction capability; minimum sensitivity and maximum robustness for operability.

Lightweight structures and advanced materials have been identified as a critical need since the reduction of structural mass translates directly to vehicle additional performance, reduced cost, and increased up and down mass capability.

Research should be conducted to demonstrate technical feasibility during Phase 1 and show a path toward a Phase 2 prototype demonstration. Demonstrate manufacturing technology that can be scaled up for very large structures.

This subtopic is also a subtopic for the "Low-Cost and Reliable Access to Space (LCRATS)" topic. Proposals to this subtopic may gain additional consideration to the extent that they effectively address the LCRATS topic (See topic O5 under the Space Operations Mission Directorate).

Lunar Operations Topic X6

This call for technology development is in direct support of the Exploration Systems Mission Directorate's (ESMD) Exploration Technology Development Program (ETDP). The purpose of this research is to develop component and subsystem level technologies to support the Constellation Program's (CxP) human lunar return missions. The initial missions will be heavily engaged in construction methods, regolith excavation, establishing self-sustaining power generation, and producing life support consumables in-situ in order to establish continuous operational capability via earth based and lunar based human and robotic assets.

The objective is to produce new technology that will reduce lunar operations workloads associated with crew extra-vehicular activities (EVA) and intra-vehicular activities (IVA), and reduce the total mass-volume-power of equipment and materials required to support both short and long duration Lunar stays as well as maximizing crew and outpost safety during landing, launch and lunar operations. The proposals must focus on component and subsystem level technologies in order to maximize the return from current SBIR funding levels. Doing so increases the likelihood of successfully producing a technology that can be readily infused into the Constellation Program.

Lunar operations are a stepping-stone toward achieving long-term space exploration goals. This research focuses on technology development for the critical functions that will secure an extended human presence on the lunar surface and ultimately enable surface exploration for the advancement of scientific research. Surface exploration begins with short duration missions to establish a foundation which leads to extensible functional capabilities. Successive buildup missions establish a continuous operational platform from which to conduct scientific research while on the lunar surface. Reducing risk and ensuring mission success depends on the coordinated interaction of many functional surface systems including life support, power, communications infrastructure, and transportation. This topic addresses technology needs associated with lunar surface systems infrastructure, interaction of humans and machines, mobility systems, payload and resource handling, regolith excavation and mitigation of environmental contaminations. For more information, see the following websites:

<http://www.nasa.gov/exploration/home/LER.html> [3]

http://www.nasa.gov/multimedia/podcasting/Haughton_Mars_project.html [4]

<http://robonaut.jsc.nasa.gov/index.asp> [5]

http://www.nasa.gov/centers/ames/multimedia/images/2008/K_10_38.html [6]

<http://www.lpi.usra.edu/meetings/leagilewg2008/pdf/4001.pdf> [7]

http://www.nasa.gov/home/hqnews/2008/jun/HQ_08149_Moses_Lake.html [8]

Sub Topics:

X6.01 Robotic Systems for Human Exploration

Lead Center: JSC

Participating Center(s): ARC, KSC

The objective of this subtopic is to provide advanced capabilities for lunar surface system assets that deliver, handle, transfer, construct, and prepare site infrastructure for lunar operations. This includes robust dexterous manipulation capabilities; large and small cargo transporters for delivery and deployment of construction materials, power generation systems, and habitable enclosures.

This subtopic seeks to develop technologies that reduce the risk of Extra-Vehicular Activity (EVA), facilitates remote robotic operations by both flight crew and ground control, and enables autonomous robotic operations. Automation and robotics capabilities include the ability to use robots for site setup and 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: systematic site survey (engineering and/or science), inspection, emergency response, site preparation (clearing, leveling, excavation, etc.), instrument deployment, payload offloading, dexterous manipulation, and regolith handling for In-situ Resource Utilization.

Maximizing the useful life of surface assets is essential to a successful lunar program. Material components must be robust and tolerate extreme temperature swings and endure harsh environmental effects due to solar events, micrometeorite bombardment, and abrasive lunar dust.

Proposals are sought for the following technology needs:

- Low-mass, high-strength, long-life, non-pneumatic wheel assembly capable of spreading the supported load over a large 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. Low psi contact patch. Minimal deformation of wheel under varying terrain makeup. Minimal rolling resistance. High performance in 4-sigma soil. 10,000 km expected life. 40K to 400K operating temperature range. Supports 100x its own mass.
- Active and passive damping materials for suspension components that provide extended range of motion (45 degrees in pitch), extreme temperature tolerance (40K to 400K), reactive rates of 1-3 msec, and withstand torsional forces of 3000 N-m.
- Active suspension components that reclaim and store energy absorbed through the suspension system.
- Fluid and electrical connectors that can be repeatedly mated and de-mated (5000+ cycles) without failure in a contaminating environment consisting of regolith (abrasive dust) grains ranging in size from 100um down to 10um. Capable of carrying up to 10kw of power transmission or withstanding up to 3000psi

pressures.

- Low power sensors for inspection and surface navigation and obstacle avoidance that are not adversely affected by the accumulation of lunar dust on the sensor. Developing robust sensor technologies will enable mobility assets to execute automated path planning, automated driving, and obstacle avoidance.
- Robot user interfaces enabling more efficient interaction with robots, facilitating situational awareness and telepresence, and reducing the amount of interaction effort required to operate robots. Appropriate user interfaces will support humans and robots operating in a shared space, close but separated, line-of-sight remote, and ground control remote. Particular interest is given to systems that robustly support robot operations with up to 10 seconds of communications delay.
- Modular implements for digging, collecting, transporting and dumping lunar soil. The excavation rates are in the order of 50 kg/hr for regolith mining for O₂ production and 300 kg/hr for Site preparation tasks. Total amounts of regolith required are 100 tons for O₂ production and over 2,000 tons for a full outpost deployment. Excavation capabilities involve excavation and collection of both unconsolidated and consolidated surface regolith. Regolith Excavation includes tasks such as clearing and leveling landing areas and pathways, buildup of berms (2.5 m high) and burying of reactors or habitats for radiation protection (2 m deep), and regolith transportation for oxygen production (500 m distance) . Robotic excavation hardware must be able to operate over broad temperature ranges (40 K to 400 K) and in the presence of abrasive lunar regolith and partial-gravity environments. Expectations for maintenance by crew must be minimal and affordable (annual cycle). Therefore, general attributes desired for all proposed hardware include the following: lightweight, abrasion resistant, vacuum and large temperature variation compatible materials, low power, robust/low maintenance, and minimize dust generation/saltation during operation.
- Large surface area, i.e., 100 m X 100 m, soil stabilization/solidification techniques to prevent dust and regolith disturbances/ejecta from vehicular or suited EVA traffic (7 - 70 kilopascal bearing pressure).

X6.02 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.

Lunar lander and surface systems will likely employ common hatch and airlock systems for docking, mating, and integration of spacecraft, habitat, EVA, and mobility elements. The large number of EVAs will require hatches that are safe if non-pressure assisted, and do not have to be serviced or replaced regularly. Lunar lander and surface systems will require materials and mechanisms that do not collect dust and do not abrade when in contact with lunar regolith. Technologies are also needed to remove lunar regolith, including dust, from materials and mechanisms. Lunar Surface systems will require EVA compatible connectors for fluid, power, and other umbilicals for transfer of consumables, power, data, etc. between architecture elements that will maintain functionality in the

presence of lunar regolith, including dust. Lunar surface systems (power, mobility, communications, etc.) will require gimbals, drives, actuators, motors, and other mechanisms with required operational life when exposed to lunar regolith, including dust. Radiators and other thermal control surfaces for lander and surface systems must maintain performance and/or mitigate the effects of contamination from lunar regolith, including dust.

Also included in the technical scope is the development of lunar regolith simulants. Simulants that are properly designed, analyzed, and produced are critical to understanding the effects of dust on humans and mission critical subsystems and how to handle and utilize regolith on the lunar surface. Proposals are requested in technology areas that improve simulant fidelities, reduce simulant manufacturing costs and schedules, and improve on simulant development processes and characterization techniques and methods.

Lunar Regolith Simulants

- Should cost
- Should cost
- Be producible in quantities up to 30 tons/year;

- Have reproducible production processes;

- Have particle size distributions representative of lunar regolith from 0.5 to 1000µm in size.

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 out gassing 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.

Mechanical Systems

- Should achieve
- Should achieve dynamic seal wear life of 20 million cycles;

- Should achieve 300% improvement in bearing life (frictional torque vs. time) relative to lubricated SOA bearings contaminated with lunar fines.

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.

Materials and Coatings

- Should demonstrate reduced initial contamination (>90%) compared to conventional materials;

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- Should demonstrate improved efficiency of cleaning processes (>99% removal of initial contamination) without damage.

Another area of interest encompassed by this subtopic is alternative technologies for lunar dust removal that may be used in a variety of lunar surface applications. Both manual and automated cleaning systems are sought and may be derived from any or a combination of particle removal forces appropriate for use on the lunar surface.

Cleaning Systems

- Should demonstrate >99% removal of dust contamination. Tolerable contamination levels will be application specific.

Research should be conducted to demonstrate technical feasibility during Phase 1 and show a path to hardware or production demonstration in Phase 2. When possible, a demonstration unit or material quantity should be delivered for functional and environmental testing and characterization and evaluation at the end of Phase 2.

Energy Generation and Storage Topic X7

This topic includes technology development for batteries, fuel cells, regenerative fuel cells, and fission and isotopic power systems for the Altair lunar lander and surface operations on the Moon and Mars. Technologies developed must be infused into these Constellation program elements: primary fuel cells for the Altair lunar lander descent stage, secondary batteries for the Altair ascent stage, secondary batteries for extravehicular activities (EVA) suits, and regenerative fuel cells, fission and isotopic power systems on the Moon and Mars to power habitats, in situ resource production, and mobility systems. Specific technology goals and component needs are given in the sub-topics. General mission priorities for energy storage and generation include:

- EVA suits require secondary batteries sufficient to power all portable life support, communications, and electronics for an 8-hour mission with minimal volume. Battery operation required for six months and 100 recharge cycles with a shelf life of at least two years. Mission priorities include human-safe operation; 8-hr duration; high specific energy; and high energy-density.
- Secondary batteries for the Altair ascent stage require nominally 10 recharge cycles with 1.7 kW nominal power and 2 kW peak power, operating for 7 hours continuously. Mission priorities include human-safe, reliable operation and high energy-density in a 0 - 30°C and 0 - 1/6 gravity environment.

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- The Altair descent stage requires a fuel cell with a nominal power level of 3 kW with 5.5 kW peak, operating for 220 hours continuously. Mission priorities include human-safe reliable operation; the ability to scavenge available fuel; and high energy-density.
 - Regenerative fuel cells, which combine a fuel cell with a water electrolyzer, have been baselined for lunar surface system operations. Mission priorities include reliable, long-duration maintenance-free operation; human-safe operation; high specific-energy; and high system efficiency in a 0 - 100°C, 1/6 gravity environment.
 - 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, as well as Mars outposts.
 - Power systems for lunar rovers require human-safe operation; reliable, maintenance-free operation; and high specific-energy.

Sub Topics:

X7.01 Advanced Space Rated Batteries

Lead Center: GRC

Participating Center(s): JPL, JSC

Advanced battery systems are sought for use in Exploration mission applications including power for landers, rovers, and extravehicular activities. Areas of emphasis include advanced cell chemistries with the aggressive mass and volume performance improvements and safety advancements in human-rated systems over state-of-the-art lithium-based systems. Rechargeable cell chemistries with advanced non-toxic anode and cathode materials and nonflammable electrolytes are of particular interest.

The focus of this solicitation is on advanced cell components and materials to provide mass and volume improvements and safety advancements that contribute to the following goals:

- Specific energy (cell level) > 300 Wh/kg at C/2 and 0°C;
- Energy density (cell level) > 600 Wh/l at C/2 and 0°C;
- Operating Temperature Range from 0°C to 30°C;
- Tolerance to abuse such as overcharge and over temperature conditions;
- Calendar life > 5 years; cycle life 250 cycles at 100% depth of discharge.

Systems that combine all of the above characteristics and demonstrate a high degree of safety are desired. Cell safety devices such as shutdown separators, current limiting devices that inhibit or prevent thermal runaway, cell venting, and flame or fire; autonomous safety features that result in safe, non-flammable, non-hazardous operation especially for human-rated applications are of particular interest. Safety features that enhance the performance of high-power/high-rate cells that operate at >30°C discharge rates are also of 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.

X7.02 Surface Nuclear Power Systems

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 systems to power habitats, resource production, and mobility systems on the Moon and Mars. Nuclear 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. Isotopic technologies that improve the utilization of a limited fuel supply and have extensibility to fission systems are sought. Performance goals include reducing overall system mass, volume and cost, and increasing safety and reliability.

Specific technology topics of interest are:

- High efficiency (>20%) power conversion at 900 K;
- Electrical power management, control and distribution (1-5 kV);
- High temperature, low mass (2) radiators, liquid metal/liquid metal and liquid metal/gas heat exchangers (>90% effectiveness) and electromagnetic pumps (>20% efficiency);
- Deployment systems/mechanisms for large radiators (~3m x 15m);
- High temperature (>900 K) materials or coatings compatible with local soil and atmospheric environments;
- Systems/technologies to mitigate planetary surface environments including dust accumulation, wind, planetary atmospheres, corrosive soils, etc.;
- System designs to provide autonomous control for 10-year operation, including sensor and control technologies;
- Radiation tolerant systems and materials enabling robust, long life operation.

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.

X7.03 Fuel Cells for Surface Systems

Lead Center: GRC

Participating Center(s): JPL, JSC

Advanced primary fuel cell and regenerative fuel cell energy storage systems are baselined to provide descent power for the Altair lander and stationary power for lunar bases. Technology advances that reduce the weight and volume, improve the efficiency, life, safety, system simplicity and reliability of PEM fuel cell, electrolysis, and regenerative fuel cell systems are desired. Proposals are sought which address the following areas:

Advanced Conductive Fuel Cell Water Separator

Research directed towards improving the water separating capability of a planar separator internal to each fuel cell in a fuel cell stack. Proposals directed at developing such advanced separator materials must meet the following criteria to be considered relevant.

The separator:

- Must be wettable with water, and have a contact angle less than 30 degrees;
- Must allow water to penetrate and be transferred through the plane of the separator at a rate of at least 0.33 grams of water per hour per square centimeter of separator planar area;
- Must not permit gas vapor to penetrate through the separator up to at least 30 psid (i.e., a bubble pressure point of at least 30 psid);
- Must be electrically conductive, and have a resistivity of no more than 7.0×10^{-3} Ohm-cm;
- Ideally should be compatible with a fuel cell fabrication process step that occurs at 1000°C with a compressing force of at least 600 psi. (The separator will not need to operate at these conditions, but could be subjected to these conditions during fuel cell fabrication). This bullet is not a requirement but a desirable characteristic.

Hydrogen/Oxygen Dual Gas Pressure Regulator

Research directed towards improving the regulators that regulate hydrogen and oxygen gases down to a usable pressure for the fuel cell. The regulated pressure needs to be controlled so that the pressure differential between the gases is within a few psi. NASA is interested in developing a single mechanical component which functions as a dual gas regulator that can reliably regulate these gases from high pressure source (>500psi) down to

Advanced Electrocatalyst Materials for Fuel Cells and Electrolyzers

Research directed towards improving the kinetics of oxygen reduction and oxygen evolution. Nano-phase, high-surface area unsupported platinum-alloys, incorporating cobalt, nickel and iron are potential candidates for improving the kinetics of oxygen reduction. Oxides of ruthenium and iridium are particularly promising electrocatalysts for the oxygen evolution reaction. In addition to performance, the new materials must exhibit durability for over 10,000 hours of operation with no more than 20% loss in performance. Proposals directed at

developing such advanced nano-phase materials, understanding composition/property relationships, and demonstrating their characteristics in operating fuel cells will be considered directly relevant to achieving the long-term goals of the Explorations Missions.

- Fuel cell MEA efficiency >75% (>0.92volts) @ 200 mA/cm²;
- Electrolysis MEA efficiency >85% (2).

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.

Cryogenic Systems Topic X8

The Exploration Systems architecture presents cryogenic storage, distribution, and fluid handling challenges that require new technologies to be developed. Reliable knowledge of low-gravity cryogenic fluid management behavior is lacking and yet is critical for Altair and Ares in the areas of storage, distribution, and low-gravity propellant management. Additionally, Earth-based and lunar surface missions will require success in storing and transferring liquid and gas commodities. Some of the technology challenges are for long-term cryogenic propellant storage and distribution; cryogenic fluid ground processing and fluid conditioning; liquid hydrogen and liquid oxygen liquefaction processes on the lunar surface. Furthermore, specific technologies are required in valves, regulators, instrumentation, modeling, mass gauging, cryocoolers, and passive and active thermal control techniques. The technical focus for component technologies is for accuracy, reduced mass, minimal heat leak, minimal leakage, and minimal power consumption. The anticipated technologies proposed are expected to increase reliability, increase cryogenic system performance, and are capable of being made flight qualified and/or certified for the flight systems and dates to meet Exploration Systems mission requirements.

Sub Topics:

X8.01 Cryogenic Fluid Transfer and Handling

Lead Center: KSC

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

This subtopic solicits cryogenic storage and transfer technologies to enable NASA Exploration goals. This includes a wide range of applications, scales, and environments on ground, in orbit, and on the Lunar or Martian surface. Specifically:

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- Passive thermal control for ZBO (zero boil-off) storage of cryogenics for both long term (>200 days for LOX/LH₂) on the lunar surface and short term (14 days for LH₂, LOX) on orbit. Insulation for both ground and flight.
 - Active thermal control for long term ZBO storage for lunar surface and space applications. Technologies include 20 K cryocoolers for Mars missions, cryocooler integration techniques, heat exchangers, distributed cooling, and circulators. Scavenging of residual propellants.
 - Zero gravity cryogenic control devices including thermodynamic vent systems, spray bars and mixers, and liquid acquisition devices.
 - Advanced spacecraft valve actuators using piezoelectric ceramics. Actuators that can reduce the size and power while minimizing heat leak and increasing reliability.
 - Propellant conditioning and densification technologies for Earth based applications, scaled for Altair or EDS tanks. Destratification technologies and recirculation systems for homogeneous tank loads. Reliability and operability upgrades over past densification systems.
 - High capacity liquid oxygen pump systems capable of delivering high quality of liquid over a wide flow range between 500 GPM to 2000 GPM are sought. Special emphasis on variable control pumping, parallel pumping, system reliability and robustness, and advanced pump sealing technology is needed.
 - Liquefaction of oxygen on the Lunar surface, including passive cooling with radiators, cryocooler liquefaction, or open cycle systems that work with HP electrolysis. Efficiency, mass savings, and reliability upgrades are needed. Heat pumps, switches, and heat pipes to control energy flow at low temperatures. Deployable radiators and radiation shields.

X8.02 Cryogenic Instrumentation for Ground and Flight Systems

Lead Center: GRC

Participating Center(s): JPL, KSC, MSFC, SSC

This subtopic includes technologies for reliable, accurate cryogenic propellant instrumentation needs in-space, on the lunar surface, and on the Earth. Innovative concepts are requested to enable accurate measurement of cryogenic liquid mass in low-gravity storage tanks, to enable the ability to detect in-space and on-pad leaks from the storage system, and to address other cryogenic instrumentation needs. Cryogenic propellants such as hydrogen, methane, and oxygen are required for many current and future space missions. 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.

Propellant mass gauging provides accurate measurement of cryogenic liquid mass (LH₂, LO₂, and LCH₄) in low gravity storage tanks, and is critical to allowance of smaller propellant tank residuals and assuring mission success. Both low-gravity gauging (measurement uncertainty

Leak detection technologies impact cryogenic systems for space transportation orbit transfer vehicles, lunar surface, and launch site ground operations. These systems will be operational both in atmospheric conditions and in vacuum with multiple sensor systems distributed across the vehicle or a region of interest to isolate leak location. Methane and hydrogen leak detection sensors with milli-second response times and 1 ppm detection sensitivity in

air are desired for ground and launch operations.

Other cryogenic instrumentation needs include:

- Miniature cryogenic pressure sensors (0 - 1 atm) for use under MLI blankets.
- Zero dead-volume in-line pressure sensors for use in liquid hydrogen flow streams.
- Real-time in-situ measurements of ppm levels of N₂, O₂, and H₂O in gaseous helium purge streams. Sensors that can survive the temperature range 20 K - 300 K and the vibration loads on a launch platform are especially desired.
- Minimally intrusive in-situ measurements of liquid hydrogen and liquid oxygen purity levels in real time. The goal is to accurately measure cryogenic propellant liquid purity levels (99% - 100% purity) in ground test stands during test operations. Helium and nitrogen impurity levels are of specific interest, but the sensors must be able to measure overall purity level of the cryogenic liquid.
- Minimally invasive cryogenic liquid flow measurement sensors for rocket engine feed lines, and sensors to detect and quantify two-phase flow (bubbles) within the feed lines.
- Non-intrusive flowmeters for high-pressure (up to 6,000 psi) gaseous helium distribution lines are sought for flow rates ranging from a trickle flow up to 1500 SCFM. Ultrasonic clamp-on flowmeters are especially desired, but must be able to sense the flow through 2" Schedule-XX pipe (0.436" wall thickness).
- Position indicators and long life application of the instrumentation for deep space missions.

Thermal Protection Systems Topic X9

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. Better performing ablative TPS than currently available is needed to satisfy requirements of the most severe CEV missions, e.g., Mars Landing with 8 km/s entry and Mars Sample Return with 12-15 km/s Earth entry. Beyond the improvement needed in ablative TPS materials, more demanding future missions such as large payload missions to Mars will require novel entry system designs that consider different vehicle shapes, deployable or inflatable configurations and integrated approaches of TPS materials with the entry system sub-structure.

Sub Topics:

X9.01 Ablative Thermal Protection Systems

Lead Center: ARC

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

The technologies described below support the goal of developing higher performance ablative TPS materials for higher performance CEV as well as future Exploration missions.

- Developments are sought for ablative TPS materials and heat shield systems that exhibit maximum robustness, reliability and survivability while maintaining minimum mass requirements, and capable of enduring severe combined convective and radiative heating, including: development of acreage materials, adhesives, joints, penetrations, and seals. Two classes of materials will be required.
 - One class of materials, for Mars aerocapture and entry, will need to survive heat fluxes of 200-400 W/cm² (primarily convective) and integrated heat loads of up to 25 kJ/cm². These materials or material systems must improve on the current state-of-the-art recession rates of 0.25 mm/s at heating rates of 200 W/cm² and pressures of 0.3 atm and improve on the state-of-the-art areal mass of 1.0 g/cm² required to maintain a bondline temperature below 250°C.
 - The second class of materials, for Mars return, will need to survive heat fluxes of 1500-2500 W/cm², with radiation contributing up to 75% of that flux, and integrated heat loads from 75-150 kJ/cm². These materials or material systems must improve on the current state-of-the-art recession rates of 1.00 mm/s at heating rates of 2000 W/cm² and pressures of 0.3 atm and improve on the state-of-the-art areal mass of 4.0 g/cm² required to maintain a bondline temperature below 250°C.
- In-situ heat flux sensors and surface recession diagnostics tools are needed for flight systems to provide better traceability from the modeling and design tools to actual performance. The resultant data will lead to higher fidelity design tools, risk reduction, decreased heat shield mass and increases in direct payload. The heat flux sensors should be accurate within 20%, surface recession diagnostic sensors should be accurate within 10%, and any temperature sensors should be accurate within 5% of actual values.
- Non Destructive Evaluation (NDE) tools are sought to verify design requirements are met during manufacturing and assembly of the heat shield, e.g. verifying that anisotropic materials have been installed

in their proper orientation, that the bondline as well as the TPS materials have the proper integrity and are free of voids or defects. Void and/or defect detection requirements will depend upon the materials being inspected. Typical internal void detection requirements are on the order of 6-mm, and bondline defect detection requirements are on the order of 25.4-mm by 25.4-mm times the thickness of the adhesive.

- Advances are sought in ablation modeling, including radiation, convection, gas surface interactions, pyrolysis, coking, and charring. There is a specific need for improved models for low and mid density as well as multi-layered charring ablators (with different chemical composition in each layer). Consideration of the non-equilibrium states of the pyrolysis gases and the surface thermochemistry, as well as the potential to couple the resulting models to a computational fluid dynamics solver, should be included in the modeling efforts.

Technology Readiness Levels (TRL) of 4 or higher are sought.

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.

This subtopic is also a subtopic for the "Low-Cost and Reliable Access to Space (LCRATS)" topic. Proposals to this subtopic may gain additional consideration to the extent that they effectively address the LCRATS topic (See topic O5 under the Space Operations Mission Directorate).

X9.02 Advanced Integrated Hypersonic Entry Systems

Lead Center: ARC

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

The technologies below support the goal of developing advanced integrated hypersonic entry systems that meet the longer term goals of realizing larger payload masses for future Exploration missions.

- Advanced integrated thermal protection systems are sought that address: (1) thermal performance efficiency (i.e., ablation vs. conduction), (2) in-depth thermal insulation performance (i.e., material thermal conductivity and heat capacity vs. areal density), (3) systems thermal-structural performance, and (4) system integration and integrity. Such integrated systems would not necessarily separate the ablative TPS material system from the underlying sub-structure, as is the case for most current NASA heat shield solutions. Instead, such integrated solutions may show benefits of technologies such as hot structures and/or multi-layer systems to improve the overall robustness of the integrated heat shield while reducing its overall mass. The primary performance metrics for concepts in this class are increased reliability, reduced areal mass, and/or reduced life cycle costs over the current state of the art.
- Advanced multi-purpose TPS solutions are sought that not only serve to protect the entry vehicle during primary planetary entry, but also show significant added benefits to protect from other natural or induced environments including: MMOD, solar radiation, cosmic radiation, passive thermal insulation, dual pulse

heating (e.g., aero capture followed by entry). Such multi-purpose materials or systems must show significant additional secondary benefits relative to current TPS materials and systems while maintaining the primary thermal protection efficiencies of current materials/systems. The primary performance metrics for concepts in this class are reduced areal mass for the combined functions over the current state of the art.

- Integrated entry vehicle conceptual development is sought that allow for very high mass (> 20 mT) payloads for Earth and Mars entry applications. Such concepts will require an integrated solution approach that considers: TPS, structures, aerodynamic performance (e.g., L/D), controllability, deployment, packaging efficiency, system robustness / reliability, and practical constraints (e.g. launch shroud limits, ballistic coefficients, EDL sequence requirements, mass efficiency). Such novel system designs may include slender or winged bodies, deployable or inflatable entry systems as well as dual use strategies (e.g., combined launch shroud and entry vehicle). New concepts are enabling for this class of vehicle. Key performance metrics for the overall design are system mass, reliability, complexity, and life cycle cost.
- Advances in Multidisciplinary Design Optimization (MDO) are sought specifically in application to address combined aerothermal environments, material response, vehicle thermal-structural performance, vehicle shape, vehicle size, aerodynamic stability, mass, vehicle entry trajectory / GN&C, and cross-range, characterizing the entry vehicle design problem.

Technology Readiness Levels (TRL) of 4 or higher are sought.

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.

This subtopic is also a subtopic for the "Low-Cost and Reliable Access to Space (LCRATS)" topic. Proposals to this subtopic may gain additional consideration to the extent that they effectively address the LCRATS topic (See topic O5 under the Space Operations Mission Directorate).

Cryogenic and Non-Toxic Storable Propulsion Topic X10

The Exploration Systems architecture presents propulsion challenges that require new technologies to be developed. Non-toxic engine technologies are being explored for use in lieu of the currently operational nitrogen tetroxide (NTO) and monomethylhydrazine (MMH) systems. Safety concerns with toxic propellants drive mission planners to the use of more costly propulsion modules that are fueled and sealed on the ground and can limit operational flexibility on the launch pad. There are also concerns with exhaust residue from toxic systems, which may be carried into habitats for lunar and Mars systems. To address these challenges, the focus will be on the

development of cryogenic and non-toxic propulsion technologies to support informed decisions on implementation in the Exploration architecture. The major components of this effort will focus on reaction control systems, main engine, and deep throttling descent engines. A summary of some of the current activities is located at:

<http://spaceflight systems.grc.nasa.gov/Advanced/Capabilities/PCAD/> [9]

The anticipated technologies to be proposed are expected to increase reliability, increase system performance, and to be capable of being made flight qualified and certified for the flight systems to meet Exploration Systems mission requirements.

Sub Topics:

X10.01 Cryogenic and Non-Toxic Storable Propellant Space Engines

Lead Center: GRC

Participating Center(s): JSC, MSFC

This subtopic intends to examine a range of key technology options associated with cryogenic and non-toxic storable propellant space engines. The primary mission for the engines 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, methanol, monopropellants, or other non-toxic fuel blends. Key performance parameters:

- Reaction control thruster development is in the 25-500-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 3,500-8,000-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:

- Non-toxic fuel blends or monopropellants that meet performance targets while improving safety and reducing handling operations as compared to current state-of-the-art storable propellants.
- Low-mass propellant injectors that provide stable, uniform combustion over a wide range of propellant inlet conditions.
- High temperature materials, coatings and/or ablatives for injectors, 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 propellant valves that tolerate space and lunar environments with reduced volume, size, and weight is also desirable.

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

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.

Exploration Crew Health Capabilities Topic X11

Human space flight is associated with losses in muscle strength, bone mineral density and aerobic capacity. Crewmembers returning from the International Space Station (ISS) can lose as much as 10-20% of their strength in weight bearing and postural muscles. Likewise; bone mineral density is decreased at a rate of ~1% per month. Although aerobic capacity has not been formally measured in returning ISS crew, short duration Space Shuttle crewmembers have been shown to undergo a 22% reduction in VO₂max in response to space flight. During future exploration missions such physiological decrements represent the potential for a significant loss of human performance which could lead to mission failure and/or a threat to crewmember health and safety. The ability to estimate the physical cost of exploration tasks, monitor crew health and fitness, and to provide effective hardware for exercise countermeasures use will be valuable in supporting safe and successful space exploration. Exercise systems is seeking technologies or devices to provide resistive and aerobic exercise in flight or simulate an Extra Vehicular Activity (EVA) suit on the ground. Visit the following for additional information:

<http://hacd.jsc.nasa.gov/projects/ecp.cfm> [10]

<http://hacd.jsc.nasa.gov/projects/eva.cfm> [11]

Sub Topics:

X11.01 Crew Exercise System

Lead Center: GRC

Participating Center(s): JSC

Human space flight is associated with losses in muscle strength, bone mineral density and aerobic capacity. The ability to estimate the physical cost of exploration tasks, monitor crew health and fitness, and to provide effective hardware for exercise countermeasures use will be valuable in supporting safe and successful space exploration.

Exercise Systems is seeking technologies or devices to provide resistive and aerobic exercise in flight.

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- Compact, reliable, multi-function exercise devices/systems are required 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 2 times per 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 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 such that post-mission muscle strength is maintained at or above 80% of baseline values. The same device must be capable of providing whole-body aerobic exercise levels necessary to maintain aerobic capacity at or above 75% of baseline VO₂max. Finally, the ideal device should also stimulate the sensory-motor system which controls balance and coordination.
 - Identify compact, multi-function exercise devices to protect muscle and cardiovascular health during lunar sortie missions (missions with a total duration of less than 30 days). This device must be 20 lbs or less including all accessories (or demonstrated to be within this allotment for a flight unit if the ground prototype exceeds 20 lbs), 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 can be stowed within 1 cubic foot of space aboard the Orion vehicle. The device must require no crew calibration or maintenance (for missions less than 30 days), require minimal deployment/setup time (easily portable between vehicles), and ideally 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.

Phase 1 Requirements: a fully developed concept, complete with feasibility analyses and top-level drawings. A breadboard or prototype is highly desired.

X11.02 EVA Suit Simulator

Lead Center: GRC

Participating Center(s): JSC

Human space flight is associated with losses in muscle strength, bone mineral density and aerobic capacity. The ability to estimate the physical cost of exploration tasks, monitor crew health and fitness, and to provide effective hardware for exercise countermeasures use will be valuable in supporting safe and successful space exploration.

Exercise Systems is seeking technologies or devices to simulate an Extra Vehicular Activity (EVA) suit on the ground.

A wearable system that simulates the mechanical properties of the current extravehicular activity (EVA) space suit is sought. System should be lightweight (less than 30 pounds), easy to don/doff (especially in the supine position), replicate the mechanical properties of a space suit (in terms of resistance to motion and mass and inertia), and able to be worn during conduct of simulated lunar tasks that last up to 4 hours. Suit system must be adjustable to accommodate individuals of different height and weight. Joints of primary interest to simulate in this system are the shoulder, elbow, trunk, hip, and knee.

Phase 1 Requirements: a fully developed concept, complete with feasibility analyses and top-level drawings. A breadboard or prototype is highly desired.

Behavioral Health and Performance Topic X12

The Behavioral Health and Performance topic is interested in developing strategies, tools, and technologies to mitigate Behavioral Health and Performance risks. The Behavioral Health and Performance topic is seeking tools and technologies to prevent performance degradation, human errors, or failures during critical operations resulting from: fatigue or work overload; deterioration of morale and motivation; interpersonal conflicts or lack of team cohesion, coordination, and communication; team and individual decision-making; performance readiness factors (fatigue, cognition, and emotional readiness); and behavioral health disorders.

For 2009, the Behavioral Health and Performance topic is interested in the following technologies: Crew autonomy assessment tools and unobtrusive behavioral health monitoring tools. Proposals may respond to one or more of these areas.

<http://humanresearch.jsc.nasa.gov/elements/smo/nra.asp> [12]

<http://www.nsbri.org/Research/Psycho.html> [13]

Sub Topics:

X12.01 Crew Autonomy Assessment for Exploration

Lead Center: JSC

The NASA Behavioral Health and Performance Program Element (BHP) identifies and characterizes the behavioral health and performance risks associated with training, living and working in Space, and return to Earth. BHP develops strategies, tools, and technologies to mitigate these risks. Currently, BHP has the need for behavioral health and assessment tools relevant to autonomy during Exploration Missions.

The aim of the current task is to identify the optimal level of autonomy by providing a tool that will objectively and unobtrusively measure both crew autonomy and its relevant outcomes (performance, empowerment, satisfaction, cohesion, etc.). The technologies will be able to provide data for BHP to interpret how changes in crew autonomy during a mission influence the relevant team outcomes that are measured.

Objectives:

- Determine optimal level of autonomy needed for different spaceflight missions or mission phases;
- Design and/or enhance unobtrusive tools that measure crew autonomy and its relevant team outcomes;
- Establish how autonomy levels change within and across missions;
- Interpret how these changes in autonomy influence important team outcomes.

Requirements: The Crew Autonomy Assessment shall:

- Be unobtrusive
- Require minimal crew time or effort
- Detect changes in team (ground and flight crew) autonomy and team outcomes (those that are chosen)

Phase 1 Requirements: Develop Requirements for Crew Autonomy Assessment

- An assessment of current methods through which to monitor/measure autonomy and relevant team outcomes within the DOD and other agencies will be provided;
- An assessment of current technologies that unobtrusively monitor crew autonomy and relevant team outcomes (if any) will also be conducted;
- Recommendations regarding enhancements to current technologies or the development of new technologies will be presented;
- The spaceflight environment (current and future) and models related to autonomy and its relevant team outcomes will be assessed in order to determine the optimal requirements for developing a Crew Autonomy Assessment suitable for NASA human space exploration.

Phase 2 Requirements: Crew Autonomy Assessment Prototype developed based on accurate models and Phase 1 findings.

- Develop prototype hardware;
- Develop manual and troubleshooting guide;
- Evaluate and test the functionality of the prototype device.

X12.02 Behavioral Health Monitoring Tools

Lead Center: JSC

The NASA Behavioral Health and Performance Program Element (BHP) identifies and characterizes the behavioral health and performance risks associated with training, living and working in Space, and return to Earth. BHP develops strategies, tools, and technologies to mitigate these risks. Currently, BHP has the need for behavioral health monitoring tools specific to the long duration Exploration Mission environment.

The aim of the current task is to provide requirements for a tool that will unobtrusively monitor behavioral health of the individual crew member while on a mission. The objective of this technology would be to monitor changes in behavioral health and automatically generate meaningful feedback for astronauts and flight surgeons, regarding their individual behavioral health status.

The technologies will unobtrusively monitor markers of behavioral health such as body language and voice acoustics (not including facial recognition software).

The technologies will provide meaningful feedback to the astronaut and flight surgeon regarding behavioral health status; if decrements in behavioral health are detected, the technologies should provide feedback regarding potential causes of decrements.

Requirements: The Behavioral Health Assessment Tool shall:

- Be unobtrusive and function autonomously;
- Require minimal crew time or effort to train and utilize;
- Monitor objective indications of behavioral health;
- Provide meaningful feedback to astronauts and flight surgeons regarding individual behavioral health status;
- If decrements are detected, the technologies shall provide meaningful feedback to astronauts and flight surgeons regarding potential causes of decrements and recommendations for potential countermeasures.

Phase 1 Requirements: Develop Requirements for Behavioral Health Monitoring Technology

- An assessment of current methods through which to monitor behavioral health during autonomous

missions within DOD and other agencies will be provided;

- An assessment of current technologies that unobtrusively monitor behavioral health (not including facial recognition software) will also be conducted;
- Recommendations regarding enhancements to current technology or the development of a new technology will be presented;
- The spaceflight environment (current and future) and models related to behavioral health will be considered in order to develop requirements for a Behavioral Health Monitoring Technology suitable for NASA human space exploration missions.

Phase 2 Requirements: Behavioral Health Monitoring Technology Prototype developed based on accurate models and Phase 1 findings.

- Develop prototype hardware/software;
- Develop manual and troubleshooting guide;
- Evaluate and test the functionality of the prototype device.

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. Research and development activities in the Space Human Factors and Food Systems topic address challenges that are fundamental to design and development of the next generation crewed space vehicles. These challenges include: (1) understanding the requirements for information feedback to the crew and developing technologies to ensure these requirements are met, (2) building tasks and tools that are compatible with humans and that enable human performance consistent with mission success, and (3) providing extended shelf life foods with improved nutritional content, quality and reduced packaging mass. This Topic seeks methods for monitoring, modeling, and predicting human performance in the spaceflight environment. The Space Human Factors and Food Systems is seeking new Space Human Factors Assessment Tools and Advanced Food Technologies that utilize non-foil barriers and allow food processing or preparation in a reduced gravity and pressure environment.

http://humanresearch.jsc.nasa.gov/elements/smo/docs/shfh_evidence_report_summary.pdf [14]

<http://hefd.jsc.nasa.gov/aft.htm> [15]

Sub Topics:

X13.01 An Automated Tool for Human Factors Evaluations

Lead Center: JSC

Participating Center(s): ARC

This subtopic calls for a Small Business Innovative Research project to develop an automated tool to assist non-human factors engineers to conduct human factors evaluations. Human factors evaluations are essential in gathering human performance data and analyzing the usability of new design concepts. These evaluations are generally carried out by human factors experts due to the level of expertise required. However, in some cases, it would both save time and cost if a tool is available for non-human factors engineers to carry out a standardized evaluation procedure to obtain the needed data and with comparable quality.

The tool therefore shall provide a comprehensive set of measurement methods and guide non-human factors engineer to carry out human factors evaluations. The tool development shall include defining a comprehensive set of commonly used human factors evaluation methods that allow engineers to gather relevant human factors data. Through a user-friendly interface, the tool shall recommend evaluation metrics, provide step-by-step guidance for setting up the evaluation, and summarize/store evaluation data. The ability for the tool provide interfaces for human factors data acquisition systems is highly desirable.

An algorithm for the tool is expected as the deliverable for Phase 1 and a prototype is expected should the project continue on to Phase 2.

X13.02 Situational Awareness for Multi-Agent Operations

Lead Center: JSC

Participating Center(s): ARC

This subtopic calls for a Small Business Innovative Research project to develop a situation awareness and conflict resolution tool for a wide-area multi-agent operation environment with substantial time delays. Humans and robots in future Lunar or Mars surface operations would be operating both on the Lunar (Mars) surface and on Earth remotely to carry out a common task. Consequently, substantial communication delay would make tasks planning and execution difficult. The goal of this SBIR is to develop a tool so multiple agents can work harmoniously regardless of geographical locations.

The tool therefore shall overcome the hurdle of communication delays and (1) enable situation awareness by providing timely information of tasks conducted by other agents, (2) ensure that newly generated procedures mesh well with the originally scheduled activities, (3) allow operators to poll state data from all agents at any moment, and (4) provide recommendations for best task planning and procedures.

An algorithm for the tool is expected as the deliverable for Phase 1 and a prototype is expected should the project continue on to Phase 2.

X13.03 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.

It will require approximately 10,000 kg of packaged food for a 6-crew, 1000 day mission to Mars. The packaged food will require that the safety, nutrition, and acceptability are maintained at reasonable levels for the entire 5-year shelf life. Therefore, this subtopic request will concentrate on technologies that use a systems approach to provide food in remote locations with limited mass, volume, power, and waste is required.

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 technologies that will allow these raw ingredients to maintain their functionality and nutrition for 5-years. This food system would also 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.

There are some unique parameters that need to be considered when developing the technologies. 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. In addition, there also will not be any significant refrigerator or freezer available.

The response to this subtopic should include a plan to develop a technology that will enable safe and timely food processing and food preparation in reduced cabin pressure and reduced gravity.

Phase 1 Requirements: Phase 1 should concentrate on the scientific, technical, and commercial merit and feasibility of the proposed innovation resulting in a feasibility report and concept, complete with analyses and top-level drawings.

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, within the Human Research Program uses the NASA Research Announcement as a primary means of soliciting research to understand the health risks and reduce the uncertainties in risk projection; however, there are areas where the SBIR program contributes. Specific areas where SBIR technologies can contribute to NASA's overall goal include: reliable radiation monitoring for manned and unmanned spaceflight; and radiation damage imaging.

http://hacd.jsc.nasa.gov/projects/space_radiation_overview.cfm [16]

<http://spaceradiation.usra.edu/> [17]

<http://www.nsbri.org/Research/Radiation.html> [18]

Sub Topics:

X14.01 Active Charged Particle and Neutron Radiation Measurement Technologies

Lead Center: ARC

Participating Center(s): JSC

For exploration class missions, there is extraordinary premium on compact and reliable active detection systems to meet very stringent size and power requirements. NASA requires compact, low power, active monitors that can measure charged particle spectrum and flux separately from neutrons and other radiations. Also, NASA requires compact active neutron spectrometers that can measure the neutron component of the dose separate from the charged particles. Advanced technologies up to technology readiness level (TRL) 4 are requested in the following areas:

Charged Particle Spectrometer

Measure charge and energy spectra of protons and other ions ($Z = 2$ to 26) and be sensitive to charged particles with LET of 0.2 to 1000 keV/m. For Z less than 3, the spectrometer should detect energies in the range 30 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. Design goals for mass should be 2 kg and for volume, 3000 cc. The spectrometer should be able to measure charged particles at both ambient conditions in space (0.01 mGy/hr) and during a large solar particle event (100 mGy/hr). The time resolution should be less than or equal to 1 minute. The spectrometer shall be able to perform data reduction internally and provide processed data.

Neutron Spectrometer

Measure neutron energy spectra in the range of 0.5 MeV to 150 MeV. Measure neutrons at ambient conditions such that proton/ion veto capability should be approaching 100% at solar minimum GCR rates; measure ambient dose equivalent of 0.02 mSv in a 1 hour measurement period, using ICRP 74 (1997) conversion factors; store all necessary science data for post measurement data evaluation. Design goals for mass and volume should be 5 kg and 6000 cc, respectively.

X14.02 Miniature Radiation Pulse Processing Electronics

Lead Center: ARC

Participating Center(s): JSC

For Exploration class missions, there is extraordinary premium on compact and reliable active detection systems to meet very stringent size and power requirements. Miniaturized electronics for radiation pulse processing would be important to help reduce size/power needs. Very small technologies (chips) are developed by the computer industry that may be adaptable to process radiation induced pulses from detectors to provide multi-channel analysis (MCA) and other analysis functions with very low power and size requirements. This is a need for NASA as power and size requirements are severely tightened on future missions to the Moon and beyond. Advanced technologies up to technology readiness level (TRL) 4 are requested in this area.

The miniature processor must not exceed 0.2 W of power and have a volume not to exceed 20 cc. A communication interface, such as USB or other serial interface, is required. A fast clock rate is required, not less than 100 MHz. An analog-to-digital converter, minimum sample rate of 10 M samples per second. Could be part of chip or on the same board with chip. Requires adequate pulse height measurement to perform MCA, e.g., peak hold, digital waveform processing, or other approach. MCA should cover the input pulse height range of .002 to 10 volts (or equivalent) in either 100 channels on log scale or in two linear spectra of not less than 250 channels each with different gains.

Inflight Biological Sample Preservation and Analysis Topic X15

Flight resources such as the International Space Station and the Lunar outpost are essential assets for the Human Research Program goals of quantifying the human health and performance risks for crews during exploration missions. However, the resources for carrying supplies and returning biological samples to/from these assets are limited. Thus, the Human Research Program must identify the means for inflight sample analysis or unique sample processing techniques that minimize the need to return conditioned human samples for analysis. The Inflight Biological Sample Preservation and Analysis topic is seeking innovative technologies or techniques to: provide On Orbit Ambient Biological Sample Preservation Techniques and On Orbit Biologic Sample Analysis capabilities.

Sub Topics:

X15.01 Alternative Methods for Ambient Preservation of Human Biological Samples during Spaceflight and Lunar Operations

Lead Center: JSC

Measurement of blood and urine analytes is a common clinical medicine practice used for differential disease diagnosis and determination of the therapeutic response to treatment. Accurate biochemical results depend on maintaining the integrity of blood and urine samples until analyses can be completed. Improper sample collection, handling, or preservation may lead to critical errors in diagnostic interpretation of analytical results. Traditional methods have been developed that include the use of sample component separation by means of centrifugation, refrigeration, freezing or the addition of preservatives to maintain the integrity of biological samples. While such techniques are easily achieved in a routine clinical setting, the spaceflight environment presents unique challenges to sample processing and stowage. Thus, novel on-orbit methods for the ambient preservation of biological samples are critical for scientific research, monitoring of crew health and evaluation of countermeasure efficacy. The development of alternative innovative techniques with advantages over currently used methods for processing and preserving biological samples at ambient temperatures during spaceflight that provide a high level of reliability in maintaining a wide array of both blood and urine analytes over a long period of ambient stowage is highly desirable.

Automation for Vehicle Habitat Operations Topic X1.01

Automation 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, leading to increased efficiency and reduced mission risk. To enable the application of intelligent automation and autonomy techniques, the technologies need to address two significant challenges: adaptability and software validation. Proposals are solicited in the areas of:

- **Automation Support Tools:** Support tools are needed to facilitate the authoring and validation of plans and execution scripts. Tools that are not tied specifically to one executive would provide NASA the most flexibility. Examples include: Graphical tool for monitoring and debugging plan execution and 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. Examples: Command and supervise complex tasks while projecting the outcome 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.
- **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).

Sub Topics:

Reliable Software for Exploration Systems Topic X1.02

This subtopic seeks to develop 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 contractors) and not specialists. 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. 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). Specific software engineering tools and methods are sought in the following areas:

- 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 against high-fidelity hardware-in-the-loop test-beds 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);
- Methods and tools for development and validation of autonomic software systems (systems that are self protecting and self healing).

Sub Topics:

Radiation Hardened/Tolerant and Low Temperature Electronics and Processors Topic X1.03

Constellation projects that are designed to leave low-earth orbit (Orion, Ares V Earth Departure Stage, Altair, Lunar Surface Systems, EVA suits, etc.) require avionic systems, components, and controllers that are capable of operating in the extreme temperature and radiation environments of deep space, the lunar surface, and eventually the Martian surface. Spacecraft vehicle electronics will be required to operate across a wide temperature range and must be capable of enduring frequent (and often rapid) thermal-cycling. Packaging for these electronics must be able to accommodate the mechanical stress and fatigue associated with the thermal cycling. Spacecraft vehicle electronics must be radiation hardened for the target environment. They must be capable of operating through a minimum total ionizing dose (TID) of 100 krad (Si) or more and providing single-event latchup immunity (SEL) of 100 MeV cm²/mg or more.

Considering the extreme environment performance parameters for thermal and radiation extremes, proposals are sought in the following specific areas:

- Low power, high efficiency, radiation-hardened processor technologies;
- Field Programmable Gate Array (FPGA) technologies;
- Innovative radiation hardened volatile and nonvolatile memory technologies;
- Tightly-integrated electronic sensor and actuator modules that include power, command and control, and processing;
- Radiation-hardened analog application specific integrated circuits (ASICs) for spacecraft power management;
- Radiation-hardened DC-to-DC converters and point-of-load power distribution circuits;
- 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 radiation hardness and low-temperature (-230°C) analog and mixed-signal circuit performance;
- Packaging capable of surviving numerous thermal cycles and tolerant of the extreme temperatures on the Moon and Mars, which includes the use of appropriate materials including substrates, die-attach, encapsulants, thermal compounds, etc.

Sub Topics:

Integrated System Health Management for Ground Operations 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 within a very brief timeframe and with high certainty. Health management is essential for dormant periods between human habitation, and for transition of assets (such as lunar habitats) to crewed operations. In addition, the long-duration health of software systems themselves are also critical. 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, communications, and software. Proposals that involve the use of existing testbeds or facilities at NASA are strongly encouraged. Specific technical areas of interest are methods and tools for:

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- Early-stage design of health management functionality during the development of space systems, including failure detection methods, sensor types and locations that enable fault detection to line replaceable units.
 - Sensor validation and robust state estimation in the presence of inherently unreliable sensors. Focus on data analysis and interpretation using legacy sensors.
 - Model-based fault detection and isolation in rocket propulsion systems based on existing sensor suites during pre-launch and flight mission operations that enables fault detection within time ranges to allow mission abort.
 - Automatic construction of models used in model-based diagnostic strategies, limiting model construction times to 60% of the time required using manual methods.
 - Advanced built-in-tests for spacecraft avionics that provide 95% functional coverage and reduce or eliminate the need for extensive functional verification and to predict remaining life of avionics systems.
 - Prognostic techniques able to anticipate system degradation before loss of critical functions and enable further improvements in mission success probability, operational effectiveness, and automated recovery of function.
 - Approaches for effective utilization of 100% of the health information on critical functions from spacecraft and launch vehicles with integration to ground based systems using commercial health information from programmable logic controller and RAS system.
 - Techniques that address the particular constraints of maintaining long-duration systems health of structures, mechanical parts, electronics, and software systems on lunar surfaces are of special interest.

Sub Topics:

Spacecraft Cabin Atmosphere Revitalization and Particulate Management Topic X2.01

Cabin Atmosphere Revitalization

Atmosphere revitalization developmental activities target process technologies and equipment to condition and supply gaseous oxygen at pressures at or above 3,600 psia and achieve mass closure by recycling resources. As well, portable means for atmosphere revitalization that have synergy with extravehicular activity (EVA) equipment pertaining to trace contaminant control, carbon dioxide removal, humidity control are target technology areas. Durable, dust-tolerant fluid connections support the EVA and life support system infrastructure. Details on areas of emphasis are the following:

High Pressure Oxygen Gas Supply and Conditioning: Process technologies leading to an on-demand, in-flight renewable 3,600-psia oxygen supply are of interest. Process technologies and techniques must be capable of conditioning oxygen for temperature, pressure, and water content using oxygen from several sources. Source oxygen may originate directly from the cabin atmosphere or from gaseous storage, cryogenic storage, and/or on-demand production from water electrolysis or in-situ resource utilization processes.

There is specific interest in process technologies to remove water from saturated oxygen to provide a product having a dewpoint below -62°C.

Atmospheric Resource Recycling Techniques: Process technologies suitable for conditioning and converting gaseous products produced by the Sabatier CO₂ reduction reaction to useful products are of interest. Of particular interest are process technologies to recover moisture from a saturated stream of methane that contains residual CO₂ and hydrogen reactants, to convert methane to products such as low molecular weight alcohols or other compounds suitable for use in power co-generation via fuel cells or other means, and to produce a solid carbon product via a regenerative process based on the Bosch reaction or a variant of the Bosch reaction.

Particulate Matter Management

Particulate matter suspended in the habitable cabin atmosphere is a challenge for all phases of crewed lunar surface exploration missions. Removing and disposing of particulate matter originating from sources internal to the habitable cabin and from lunar surface dust intrusion into the cabin environment is of interest. Staged techniques employing combinations of course media filtration (>50 micron size), inertial separation (2.5 micron size), and fine media filtration (

Atmosphere Revitalization for EVA

Synergy exists between cabin atmosphere revitalization and EVA suits. Common functions include trace contaminant control, CO₂ partial pressure control, and humidity control.

Trace Contaminant Control for EVA Suits: EVA suits designed for long durations with minimal maintenance will require new methods of trace contaminant control to maintain spacesuit environments below Spacecraft Maximum Allowable Concentrations for toxic or irritating chemicals. Historically this has used activated charcoal. In the case of ISS EVA, the charcoal is regenerable with heat. A need exists for a reduced power solution, such as vacuum regeneration of a sorbent, or another, innovative, low consumable solution. Consideration of on-back, real-time EVA regeneration as well as post EVA regeneration is acceptable.

Mars EVA CO₂ and Humidity Control: ISS EVA suits utilize heat regenerable CO₂ removal systems. These systems are heavy and require significant power for regeneration. Lunar EVA suits are planned to use a lightweight, vacuum regenerable amine system to remove CO₂ and humidity from the suit. It is envisioned this concept could be extensible to Mars suits with the addition of sweep gas to prevent intrusion of the Martian atmosphere. An innovative CO₂ and humidity removal system that could remove CO₂ and humidity while eliminating gas losses to the Martian atmosphere, remain lightweight, and utilize minimal power is desired. Consideration of on-back, real-time EVA regeneration as well as post EVA regeneration is acceptable.

Dust Tolerant Quick Disconnects for High and Low Pressure Fluids

Connections will need to be made between the EVA suits and lunar and Martian vehicles in environments where dust will be present. A lightweight QD that excludes dust during connections and disconnections is required.

Sub Topics:

Spacecraft Habitation Systems, Water Recovery and Waste Management Topic X2.02

Habitation, water recovery and waste management systems supporting critical needs for lunar mission architectures are requested. Improved technologies are needed for clothing/laundry, recovery of water, recovery of other resources, stabilization of wastes and safe long term storage of waste residuals. Proposals should explicitly describe the weight, power, and volume advantages of the proposed technology and be compatible with the lunar and microgravity environments described in the overall X2 topic description.

Clothing/Laundry Systems

Clothing and towels are a major consumable and trash source. Advanced durable fabrics to enable multiple crew wear cycles before cleaning/disposal are required. The laundry system should remove/stabilize combined perspiration salt/organic/dander and lunar dust contaminants, preserve flame resistance properties and use cleaning agents compatible with biological water recovery technologies. Proposals using water for cleaning should use significantly less than 10 kg of water per kg of clothing cleaned.

Waste Management

Wastes (trash, food scraps, feces, water brines, clothing) must be managed to protect crew health, safety and quality of life, to avoid harm of planetary surfaces, and to recover useful resources. Areas of emphasis include: stabilization (particularly water removal and recovery) and solid waste storage and odor control (e.g., catalytic and adsorptive systems). Preferred stabilization methods will dry solids to less than 60% water activity and sterilize and/or prevent microbial growth. Waste compactors must reduce trash to less than 10% of hand compacted volume after any spring-back. Odor control technologies should reduce gaseous contaminants in air to below NASA's Space Maximum Allowable Concentration levels and below the human odor threshold. Lunar-Martian storage containers are desired that are lightweight, low in resupply stowage volume, easily deployable and capable of containing space mission wastes and residuals on Lunar or Martian surfaces without rupture for 400 years.

Water Recovery

Efficient technologies are desired for treatment to potability of wastewater including urine, brines, humidity condensate, hygiene water, and in situ lunar water. Areas of emphasis include: primary treatment reducing 1000 mg/L TOC to less than 100mg/L, post-treatment reducing 100 mg/L TOC to

Sub Topics:

Spacecraft Environmental Monitoring and Control Topic X2.03

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 life support system is functioning properly. The sensors may also provide data to automated control systems. All proposed technologies should have a 2 year shelf-life, including any calibration materials (liquid or gas). The technologies will need to function in low pressure environments (~8 psi) and may see unpressurized storage. Significant improvements are sought in miniaturization, accuracy, precision, and operational reliability, as well as long life, in-line operation, self-calibration, reduction of expendables, low energy consumption, and minimal operator time/maintenance for monitoring and controlling the life-support processes.

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- Microbial monitoring in water
 - 2 year shelf-life; this requirement precludes the usual antibody techniques which have lifetime limitations. Sufficient precision to resolve the following: 50 CFU/ml bacteria; coliform and fungi are required to be zero per 100 ml; zero counts of parasitic protozoa

 - Microbial control of surfaces, typically done by chemically treated wipes or ultraviolet
 - Microbial Controls should be recyclable w/reduced consumables

 - Improved Oxygen Monitor for breathing air
 - +/- 0.05%, must operate in variable pressure 8-14.7 psia and survive exposure to vacuum

 - Broad spectrum Trace Contaminant Monitor, for air, with 2 year shelf life

Sub Topics:

Spacecraft Fire Protection Topic X2.04

NASA's fire protection strategy consists of strict control of ignition sources and flammable materials, early detection and annunciation of fires, and effective fire suppression and response procedures. Providing effective and efficient means for conducting and monitoring post-fire cleanup and restoration of the cabin atmosphere to a habitable environment are also major concerns. While proposals for novel technologies in all of these areas are applicable, they are particularly sought in the areas of nonflammable crew clothing and advanced carbon monoxide sensors for fire detection and monitoring the progress of post-fire cleanup.

The requirements for crew clothing are balanced between appearance, comfort, wear, flammability and toxicity. Ideally, crew clothing should have durable flame resistance in a 34% O₂ (by volume) enriched environment through all end-use conditions including cleaning methods and frequency.

Fire detection strategies are being developed that combine advanced particulate detection technology with sensors that detect gaseous combustion products. Monitoring of carbon monoxide is being targeted both for fire detection and to monitor the progress of post-fire cleanup. A robust optical method is desired that has the dynamic range required to detect and monitor CO from approximately 1 to 500 ppm with resolution to 1 ppm CO. In addition to being sufficiently rugged, this sensor must have minimal mass, power, and volume requirements and exhibit high degrees of reliability, minimal maintenance, and self-calibration under varying humidity and ambient pressures.

Sub Topics:

Spacecraft Thermal Control Systems Topic X2.05

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 system designs also must accommodate the harsh thermal environments associated with these missions. Modular, reconfigurable designs could limit the number of required spares.

The lunar environment presents several challenges to the design and operation of active thermal control systems. During the approximately 2 hour lunar orbit, the environment can range from extremely cold to near room temperature. Polar lunar bases will see unrelenting cold thermal environments, as will the radiators for Martian transit spacecraft. In both cases the effective sink temperature will approach absolute zero.

Innovative thermal management components and systems are needed to accomplish the rejection of waste heat during these future missions. Advances are sought in the general areas of radiators, thermal control loops, thermal system equipment, and EVA thermal control.

Systems with enhanced thermal mass may be required to deal with the lunar orbital environment. Variable emissivity coatings (near unity emissivity with the ability to reduce emissivity by at least a factor of ten), clever working fluid selection (a freezing point approaching 150K), or robust design could be used to prevent radiator damage from freezing in cold environments at times of low heat load.

Part of the thermal control system in a habitable volume is likely to be a condensing heat exchanger, which should be designed to preclude microbial growth. Small, highly reliable, heat pumps could be used to provide 278 K cold fluid to the heat exchanger, allowing the loop temperatures to approach 300 K, thus reducing the size of the radiators.

Future space systems may generate waste heat in excess of 10 kW which could either be rejected or redirected to areas which require it. Novel thermal bus systems which can collect, transport (over a distance of ~30 meters), and provide heat for components are sought. The system should be highly flexible and adaptable to changes in equipment locations. Possible systems include single and two-phase pumped fluid loops, capillary-based loops, and heat pumps. Innovative design of the loops and components is needed.

Historically spacesuits have used water sublimators to provide heat rejection. Development of a low-venting or non-venting regenerable individual life support subsystem(s) concept for crewmember cooling and heat rejection is desired. Systems that integrate spacesuit thermal control systems with other life support tasks, such as removal of expired water vapor and CO₂ are highly desirable. Interests include low cost lightweight spacesuit compatible freezable radiators for thermal control and variable conductance flexible EVA spacesuit garments that can function as a radiator or as an insulator as required. Sensible heat loads average 300 W and peak at 800 W. Spacesuit cooling garments have water flow rates of approximately 100 kg/hr.

Sub Topics:

Oxygen Production from Lunar Regolith Topic X3.01

Oxygen (O₂) production from lunar regolith processing consists of receiving regolith from the excavation subsystem into a hopper, transferring that regolith into a chemical or an electrochemical reactor, intermediate reactions to produce O₂ and regenerate reactants if required, purification of the O₂ produced, and removal of processed regolith from the reactor to an outlet hopper. Three O₂ production from lunar regolith reaction concepts are currently under development: Hydrogen reduction, Carbothermal reduction, and Molten Oxide Electrolysis at initial lunar Outpost production scale of 1 to 2 MT per year (70% per year operations). This subtopic is seeking hardware, subsystem, and system components and technologies for insertion and integration into on-going oxygen extraction from regolith development and demonstration efforts. Items of particular interest are:

- Move feedstock material from hopper on ground to 2 m height for reactor inlet hopper; 40 kg/hr; material size
- Inlet/outlet regolith hopper design and valve/seal concepts with no gas leakage, 1000's of operating cycles with abrasive lunar material, and minimum heat loss.
- Removal of 5 to 10 kg of molten material from molten electrolysis cell with metal slag processing and purification into individual metals.
- Water condensers that use the space environment for water condensation/separation with minimal energy usage.
- Gas Separators that provide low pressure drop separation of the system and product gas streams from impurities (e.g., HCl, HF, H₂S, SO₂); the process should be regenerable and the output contaminant concentration should be less than 50ppb.
- Removal of dissolved ions in water by methods other than de-ionization resins to meet water electrolysis purity requirements (minimum resistivity of 1M-Ohms-cm). Ions of interest are dissolved metal ions (Fe, Cr, Co, Ni, Zn) at concentration of 0.01% and dissolved anions (Cl, F, S) at concentrations of 0.01%-2%. The process should be regenerable, minimize consumables, and minimize water loss.
- Contaminant resistant, high temperature water electrolysis concepts.
- Advanced reactor concepts for carbothermal reduction or molten oxide electrolysis.

Phase 1 proposals should demonstrate technical feasibility of the technology or hardware concept through laboratory validation of critical aspects of the innovation proposed, as well as the design and path toward delivering hardware/subsystems in Phase 2 for incorporation into existing development activities. Interface requirements for on-going development efforts will be provided after selection. Proposers are encouraged to use the Lunar Sourcebook at a minimum for understanding lunar regolith material parameters in the design and testing of hardware proposed. It is also recommended that JSC-1a simulants be used during testing unless a more appropriate simulant can be obtained or manufactured.

Sub Topics:

Lunar ISRU Development and Precursor Activities Topic X3.02

The incorporation of ISRU concepts is an on-going effort which requires an evaluation of the benefits and risks through computer modeling and testing under laboratory, analog field, and simulated lunar environmental

conditions (1/6 g and vacuum). While excavation and oxygen extraction from regolith are included in lunar architecture plans, it is recognized that evaluating the feasibility and benefits of other technologies and concepts not ready for insertion into these efforts should be pursued. This subtopic is aimed at providing development support capabilities and hardware to advanced potentially beneficial ISRU concepts not yet ready for incorporation into current ISRU system laboratory and field test activities. Proposals aimed at the following are of particular interest:

- Mineral beneficiation concepts to separate iron oxide-bearing material from bulk regolith; up to 20 kg/hr based on hydrogen reduction. Hardware/concepts need to be designed for compatibility with both 1/6 g flight experiments and ground vacuum experiments.
- Lunar regolith storage and granular flow computer models, devices, and instruments to evaluate regolith flow and manipulation under 1/6 g flight and ground vacuum experimental conditions.
- Granular materials mixing and separation for reactor feedstock conditioning: remove material > 0.5 cm diameter before dumping into storage bin during excavation operation for oxygen extraction from regolith.
- Processing concepts for production of carbon monoxide, carbon dioxide, and/or water from plastic trash and dried crew solid waste using solar thermal or electrical/heat energy. In-situ produced oxygen or other reagents/consumables must be identified and quantified; recycling schemes for reagents to minimize consumables should be evaluated.
- Thermal energy storage and utilization using bulk or processed regolith.

Phase 1 proposals should demonstrate technical feasibility of the technology and/or subsystem through laboratory validation of critical aspects of the innovation proposed, as well as the design and path toward delivering hardware/subsystems in Phase 2.

Sub Topics:

Advanced Radiation Shielding Materials and Structures Topic X4.01

Advances in radiation shielding materials and structures technologies are needed to protect humans from the hazards of space radiation during NASA missions. The primary area of interest for this 2009 solicitation is radiation shielding materials systems for long-duration lunar surface galactic cosmic radiation (GCR) protection. The innovative materials systems should have radiation shielding effectiveness approaching that of polyethylene, for an equivalent areal density (grams per square centimeter). This can be determined either by radiation transport calculations or by radiation exposure measurements. 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 include the following:

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- Innovative lightweight radiation shielding materials and structures to shield humans in crew exploration vehicles, landers, habitats, and rovers;
 - Physical, mechanical, structural, and other relevant characterization data to validate and qualify multifunctional radiation shielding materials and structures;
 - Innovative processing methods to produce quality-controlled advanced radiation shielding materials of all forms.

Sub Topics:

Expandable Structures Topic X4.02

This subtopic solicits innovative structural concepts that support the development of lightweight structures technologies that could be applicable to lunar surface system habitats. The targeted innovative lightweight structures are for primary pressurized volumes and secondary structures that must be deployed during or after expansion of the primary volume such as the floor and work surfaces. Innovations in technology are needed to minimize launch mass, size and costs, while increasing operational volume and maintaining the required structural performance for loads and environments.

Of particular interest are inflatable structures which are considered to be viable solutions for increasing the volume in habitats, airlocks, and potentially other crewed vessels. However, areas of risk need to be mitigated to build confidence in the use of these structures, in particular: consistent and reproducible mechanical behavior, durability in the presence of micrometeoroid impact, crew-induced and ground handling damage, and repair techniques for long term survivability. Other interests include preintegration solutions, launching pressurized volume in an expandable, and addressing lunar surface deployment concerns.

Also of interest are innovative deployable secondary structures that have minimal mass and high packaging efficiency. These secondary multi-functional structures provide highly robust, stiff and mass efficient surfaces that enable the useful outfitting and pre-integration of subsystems within the primary structural volume.

Development of concepts can include structural components, 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 X4.03

This subtopic focuses on the development of high power and high specific torque density actuators (e.g., motors and gear boxes) that will operate on the lunar surface exposed to the day/night cycle. They will need to operate over a temperature range of approximately 40 K to 403 K. A five year lifetime is desired. The component technologies developed in this effort will be utilized for rovers, cranes, 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 with partial gravity, abrasive dust, and full solar and cosmic 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 innovative long life, light weight, wide temperature range motors (in the range of one to five kWatts), gear boxes, lubricants, and closely related components that are suitable for the environments discussed above.

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:

Composite Structures - Practical Monitoring and NDE for Composite Structures Topic X5.01
Orion backshell, Aries Payload fairing, and Lander struts and composite pressure vessel option, COPV and composite tankage and Habitat modules are only a few of the many weight-reducing applications for composites that need efficient and modular systems to accomplish monitoring and NDE for them to be practical.

This subtopic seeks the development of technologies to detect, locate and characterize indications of a failure far enough ahead that routine actions can be taken to rectify the situation. Perform monitoring such that models can be built of event behaviors and structural response condition can be determined. Monitoring and/or NDE changes can be made with minimum cost/operations.

Performance Goals/Metrics:

- Provide impending system failure indications with sufficient time to take action to reduce the risk of catastrophic failure;
- Increase the number of sensor locations per pound of monitoring weight by 50%;

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- Decrease the system monitoring electronics weight by 50%;
 - Decrease total wiring required for monitoring by 50%;
 - Decrease the time to plan and install monitoring by 50%;
 - Decrease the overall life-cycle cost per sensor by 50%;
 - Decrease total data rate required from the sensor data acquisition location by 50%;
 - Decrease time to perform NDE inspections by 50%;
 - Decrease the expected cost of instrumentation changes/upgrades by 50%.

Technologies sought include: smart sensors, wireless passive sensors, flexible sensors for highly curved surfaces, direct-write film sensors, real-time compact NDE imagers for damage inspection, highly accurate defect and tool position determination.

Applications include: Advanced composite structures such as cryo-tanks, large area composites such as launch vehicle fairings, habitable volumes, hard to access/inspect composite members, as well as metallic pressurized structures of all kinds. Interior as well as exterior measurements of the pressure vessel are needed.

This subtopic is also a subtopic for the "Low-Cost and Reliable Access to Space (LCRATS)" topic. Proposals to this subtopic may gain additional consideration to the extent that they effectively address the LCRATS topic (See topic O5 under the Space Operations Mission Directorate).

Sub Topics:

Composite Structures - Cryotanks Topic X5.02

The use of composite materials for smaller cryotanks offers the potential of significant weight savings. Composite cryotank technology would be applicable to EDS propellant tanks, Altair propellant tanks, lunar cryogenic storage tanks and Ares V tanks. A material system (resin+fiber) which displays high resistance to microcracking at cryogenic temperatures is necessary for linerless cryotanks, which provide the most weight-saving potential.

This subtopic will focus on development of toughened, high strength composite materials, because the literature indicates that they have the highest microcrack resistance at cryogenic temperatures. Greatest interest is in novel approaches to increase resin strength and/or reduce resin CTE, thereby increasing resistance to microcracking at cryogenic temperature.

Performance would be evaluated by a characterization program, which would ideally generate temperature-dependent material properties including strength, modulus, and CTE as functions of temperature. Additionally, notch sensitivity, plain strain fracture toughness, and microcracking fracture toughness as functions of temperature are desirable. Tests will need to be performed at temperatures between -273°C and 180°C to fully characterize any nonlinearity in material properties with changes in temperature.

Initial property characterization would be done at the coupon level in Phase 1. Generation of design allowables, characterization of long-term material durability, and fabrication of larger panels would be part of follow-on efforts.

Sub Topics:

Composite Structures - Manufacturing Topic X5.03

The SBIR subtopic area of Composites Materials and Manufacturing centers on developing lightweight structures using advanced materials technologies, and new manufacturing processes. The objective of the subtopic is to advance technology readiness levels of composite materials and manufacturing for Ares launch vehicle applications resulting in structures having consistent, predictable response.

Areas of interest include: polymer matrix composites (PMCs), large-scale manufacturing; innovative automated processes (e.g., fiber placement); advanced non-autoclave curing; bonding of composite joints; and damage-tolerant/repairable structures.

Performance metrics include: achieving adequate structural and weight performance; analysis supported by test approach; manufacturing and life-cycle affordability; ability to demonstrate capabilities at the laboratory scale and confidence for scale-up; validation of confidence in design, materials performance, and manufacturing processes; quantitative risk reduction capability; minimum sensitivity and maximum robustness for operability.

Lightweight structures and advanced materials have been identified as a critical need since the reduction of structural mass translates directly to vehicle additional performance, reduced cost, and increased up and down mass capability.

Research should be conducted to demonstrate technical feasibility during Phase 1 and show a path toward a Phase 2 prototype demonstration. Demonstrate manufacturing technology that can be scaled up for very large structures.

This subtopic is also a subtopic for the "Low-Cost and Reliable Access to Space (LCRATS)" topic. Proposals to this subtopic may gain additional consideration to the extent that they effectively address the LCRATS topic (See topic O5 under the Space Operations Mission Directorate).

Sub Topics:

Robotic Systems for Human Exploration Topic X6.01

The objective of this subtopic is to provide advanced capabilities for lunar surface system assets that deliver, handle, transfer, construct, and prepare site infrastructure for lunar operations. This includes robust dexterous manipulation capabilities; large and small cargo transporters for delivery and deployment of construction materials, power generation systems, and habitable enclosures.

This subtopic seeks to develop technologies that reduce the risk of Extra-Vehicular Activity (EVA), facilitates remote robotic operations by both flight crew and ground control, and enables autonomous robotic operations. Automation and robotics capabilities include the ability to use robots for site setup and 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: systematic site survey (engineering and/or science), inspection, emergency response, site preparation (clearing, leveling, excavation, etc.), instrument deployment, payload offloading, dexterous manipulation, and regolith handling for In-situ Resource Utilization.

Maximizing the useful life of surface assets is essential to a successful lunar program. Material components must be robust and tolerate extreme temperature swings and endure harsh environmental effects due to solar events, micrometeorite bombardment, and abrasive lunar dust.

Proposals are sought for the following technology needs:

- Low-mass, high-strength, long-life, non-pneumatic wheel assembly capable of spreading the supported load over a large 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. Low psi contact patch. Minimal deformation of wheel under varying terrain makeup. Minimal rolling resistance. High performance in 4-sigma soil. 10,000 km expected life. 40K to 400K operating temperature range. Supports 100x its own mass.
- Active and passive damping materials for suspension components that provide extended range of motion (45 degrees in pitch), extreme temperature tolerance (40K to 400K), reactive rates of 1-3 msec, and withstand torsional forces of 3000 N-m.
- Active suspension components that reclaim and store energy absorbed through the suspension system.
- Fluid and electrical connectors that can be repeatedly mated and de-mated (5000+ cycles) without failure in a contaminating environment consisting of regolith (abrasive dust) grains ranging in size from 100um down to 10um. Capable of carrying up to 10kw of power transmission or withstanding up to 3000psi pressures.
- Low power sensors for inspection and surface navigation and obstacle avoidance that are not adversely affected by the accumulation of lunar dust on the sensor. Developing robust sensor technologies will enable mobility assets to execute automated path planning, automated driving, and obstacle avoidance.
- Robot user interfaces enabling more efficient interaction with robots, facilitating situational awareness and telepresence, and reducing the amount of interaction effort required to operate robots. Appropriate user interfaces will support humans and robots operating in a shared space, close but separated, line-of-sight remote, and ground control remote. Particular interest is given to systems that robustly support robot

operations with up to 10 seconds of communications delay.

- Modular implements for digging, collecting, transporting and dumping lunar soil. The excavation rates are in the order of 50 kg/hr for regolith mining for O₂ production and 300 kg/hr for Site preparation tasks. Total amounts of regolith required are 100 tons for O₂ production and over 2,000 tons for a full outpost deployment. Excavation capabilities involve excavation and collection of both unconsolidated and consolidated surface regolith. Regolith Excavation includes tasks such as clearing and leveling landing areas and pathways, buildup of berms (2.5 m high) and burying of reactors or habitats for radiation protection (2 m deep), and regolith transportation for oxygen production (500 m distance) . Robotic excavation hardware must be able to operate over broad temperature ranges (40 K to 400 K) and in the presence of abrasive lunar regolith and partial-gravity environments. Expectations for maintenance by crew must be minimal and affordable (annual cycle). Therefore, general attributes desired for all proposed hardware include the following: lightweight, abrasion resistant, vacuum and large temperature variation compatible materials, low power, robust/low maintenance, and minimize dust generation/saltation during operation.
- Large surface area, i.e., 100 m X 100 m, soil stabilization/solidification techniques to prevent dust and regolith disturbances/ejecta from vehicular or suited EVA traffic (7 - 70 kilopascal bearing pressure).

Sub Topics:

Surface System Dust Mitigation Topic X6.02

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.

Lunar lander and surface systems will likely employ common hatch and airlock systems for docking, mating, and integration of spacecraft, habitat, EVA, and mobility elements. The large number of EVAs will require hatches that are safe if non-pressure assisted, and do not have to be serviced or replaced regularly. Lunar lander and surface systems will require materials and mechanisms that do not collect dust and do not abrade when in contact with lunar regolith. Technologies are also needed to remove lunar regolith, including dust, from materials and mechanisms. Lunar Surface systems will require EVA compatible connectors for fluid, power, and other umbilicals for transfer of consumables, power, data, etc. between architecture elements that will maintain functionality in the presence of lunar regolith, including dust. Lunar surface systems (power, mobility, communications, etc.) will require gimbals, drives, actuators, motors, and other mechanisms with required operational life when exposed to lunar regolith, including dust. Radiators and other thermal control surfaces for lander and surface systems must maintain performance and/or mitigate the effects of contamination from lunar regolith, including dust.

Also included in the technical scope is the development of lunar regolith simulants. Simulants that are properly designed, analyzed, and produced are critical to understanding the effects of dust on humans and mission critical subsystems and how to handle and utilize regolith on the lunar surface. Proposals are requested in technology areas that improve simulant fidelities, reduce simulant manufacturing costs and schedules, and improve on simulant development processes and characterization techniques and methods.

Lunar Regolith Simulants

- Should cost
- Should cost
- Be producible in quantities up to 30 tons/year;
- Have reproducible production processes;
- Have particle size distributions representative of lunar regolith from 0.5 to 1000µm in size.

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.

Mechanical Systems

- Should achieve
- Should achieve dynamic seal wear life of 20 million cycles;
- Should achieve 300% improvement in bearing life (frictional torque vs. time) relative to lubricated SOA bearings contaminated with lunar fines.

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.

Materials and Coatings

- Should demonstrate reduced initial contamination (>90%) compared to conventional materials;
- Should demonstrate improved efficiency of cleaning processes (>99% removal of initial contamination) without damage.

Another area of interest encompassed by this subtopic is alternative technologies for lunar dust removal that may be used in a variety of lunar surface applications. Both manual and automated cleaning systems are sought and may be derived from any or a combination of particle removal forces appropriate for use on the lunar surface.

Cleaning Systems

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- Should demonstrate >99% removal of dust contamination. Tolerable contamination levels will be application specific.

Research should be conducted to demonstrate technical feasibility during Phase 1 and show a path to hardware or production demonstration in Phase 2. When possible, a demonstration unit or material quantity should be delivered for functional and environmental testing and characterization and evaluation at the end of Phase 2.

Sub Topics:

Advanced Space Rated Batteries Topic X7.01

Advanced battery systems are sought for use in Exploration mission applications including power for landers, rovers, and extravehicular activities. Areas of emphasis include advanced cell chemistries with the aggressive mass and volume performance improvements and safety advancements in human-rated systems over state-of-the-art lithium-based systems. Rechargeable cell chemistries with advanced non-toxic anode and cathode materials and nonflammable electrolytes are of particular interest.

The focus of this solicitation is on advanced cell components and materials to provide mass and volume improvements and safety advancements that contribute to the following goals:

- Specific energy (cell level) >300 Wh/kg at C/2 and 0°C;
- Energy density (cell level) >600 Wh/l at C/2 and 0°C;
- Operating Temperature Range from 0°C to 30°C;
- Tolerance to abuse such as overcharge and over temperature conditions;
- Calendar life >5 years; cycle life 250 cycles at 100% depth of discharge.

Systems that combine all of the above characteristics and demonstrate a high degree of safety are desired. Cell safety devices such as shutdown separators, current limiting devices that inhibit or prevent thermal runaway, cell venting, and flame or fire; autonomous safety features that result in safe, non-flammable, non-hazardous operation especially for human-rated applications are of particular interest. Safety features that enhance the performance of high-power/high-rate cells that operate at >30°C discharge rates are also of 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:

Surface Nuclear Power Systems Topic X7.02

NASA is interested in the development of highly advanced systems, subsystems and components for use with fission and isotopic systems to power habitats, resource production, and mobility systems on the Moon and Mars. Nuclear 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. Isotopic technologies that improve the utilization of a limited fuel supply and have extensibility to fission systems are sought. Performance goals include reducing overall system mass, volume and cost, and increasing safety and reliability.

Specific technology topics of interest are:

- High efficiency (>20%) power conversion at 900 K;
- Electrical power management, control and distribution (1-5 kV);
- High temperature, low mass (2) radiators, liquid metal/liquid metal and liquid metal/gas heat exchangers (>90% effectiveness) and electromagnetic pumps (>20% efficiency);
- Deployment systems/mechanisms for large radiators (~3m x 15m);
- High temperature (>900 K) materials or coatings compatible with local soil and atmospheric environments;
- Systems/technologies to mitigate planetary surface environments including dust accumulation, wind, planetary atmospheres, corrosive soils, etc.;
- System designs to provide autonomous control for 10-year operation, including sensor and control technologies;
- Radiation tolerant systems and materials enabling robust, long life operation.

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:

Fuel Cells for Surface Systems Topic X7.03

Advanced primary fuel cell and regenerative fuel cell energy storage systems are baselined to provide descent power for the Altair lander and stationary power for lunar bases. Technology advances that reduce the weight and volume, improve the efficiency, life, safety, system simplicity and reliability of PEM fuel cell, electrolysis, and regenerative fuel cell systems are desired. Proposals are sought which address the following areas:

Advanced Conductive Fuel Cell Water Separator

Research directed towards improving the water separating capability of a planar separator internal to each fuel cell in a fuel cell stack. Proposals directed at developing such advanced separator materials must meet the following criteria to be considered relevant.

The separator:

- Must be wettable with water, and have a contact angle less than 30 degrees;
- Must allow water to penetrate and be transferred through the plane of the separator at a rate of at least 0.33 grams of water per hour per square centimeter of separator planar area;
- Must not permit gas vapor to penetrate through the separator up to at least 30 psid (i.e., a bubble pressure point of at least 30 psid);
- Must be electrically conductive, and have a resistivity of no more than 7.0×10^{-3} Ohm-cm;
- Ideally should be compatible with a fuel cell fabrication process step that occurs at 1000°C with a compressing force of at least 600 psi. (The separator will not need to operate at these conditions, but could be subjected to these conditions during fuel cell fabrication). This bullet is not a requirement but a desirable characteristic.

Hydrogen/Oxygen Dual Gas Pressure Regulator

Research directed towards improving the regulators that regulate hydrogen and oxygen gases down to a usable pressure for the fuel cell. The regulated pressure needs to be controlled so that the pressure differential between the gases is within a few psi. NASA is interested in developing a single mechanical component which functions as a dual gas regulator that can reliably regulate these gases from high pressure source (>500psi) down to

Advanced Electrocatalyst Materials for Fuel Cells and Electrolyzers

Research directed towards improving the kinetics of oxygen reduction and oxygen evolution. Nano-phase, high-surface area unsupported platinum-alloys, incorporating cobalt, nickel and iron are potential candidates for improving the kinetics of oxygen reduction. Oxides of ruthenium and iridium are particularly promising electrocatalysts for the oxygen evolution reaction. In addition to performance, the new materials must exhibit durability for over 10,000 hours of operation with no more than 20% loss in performance. Proposals directed at developing such advanced nano-phase materials, understanding composition/property relationships, and demonstrating their characteristics in operating fuel cells will be considered directly relevant to achieving the long-term goals of the Explorations Missions.

- Fuel cell MEA efficiency >75% (>0.92volts) @ 200 mA/cm²;
- Electrolysis MEA efficiency >85% (2.

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:

Cryogenic Fluid Transfer and Handling Topic X8.01

This subtopic solicits cryogenic storage and transfer technologies to enable NASA Exploration goals. This includes a wide range of applications, scales, and environments on ground, in orbit, and on the Lunar or Martian surface.

Specifically:

- Passive thermal control for ZBO (zero boil-off) storage of cryogens for both long term (>200 days for LOX/LH₂) on the lunar surface and short term (14 days for LH₂, LOX) on orbit. Insulation for both ground and flight.
- Active thermal control for long term ZBO storage for lunar surface and space applications. Technologies include 20 K cryocoolers for Mars missions, cryocooler integration techniques, heat exchangers, distributed cooling, and circulators. Scavenging of residual propellants.
- Zero gravity cryogenic control devices including thermodynamic vent systems, spray bars and mixers, and liquid acquisition devices.
- Advanced spacecraft valve actuators using piezoelectric ceramics. Actuators that can reduce the size and power while minimizing heat leak and increasing reliability.
- Propellant conditioning and densification technologies for Earth based applications, scaled for Altair or EDS tanks. Destratification technologies and recirculation systems for homogeneous tank loads. Reliability and operability upgrades over past densification systems.
- High capacity liquid oxygen pump systems capable of delivering high quality of liquid over a wide flow range between 500 GPM to 2000 GPM are sought. Special emphasis on variable control pumping, parallel pumping, system reliability and robustness, and advanced pump sealing technology is needed.
- Liquefaction of oxygen on the Lunar surface, including passive cooling with radiators, cryocooler liquefaction, or open cycle systems that work with HP electrolysis. Efficiency, mass savings, and reliability upgrades are needed. Heat pumps, switches, and heat pipes to control energy flow at low temperatures. Deployable radiators and radiation shields.

Sub Topics:

Cryogenic Instrumentation for Ground and Flight Systems Topic X8.02

This subtopic includes technologies for reliable, accurate cryogenic propellant instrumentation needs in-space, on the lunar surface, and on the Earth. Innovative concepts are requested to enable accurate measurement of cryogenic liquid mass in low-gravity storage tanks, to enable the ability to detect in-space and on-pad leaks from the storage system, and to address other cryogenic instrumentation needs. Cryogenic propellants such as hydrogen, methane, and oxygen are required for many current and future space missions. 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.

Propellant mass gauging provides accurate measurement of cryogenic liquid mass (LH_2 , LO_2 , and LCH_4) in low gravity storage tanks, and is critical to allowance of smaller propellant tank residuals and assuring mission success. Both low-gravity gauging (measurement uncertainty

Leak detection technologies impact cryogenic systems for space transportation orbit transfer vehicles, lunar surface, and launch site ground operations. These systems will be operational both in atmospheric conditions and in vacuum with multiple sensor systems distributed across the vehicle or a region of interest to isolate leak location. Methane and hydrogen leak detection sensors with milli-second response times and 1 ppm detection sensitivity in air are desired for ground and launch operations.

Other cryogenic instrumentation needs include:

- Miniature cryogenic pressure sensors (0 - 1 atm) for use under MLI blankets.
- Zero dead-volume in-line pressure sensors for use in liquid hydrogen flow streams.
- Real-time in-situ measurements of ppm levels of N_2 , O_2 , and H_2O in gaseous helium purge streams. Sensors that can survive the temperature range 20 K - 300 K and the vibration loads on a launch platform are especially desired.
- Minimally intrusive in-situ measurements of liquid hydrogen and liquid oxygen purity levels in real time. The goal is to accurately measure cryogenic propellant liquid purity levels (99% - 100% purity) in ground test stands during test operations. Helium and nitrogen impurity levels are of specific interest, but the sensors must be able to measure overall purity level of the cryogenic liquid.
- Minimally invasive cryogenic liquid flow measurement sensors for rocket engine feed lines, and sensors to detect and quantify two-phase flow (bubbles) within the feed lines.
- Non-intrusive flowmeters for high-pressure (up to 6,000 psi) gaseous helium distribution lines are sought for flow rates ranging from a trickle flow up to 1500 SCFM. Ultrasonic clamp-on flowmeters are especially desired, but must be able to sense the flow through 2" Schedule-XX pipe (0.436" wall thickness).
- Position indicators and long life application of the instrumentation for deep space missions.

Sub Topics:

Ablative Thermal Protection Systems Topic X9.01

The technologies described below support the goal of developing higher performance ablative TPS materials for higher performance CEV as well as future Exploration missions.

- Developments are sought for ablative TPS materials and heat shield systems that exhibit maximum robustness, reliability and survivability while maintaining minimum mass requirements, and capable of enduring severe combined convective and radiative heating, including: development of acreage materials, adhesives, joints, penetrations, and seals. Two classes of materials will be required.
 - One class of materials, for Mars aerocapture and entry, will need to survive heat fluxes of 200-400 W/cm^2 (primarily convective) and integrated heat loads of up to 25 kJ/cm^2 . These materials or material systems must improve on the current state-of-the-art recession rates of 0.25 mm/s at heating rates of 200 W/cm^2 and pressures of 0.3 atm and improve on the state-of-the-art areal mass of 1.0 g/cm^2 required to maintain a bondline temperature below 250°C.
 - The second class of materials, for Mars return, will need to survive heat fluxes of 1500-2500 W/cm^2 , with radiation contributing up to 75% of that flux, and integrated heat loads from 75-150 kJ/cm^2 . These materials or material systems must improve on the current state-of-the-art recession rates of 1.00 mm/s at heating rates of 2000 W/cm^2 and pressures of 0.3 atm and improve on the state-of-the-art areal mass of 4.0 g/cm^2 required to maintain a bondline temperature below 250°C.
- In-situ heat flux sensors and surface recession diagnostics tools are needed for flight systems to provide better traceability from the modeling and design tools to actual performance. The resultant data will lead to higher fidelity design tools, risk reduction, decreased heat shield mass and increases in direct payload. The heat flux sensors should be accurate within 20%, surface recession diagnostic sensors should be accurate within 10%, and any temperature sensors should be accurate within 5% of actual values.
- Non Destructive Evaluation (NDE) tools are sought to verify design requirements are met during manufacturing and assembly of the heat shield, e.g. verifying that anisotropic materials have been installed in their proper orientation, that the bondline as well as the TPS materials have the proper integrity and are free of voids or defects. Void and/or defect detection requirements will depend upon the materials being inspected. Typical internal void detection requirements are on the order of 6-mm, and bondline defect detection requirements are on the order of 25.4-mm by 25.4-mm times the thickness of the adhesive.
- Advances are sought in ablation modeling, including radiation, convection, gas surface interactions, pyrolysis, coking, and charring. There is a specific need for improved models for low and mid density as well as multi-layered charring ablators (with different chemical composition in each layer). Consideration of the non-equilibrium states of the pyrolysis gases and the surface thermochemistry, as well as the potential to couple the resulting models to a computational fluid dynamics solver, should be included in the modeling efforts.

Technology Readiness Levels (TRL) of 4 or higher are sought.

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.

This subtopic is also a subtopic for the "Low-Cost and Reliable Access to Space (LCRATS)" topic. Proposals to this subtopic may gain additional consideration to the extent that they effectively address the LCRATS topic (See topic O5 under the Space Operations Mission Directorate).

Sub Topics:

Advanced Integrated Hypersonic Entry Systems Topic X9.02

The technologies below support the goal of developing advanced integrated hypersonic entry systems that meet the longer term goals of realizing larger payload masses for future Exploration missions.

- Advanced integrated thermal protection systems are sought that address: (1) thermal performance efficiency (i.e., ablation vs. conduction), (2) in-depth thermal insulation performance (i.e., material thermal conductivity and heat capacity vs. areal density), (3) systems thermal-structural performance, and (4) system integration and integrity. Such integrated systems would not necessarily separate the ablative TPS material system from the underlying sub-structure, as is the case for most current NASA heat shield solutions. Instead, such integrated solutions may show benefits of technologies such as hot structures and/or multi-layer systems to improve the overall robustness of the integrated heat shield while reducing its overall mass. The primary performance metrics for concepts in this class are increased reliability, reduced areal mass, and/or reduced life cycle costs over the current state of the art.
- Advanced multi-purpose TPS solutions are sought that not only serve to protect the entry vehicle during primary planetary entry, but also show significant added benefits to protect from other natural or induced environments including: MMOD, solar radiation, cosmic radiation, passive thermal insulation, dual pulse heating (e.g., aero capture followed by entry). Such multi-purpose materials or systems must show significant additional secondary benefits relative to current TPS materials and systems while maintaining the primary thermal protection efficiencies of current materials/systems. The primary performance metrics for concepts in this class are reduced areal mass for the combined functions over the current state of the art.
- Integrated entry vehicle conceptual development is sought that allow for very high mass (> 20 mT) payloads for Earth and Mars entry applications. Such concepts will require an integrated solution approach that considers: TPS, structures, aerodynamic performance (e.g., L/D), controllability, deployment, packaging efficiency, system robustness / reliability, and practical constraints (e.g. launch shroud limits, ballistic coefficients, EDL sequence requirements, mass efficiency). Such novel system designs may include slender or winged bodies, deployable or inflatable entry systems as well as dual use strategies (e.g., combined launch shroud and entry vehicle). New concepts are enabling for this class of vehicle. Key performance metrics for the overall design are system mass, reliability, complexity, and life cycle cost.
- Advances in Multidisciplinary Design Optimization (MDO) are sought specifically in application to address combined aerothermal environments, material response, vehicle thermal-structural performance, vehicle shape, vehicle size, aerodynamic stability, mass, vehicle entry trajectory / GN&C, and cross-range, characterizing the entry vehicle design problem.

Technology Readiness Levels (TRL) of 4 or higher are sought.

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.

This subtopic is also a subtopic for the "Low-Cost and Reliable Access to Space (LCRATS)" topic. Proposals to this subtopic may gain additional consideration to the extent that they effectively address the LCRATS topic (See topic O5 under the Space Operations Mission Directorate).

Sub Topics:

Cryogenic and Non-Toxic Storable Propellant Space Engines Topic X10.01

This subtopic intends to examine a range of key technology options associated with cryogenic and non-toxic storable propellant space engines. The primary mission for the engines 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, methanol, monopropellants, or other non-toxic fuel blends. Key performance parameters:

- Reaction control thruster development is in the 25-500-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 3,500-8,000-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:

- Non-toxic fuel blends or monopropellants that meet performance targets while improving safety and reducing handling operations as compared to current state-of-the-art storable propellants.
- Low-mass propellant injectors that provide stable, uniform combustion over a wide range of propellant inlet conditions.
- High temperature materials, coatings and/or ablatives for injectors, combustion chambers, nozzles and nozzle extensions.

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- 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 propellant valves that tolerate space and lunar environments with reduced volume, size, and weight is also desirable.
 - Cryogenic instrumentation such as pressure and temperature sensors that will operate for months/years instead of hours.

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:

Crew Exercise System Topic X11.01

Human space flight is associated with losses in muscle strength, bone mineral density and aerobic capacity. The ability to estimate the physical cost of exploration tasks, monitor crew health and fitness, and to provide effective hardware for exercise countermeasures use will be valuable in supporting safe and successful space exploration.

Exercise Systems is seeking technologies or devices to provide resistive and aerobic exercise in flight.

- Compact, reliable, multi-function exercise devices/systems are required 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 2 times per 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 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 such that post-mission muscle strength is maintained at or above 80% of baseline values. The same device must be capable of providing whole-body aerobic exercise levels necessary to maintain aerobic capacity at or above 75% of baseline VO₂max. Finally, the ideal device should also stimulate the sensory-motor system which controls balance and coordination.
- Identify compact, multi-function exercise devices to protect muscle and cardiovascular health during lunar sortie missions (missions with a total duration of less than 30 days). This device must be 20 lbs or less including all accessories (or demonstrated to be within this allotment for a flight unit if the ground prototype exceeds 20 lbs), 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 can be stowed within 1 cubic foot of space

aboard the Orion vehicle. The device must require no crew calibration or maintenance (for missions less than 30 days), require minimal deployment/setup time (easily portable between vehicles), and ideally 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.

Phase 1 Requirements: a fully developed concept, complete with feasibility analyses and top-level drawings. A breadboard or prototype is highly desired.

Sub Topics:

EVA Suit Simulator Topic X11.02

Human space flight is associated with losses in muscle strength, bone mineral density and aerobic capacity. The ability to estimate the physical cost of exploration tasks, monitor crew health and fitness, and to provide effective hardware for exercise countermeasures use will be valuable in supporting safe and successful space exploration.

Exercise Systems is seeking technologies or devices to simulate an Extra Vehicular Activity (EVA) suit on the ground.

A wearable system that simulates the mechanical properties of the current extravehicular activity (EVA) space suit is sought. System should be lightweight (less than 30 pounds), easy to don/doff (especially in the supine position), replicate the mechanical properties of a space suit (in terms of resistance to motion and mass and inertia), and able to be worn during conduct of simulated lunar tasks that last up to 4 hours. Suit system must be adjustable to accommodate individuals of different height and weight. Joints of primary interest to simulate in this system are the shoulder, elbow, trunk, hip, and knee.

Phase 1 Requirements: a fully developed concept, complete with feasibility analyses and top-level drawings. A breadboard or prototype is highly desired.

Sub Topics:

Crew Autonomy Assessment for Exploration Topic X12.01

The NASA Behavioral Health and Performance Program Element (BHP) identifies and characterizes the behavioral health and performance risks associated with training, living and working in Space, and return to Earth. BHP develops strategies, tools, and technologies to mitigate these risks. Currently, BHP has the need for behavioral health and assessment tools relevant to autonomy during Exploration Missions.

The aim of the current task is to identify the optimal level of autonomy by providing a tool that will objectively and unobtrusively measure both crew autonomy and its relevant outcomes (performance, empowerment, satisfaction, cohesion, etc.). The technologies will be able to provide data for BHP to interpret how changes in crew autonomy during a mission influence the relevant team outcomes that are measured.

Objectives:

- Determine optimal level of autonomy needed for different spaceflight missions or mission phases;
- Design and/or enhance unobtrusive tools that measure crew autonomy and its relevant team outcomes;
- Establish how autonomy levels change within and across missions;
- Interpret how these changes in autonomy influence important team outcomes.

Requirements: The Crew Autonomy Assessment shall:

- Be unobtrusive
- Require minimal crew time or effort
- Detect changes in team (ground and flight crew) autonomy and team outcomes (those that are chosen)

Phase 1 Requirements: Develop Requirements for Crew Autonomy Assessment

- An assessment of current methods through which to monitor/measure autonomy and relevant team outcomes within the DOD and other agencies will be provided;
- An assessment of current technologies that unobtrusively monitor crew autonomy and relevant team outcomes (if any) will also be conducted;
- Recommendations regarding enhancements to current technologies or the development of new technologies will be presented;
- The spaceflight environment (current and future) and models related to autonomy and its relevant team outcomes will be assessed in order to determine the optimal requirements for developing a Crew Autonomy Assessment suitable for NASA human space exploration.

Phase 2 Requirements: Crew Autonomy Assessment Prototype developed based on accurate models and Phase 1 findings.

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- Develop prototype hardware;
 - Develop manual and troubleshooting guide;
 - Evaluate and test the functionality of the prototype device.

Sub Topics:

Behavioral Health Monitoring Tools Topic X12.02

The NASA Behavioral Health and Performance Program Element (BHP) identifies and characterizes the behavioral health and performance risks associated with training, living and working in Space, and return to Earth. BHP develops strategies, tools, and technologies to mitigate these risks. Currently, BHP has the need for behavioral health monitoring tools specific to the long duration Exploration Mission environment.

The aim of the current task is to provide requirements for a tool that will unobtrusively monitor behavioral health of the individual crew member while on a mission. The objective of this technology would be to monitor changes in behavioral health and automatically generate meaningful feedback for astronauts and flight surgeons, regarding their individual behavioral health status.

The technologies will unobtrusively monitor markers of behavioral health such as body language and voice acoustics (not including facial recognition software).

The technologies will provide meaningful feedback to the astronaut and flight surgeon regarding behavioral health status; if decrements in behavioral health are detected, the technologies should provide feedback regarding potential causes of decrements.

Requirements: The Behavioral Health Assessment Tool shall:

- Be unobtrusive and function autonomously;
- Require minimal crew time or effort to train and utilize;
- Monitor objective indications of behavioral health;
- Provide meaningful feedback to astronauts and flight surgeons regarding individual behavioral health status;
- If decrements are detected, the technologies shall provide meaningful feedback to astronauts and flight surgeons regarding potential causes of decrements and recommendations for potential countermeasures.

Phase 1 Requirements: Develop Requirements for Behavioral Health Monitoring Technology

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- An assessment of current methods through which to monitor behavioral health during autonomous missions within DOD and other agencies will be provided;
 - An assessment of current technologies that unobtrusively monitor behavioral health (not including facial recognition software) will also be conducted;
 - Recommendations regarding enhancements to current technology or the development of a new technology will be presented;
 - The spaceflight environment (current and future) and models related to behavioral health will be considered in order to develop requirements for a Behavioral Health Monitoring Technology suitable for NASA human space exploration missions.

Phase 2 Requirements: Behavioral Health Monitoring Technology Prototype developed based on accurate models and Phase 1 findings.

- Develop prototype hardware/software;
- Develop manual and troubleshooting guide;
- Evaluate and test the functionality of the prototype device.

Sub Topics:

An Automated Tool for Human Factors Evaluations Topic X13.01

This subtopic calls for a Small Business Innovative Research project to develop an automated tool to assist non-human factors engineers to conduct human factors evaluations. Human factors evaluations are essential in gathering human performance data and analyzing the usability of new design concepts. These evaluations are generally carried out by human factors experts due to the level of expertise required. However, in some cases, it would both save time and cost if a tool is available for non-human factors engineers to carry out a standardized evaluation procedure to obtain the needed data and with comparable quality.

The tool therefore shall provide a comprehensive set of measurement methods and guide non-human factors engineer to carry out human factors evaluations. The tool development shall include defining a comprehensive set of commonly used human factors evaluation methods that allow engineers to gather relevant human factors data. Through a user-friendly interface, the tool shall recommend evaluation metrics, provide step-by-step guidance for setting up the evaluation, and summarize/store evaluation data. The ability for the tool provide interfaces for human factors data acquisition systems is highly desirable.

An algorithm for the tool is expected as the deliverable for Phase 1 and a prototype is expected should the project continue on to Phase 2.

Sub Topics:

Situational Awareness for Multi-Agent Operations Topic X13.02

This subtopic calls for a Small Business Innovative Research project to develop a situation awareness and conflict resolution tool for a wide-area multi-agent operation environment with substantial time delays. Humans and robots in future Lunar or Mars surface operations would be operating both on the Lunar (Mars) surface and on Earth remotely to carry out a common task. Consequently, substantial communication delay would make tasks planning and execution difficult. The goal of this SBIR is to develop a tool so multiple agents can work harmoniously regardless of geographical locations.

The tool therefore shall overcome the hurdle of communication delays and (1) enable situation awareness by providing timely information of tasks conducted by other agents, (2) ensure that newly generated procedures mesh well with the originally scheduled activities, (3) allow operators to poll state data from all agents at any moment, and (4) provide recommendations for best task planning and procedures.

An algorithm for the tool is expected as the deliverable for Phase 1 and a prototype is expected should the project continue on to Phase 2.

Sub Topics:

Advanced Food Technologies Topic X13.03

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.

It will require approximately 10,000 kg of packaged food for a 6-crew, 1000 day mission to Mars. The packaged food will require that the safety, nutrition, and acceptability are maintained at reasonable levels for the entire 5-year shelf life. Therefore, this subtopic request will concentrate on technologies that use a systems approach to provide food in remote locations with limited mass, volume, power, and waste is required.

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 technologies that will allow these raw ingredients to maintain their functionality and nutrition for 5-years. This food system would also 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.

There are some unique parameters that need to be considered when developing the technologies. 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. In addition, there also will not be any significant refrigerator or freezer available.

The response to this subtopic should include a plan to develop a technology that will enable safe and timely food processing and food preparation in reduced cabin pressure and reduced gravity.

Phase 1 Requirements: Phase 1 should concentrate on the scientific, technical, and commercial merit and feasibility of the proposed innovation resulting in a feasibility report and concept, complete with analyses and top-level drawings.

Sub Topics:

Active Charged Particle and Neutron Radiation Measurement Technologies Topic X14.01

For exploration class missions, there is extraordinary premium on compact and reliable active detection systems to meet very stringent size and power requirements. NASA requires compact, low power, active monitors that can measure charged particle spectrum and flux separately from neutrons and other radiations. Also, NASA requires compact active neutron spectrometers that can measure the neutron component of the dose separate from the charged particles. Advanced technologies up to technology readiness level (TRL) 4 are requested in the following areas:

Charged Particle Spectrometer

Measure charge and energy spectra of protons and other ions ($Z = 2$ to 26) and be sensitive to charged particles with LET of 0.2 to 1000 keV/m. For Z less than 3, the spectrometer should detect energies in the range 30 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. Design goals for mass should be 2 kg and for volume, 3000 cc. The spectrometer should be able to measure charged particles at both ambient conditions in space (0.01 mGy/hr) and during a large solar particle event (100 mGy/hr). The time resolution should be less than or equal to 1 minute. The spectrometer shall be able to perform data reduction internally and provide processed data.

Neutron Spectrometer

Measure neutron energy spectra in the range of 0.5 MeV to 150 MeV. Measure neutrons at ambient conditions such that proton/ion veto capability should be approaching 100% at solar minimum GCR rates; measure ambient dose equivalent of 0.02 mSv in a 1 hour measurement period, using ICRP 74 (1997) conversion factors; store all necessary science data for post measurement data evaluation. Design goals for mass and volume should be 5 kg and 6000 cc, respectively.

Sub Topics:

Miniature Radiation Pulse Processing Electronics Topic X14.02

For Exploration class missions, there is extraordinary premium on compact and reliable active detection systems to meet very stringent size and power requirements. Miniaturized electronics for radiation pulse processing would be important to help reduce size/power needs. Very small technologies (chips) are developed by the computer industry that may be adaptable to process radiation induced pulses from detectors to provide multi-channel analysis (MCA) and other analysis functions with very low power and size requirements. This is a need for NASA as power and size requirements are severely tightened on future missions to the Moon and beyond. Advanced technologies up to technology readiness level (TRL) 4 are requested in this area.

The miniature processor must not exceed 0.2 W of power and have a volume not to exceed 20 cc. A communication interface, such as USB or other serial interface, is required. A fast clock rate is required, not less than 100 MHz. An analog-to-digital converter, minimum sample rate of 10 M samples per second. Could be part of chip or on the same board with chip. Requires adequate pulse height measurement to perform MCA, e.g., peak hold, digital waveform processing, or other approach. MCA should cover the input pulse height range of .002 to 10 volts (or equivalent) in either 100 channels on log scale or in two linear spectra of not less than 250 channels each with different gains.

Sub Topics:

Alternative Methods for Ambient Preservation of Human Biological Samples during Spaceflight and Lunar Operations Topic X15.01

Measurement of blood and urine analytes is a common clinical medicine practice used for differential disease diagnosis and determination of the therapeutic response to treatment. Accurate biochemical results depend on maintaining the integrity of blood and urine samples until analyses can be completed. Improper sample collection, handling, or preservation may lead to critical errors in diagnostic interpretation of analytical results. Traditional methods have been developed that include the use of sample component separation by means of centrifugation, refrigeration, freezing or the addition of preservatives to maintain the integrity of biological samples. While such techniques are easily achieved in a routine clinical setting, the spaceflight environment presents unique challenges to sample processing and stowage. Thus, novel on-orbit methods for the ambient preservation of biological samples are critical for scientific research, monitoring of crew health and evaluation of countermeasure efficacy. The development of alternative innovative techniques with advantages over currently used methods for processing and preserving biological samples at ambient temperatures during spaceflight that provide a high level of reliability in maintaining a wide array of both blood and urine analytes over a long period of ambient stowage is highly desirable.

Sub Topics:
