The goals of this topic are to develop advanced space communications and networking technology; high-performance computers and computing architectures for space systems and data analysis; low-power electronics to enable robotic operations in extreme environments; and imaging sensors for machine vision systems and the characterization of planetary resources. Subtopics of this topic area include:

**In-Space Computing and Reconfigurable Electronics.** This subtopic includes architectures and components required for space-based computing and avionics systems. Architecture efforts will emphasize modular, fault-tolerant approaches that leverage commercial standards and COTS devices. Component work will focus on capabilities for enhancing general- and special-purpose processing to meet multiple mission goals. Products of particular interest include reconfigurable electronics, fault-tolerant, reconfigurable processor, micro-controllers and storage devices.

**Extreme Environments/Low Temperature Electronics.** This subtopic includes radiation-tolerant, wide-temperature-range digital, analog, mixed signal, dynamic member and RF electronic components, and integrated modules suitable for operation in the extreme environments of the Moon, Mars and other deep space destinations. Efforts will emphasize supporting electronics for sensors, actuators and communications. The focus of this subtopic is radiation-tolerant, analog, mixed signal, dynamic memory and RF electronic components, and integrated modules suitable for operation in extreme low-temperature space environments.

**Sensing and Imaging.** This subtopic includes orbital remote sensing for topographical and resource mapping and atmospheric profiling and control-loop sensing for robotic functions such as rendezvous and docking, assembly and construction, and precision landing. Products of particular interest include control-loop sensors for position, velocity and force, rapid detection and readout arrays for 2D and 3D imaging at 1.5 µm and multi-wavelength IR and visible laser arrays.

**Surface Networks and Access Links.** This subtopic includes communications technologies to support operational activities in space beyond low Earth orbit and on planetary surfaces in which nodes are simultaneously connected to each other, to Earth, and to the CEV via in-space relay orbiters, and via wired and wireless networks providing the bidirectional voice, video and data needed. The focus of this subtopic is on the modular, reconfigurable RF communications and networking technologies needed to support a human presence on remote lunar and planetary surfaces with short-range networks and access links to long-haul systems.

Sub Topics:

X1.01 In-Space Computing and Reconfigurable Electronics
The goal for this subtopic is the development of advanced space technology to further high-performance computers and computing architectures and reliable electronic systems that can operate effectively for long periods of time in harsh environments. These systems require management of low power and radiation, and must be reliable, robust and reconfigurable.

The objective for this development goal is to elicit novel architectural concepts and component technologies that have realistic potential and achievable applications and are responsive to the priority areas of this subtopic. Technologies will be selected based on the potential that their final end products are sustainable (affordable, reliable/safe and effective), and will advance solutions to the challenges of reusability, modularity and autonomy. Priority areas are:

**Data processing**

- General purpose processors (piece part, rather than an entire board) possessing fault tolerance at cell and or die levels, floating point and error correction.
- Technologies that reduce the physical size and power requirements of computing systems: making the data system more adaptable, modular, and cost effective.
- New standard models for analysis of interplanetary radiation and radiation belts, and technologies that enable radiation measurements such as total dose and single event effects in computing systems: enhances capability to design radiation tolerant data systems, monitor systems in flight, and predict errors and contingencies.

**Reconfigurable Electronics and Implementations**

- Reconfigurable designs and architectures that support fault tolerance and are functionally and physically modular.
- Solutions, designed around generic blocks, for recovery from multipoint failures (as opposed to single fault) component failure, where a system can monitor and identify the failing components, and self-repair or bypass small portions of the electronics. These prioritized generic blocks would enable graceful degradation of higher functions while maintaining the system core functionality.

**Data System Support Electronics**

- Radiation-hard microcontrollers, phase lock loops (PLL), and high-speed oscillators (greater than 150 MHz, equal duty cycle).
- FPGA: Environmentally tested, reliable, tolerant IO, radiation hardened cell structures, Anti-Fuse or reconfigurable.
- Robust and reliable non-volatile storage devices such as EEPROMs and FLASH memory.
Command and Data Transfer

- Inter-system data transfer communications between spacecraft subsystems based on standard interfaces that address high multi-drop throughput (10 to 100 mbps), self diagnosis, inherent redundancy and low power, and support subsystem data transfer to realize higher autonomy.

- Intra-system data transfer communications within the spacecraft subsystems, between cards within a box, to replace the conventional passive backplanes, e.g., switched fabric backplanes with fault detection and serial interfaces.

X1.02 Extreme Environment Electronics/SEE

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

Moon equatorial regions experience wide temperature swings from -180°C to +130°C during the lunar day/night cycle, and the sustained temperature at the shadowed regions of lunar poles can be as low as -230°C. Mars diurnal temperature changes from about -120°C to +20°C. All exploration endeavors, including robotic, habitat, and ISRU systems that are expected to reliably operate on the Moon or Mars surface for years will need electronics that are able to survive and operate in a wide temperature range and thermal-cycling environment. The lunar and Martian temperatures are well outside the specification range of military and commercial electronics. While many types of devices, especially Si CMOS transistors, can operate down to low temperatures. There are significant circuit design challenges that need to be addressed, especially in the case of mixed signal and analog circuits.

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

Proposals are sought in following specific areas:

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

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

- Wide temperature (-180°C to +130°C) and ultra-low temperature (-230°C) RF electronics for short range and long-range communication systems.
- Computer Aided Design (CAD) tools for predicting the electrical performance, reliability, and life cycle for low-temperature electronic systems and components.

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

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**X.1.03 Sensing and Imaging**

**Lead Center:** JPL

**Participating Center(s):** GSFC, LaRC

Sensing and imaging systems can provide a number of capabilities required for anticipated NASA missions including exploration of Mars and the Moon. Capabilities of interest include the following:

- Orbiting sensors to map:
  - Extent and concentration of useful, surface, or subsurface resources to identify promising outpost or science sites and traversable terrains;
  - Surface topography and roughness to identify promising safe landing sites for human, robotic science, and pre-provisioning missions, and to guide pinpoint landing algorithms.

- Robot-mounted sensors for: estimating robot pose and motion; recovering 3D scene structure; identifying hazards or objects of interest; identifying articulation of observed objects, and performing visual serving. Flight ready (radiation and temperature hardened), high cycle rate, and low power systems are generally preferred. Applications include:
  - Autonomous rendezvous and docking;
  - Pinpoint landing;
  - Surface navigation;
  - Surface and on-orbit assembly/construction;
  - Resource mining/processing;
  - Multi-vehicle cooperation.
Specific technologies of interest in addressing these challenges include:

- Rapid frame rate arrays for 1, 1.5 and 2 µm vision (2D and 3D);
- Multi-wavelength laser arrays;
- Flight-ready, high-speed, medium-resolution (640x480) stereo-vision sensors;
- Flight-ready, low-power lighting systems (headlights) to allow imaging during nighttime robotic operations;
- Tightly coupled inertial and vision sensors for pose estimation;
- Ground truthing systems for evaluating performance of ranging systems.

A number of related technologies are of interest but are covered under other subtopics, including:

- High power or high rep-rate lasers (S6.02, S1.04);
- Ultra-high sensitivity detectors and arrays (S4.01);
- Active and passive microwave sensors (S6.04, S6.05).

X1.04 Surface Networks & Access Links

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

To develop safe and sustainable exploration capabilities at minimum cost, while maximizing return, an incremental spiral development process will guide a build out of an integrated communication, navigation, networking, computing, informatics, and power architecture that supports all surface and proximity nodes, including humans in spacesuits, robots, rovers, human habitats, satellite relays, and pressurized vehicles.

The architecture will enable operational activities in which both fixed and mobile nodes with vastly differing communications requirements are seamlessly interoperable. Nodes are simultaneously connected to each other, to Earth, and to the CEV via in-space relay orbiters, and via wired and wireless networks that provide the bidirectional voice, video, and data needed. The need to be self-sufficient during exploration requires local control and an unprecedented level of autonomous operation to seamlessly connect the nodes and reduce operations cost. The Moon and Mars environments require SEU and extreme temperature-tolerant equipment tightly constrained by power, mass, and volume. Human presence requires at least one usable bidirectional link to the communications network at all times and high definition video to engage the public interest.

This subtopic focuses on the modular, reconfigurable RF communications and networking technologies needed to
support a human presence on remote lunar and planetary surfaces with surface-to-surface and surface-to-orbit (access) communications.

**Surface Networks**

The complexity of astronaut excursions, habitats, surface manned and unmanned rovers, and landers make surface operations and man-occupation complex and daunting tasks. Exploration of planetary surfaces will require short-range, bidirectional, multi-point links to provide on-demand, autonomous interconnection among surface-based assets. Some of the nodes will be fixed (base stations) and some will be moving (rovers and humans). This will encompass a number of communications and networking technologies for communications in the 2.4 Ghz range, including: integrated low mass, low power (100’s of milliwatts) transceivers for very short-range interfaces with sensors and other small devices; power-efficient, miniature, modular transceivers for short-range communications among large (e.g., lander) and medium-sized (e.g., rover) surface assets; reconfigurable directionally selectable, multi-frequency arrays for wide coverage, high-gain links among surface assets; miniaturized modular antenna technology for surface-to-surface communications among mobile and fixed nodes; wireless products integrated with low-power space-rated ASICs and FPGAs; short (~ 1km) range access point base stations, or wireless router bridges for extending surface network coverage; fixed, long (~ 50km) range, wireless network terminals for extending high data rate communications over large distances; self-healing ad-hoc network MAC and protocols for intelligent, autonomous link management; and networking technologies to enable autonomous, seamless interconnectivity among all nodes.

**Access Links**

To interface with orbiting relays, terminals capable of providing seamless connectivity between surface networks and orbiting relays will be positioned on lunar and planetary surfaces and in orbit. Such an access link communications system will include: high rate, efficient, solid state amplifiers capable of very high data rates over 1,000-10,000 km distances with ranging signals embedded; very low-power data rates, and cost inter-spacecraft S-band transceivers/transponders for inexpensive spacecraft; optical transceivers capable of very high data rates over 1,000-10,000 km distances; SEU and solar flare tolerant transponders capable of: programmable wide-carrier frequency ranges from S-band to Ka-band, taking GPS measurements, and handling IP at the digital level; micro software radio technology for autonomous and intelligent space applications; low mass, volume, power, and cost-stable oscillators to provide accurate time and frequencies for autonomous operations; autonomously reconfigurable receivers capable of automatic link configuration and management; microwave ranging hardware built into communication systems for rendezvous and collision avoidance; and ad hoc long range spacecraft-to-spacecraft network protocols to setup links on demand, such that each node can route data through to another node.
The goals of this topic are to develop high-performance materials, fabrics, modular vehicle structural concepts, and mechanical components for exploration systems. Major technology drivers include reducing system cost, mass, and launch volume; enabling the construction of space and surface infrastructure from modular elements; extending the performance and lifetime of systems operating in extreme environments; and providing systems with integrated diagnostic and adaptive capabilities. This topic is responsible for basic technology level research, development, and testing through experimental and/or analytical validation of novel materials and structural concepts for a wide range of exploration applications. The three subtopics include Advanced Materials and Mechanisms, Structures and Habitats, and Nanotechnology.

Sub Topics:

X2.01 Advanced Materials

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

Technology areas included in this subtopic are high performance, super lightweight structural materials, space-durable materials, multifunctional materials, and flexible material systems. Materials of interest include ceramics, metals, polymers, and their composites as well as coatings for erosion resistance and environmental protection. Proposals with innovative and revolutionary ideas in the area of advanced materials are sought for explorations applications such as:

- Flexible fabrics and thermal insulation for spacesuits and habitats;
- High strength-to-weight and high temperature composite materials for lightweight vehicle structures and power and propulsion systems;
- Self-healing materials to repair damage to spacesuits, habitats, and wire insulation electronics, sensing, and actuators for monitoring system health and adapting to changing mission conditions;
- Flexible fabrics relevant to mission needs such as inflatable systems for ballutes, habitats, airbags, parachutes, and suits;
- Innovative approaches to materials systems yielding durable, lightweight, flexible films and fabrics.

X2.02 Structures and Habitats

Lead Center: LaRC
Participating Center(s): AFRC, JSC, MSFC

This subtopic solicits innovative structural concepts, materials, and assembly techniques that support the development of modular space systems. Also needed is a criteria to judge the different concepts in terms of impact on the overall performance and weight. Structural concepts can include inflatable, erectable, deployable, or easily connected modules to create large space structures utilizing membranes, composites, or other material concepts. Modular units can provide reconfigurable structures, such as multiple-energy configurations using cables and linkages, compliant structures or mechanisms that adapt to varying surfaces, or multi-purpose integrated structures, such as load-bearing modular power distribution, thermal management, or radiation protection systems. Additionally, this subtopic includes research related to novel rotating devices, actuators, tribology, and seals. It further includes intelligent structural, electrical, and fluid interfaces to enable the assembly (or ‘self-assembly’) of modular systems.
Of particular interest are inflatable structures and habitats to minimize launch volume and costs. Large inflatable structures can be folded into compact packages for launch, pressurized for deployment once in space, and rigidized after deployment so that internal pressure is not required to maintain structural stiffness and shape.

New concepts, materials, and methods for in-space structures and habitats to enable humans to safely and effectively live and work in space are needed. Specifically, structures or habitats with integral radiation shielding, impact shielding, thermal management, and integral diagnostics/health monitoring capabilities are of interest as well as high strength-to-weight materials (e.g., foamed materials), structural elements, and beams that can be deployed or fabricated in situ. Development of smart and multifunctional modular structures, including the use of embedded sensors and actuators, is encouraged.

Also solicited are assembly technologies such as innovative connectors for joining and/or bonding techniques, module positioning and alignment concepts, component deployment or erection concepts, and component/module inspection and verification techniques. Structures and materials that support reconfigurable modular architectures are also solicited.

Modeling and structural testing techniques and analyses that support the design of modular structural concepts or their assembly are of interest. Two areas are of particular interest: one is controls-structures interaction (CSI) techniques and the second one is hybrid-test and physics based-modeling approaches. Application of advanced controls-structures interaction (CSI) techniques for measuring and controlling structural dynamics and geometry are important. Solutions for incorporation of CSI techniques for controlling such inflatable structures are also highly desirable. On hybrid modeling, ways to integrate test and physics-based models for cases where the physics-based models are not sufficient is also desirable.

X2.03 Nanostructured Materials

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

The applications of advances in Nanotechnology are anticipated to have a profound impact on NASA’s future missions by offering significant advantages in terms of cost affordability and reliability from multifunctional materials. Nanotechnology enables systems performance beyond those expected from conventional materials. While many fundamental findings are reported in the literature, there is a strong need to focus efforts on the demonstration of real benefits provided by nanostructured material systems.

It is especially interesting to meet exploration challenges with the development of high strength-to-weight and multifunctionality possible from the unique combinations of desirable properties of the nano-structured materials. The promise of high strength-to-weight, multi-functional, nano-structured materials has led to intense interest in developing them for near-term applications for human spaceflight and exploration.
Nano-structured materials of interest include, but are not limited to, the utilization of single wall, carbon, nanotube-based composites, ceramic nanofibers, and bio/nano-inspired materials and composites.

Due to the size scale and fundamental physical properties of the structures involved, a successful proposal for applications development should demonstrate a mature understanding of nano-material synthesis and material quality, as well as incorporate the development and use of new characterization methodologies to fully assess the impact of the nano-structured materials upon a given matrix or system.

The specific focus of this subtopic will include, but not be limited to:

- New materials for structures and components offering significant mass reduction and increased strength with improved thermal conductivity, low permeability, low density, and improved damage tolerance through self-repairing mechanisms;
- Application of nano-structured materials to self-healing and self-repair materials and concepts;
- Nano-structured materials offering enhanced radiation protection;
- Development of nano-material systems that are resistant to large thermal fluctuations, radiation, electrostatic charging, abrasion, and micrometeoroid debris damage;
- Nano-materials for energy generation, storage, and distribution.

Power Propulsion and Chemical Systems (PPCS) Topic X3

The goals of this topic are to develop high-efficiency power conversion/generation, energy storage, and power management and distribution systems to provide abundant power for long-duration, sustainable, human and robotic exploration missions as well as systems for the storage and handling of cryogens and other propellants. The subtopics include: Power Generation and Transmission, Energy Storage, and Cryogenic and Thermal Management.

Sub Topics:

**X3.01 Power Generation & Transmission**

Lead Center: GRC

Participating Center(s): JPL, MSFC

All innovative technologies for power generation and conversion are highly encouraged under this subtopic. Proposals addressing technologies, including solar photovoltaic conversion, thermo-photovoltaic conversion, thermoelectric conversion, and thermodynamic conversion (heat engines), etc., are encouraged. In addition, research and technology development in topics related to advanced power cabling and power management are...
Also needed.

Significant improvements in photovoltaic systems are required to enable future exploration missions. Dramatic increases in array mass specific power (>1000 W/kg), reductions in stowed volume, increases in operational voltages to 1000V, increases in radiation hardness enabling reliable operation in high-radiation environments, increases in survivability over wide temperature extremes, as exists on a lunar surface, and developments of automated deployment systems for surface power applications. Developments are sought for photovoltaic cells on flexible, ultra-lightweight substrates, array technologies that maintains the high mass specific power of these cells, nanostructures incorporated to enhance the performances of thin-film, organic/inorganic, or single-crystal photovoltaic cells and thermo-photovoltaic cells. Demonstrations of high efficiency, lightweight, concentrator cell and supporting array techniques, multi-quantum well and multi-quantum dot devices, and advanced multi-band gap devices are also of interest. Advanced photovoltaic areas of emphasis include high-efficiency quantum well technology. Nano-engineered materials are an area of emphasis for all of these applications.

High power solar dynamic power conversion systems, including Brayton and Stirling, support the development of solar-electric propulsion and power systems requiring low overall system specific mass (kg/kW). The objectives for solar dynamic systems, with power output capacities ranging from 100W to >100kW, require demonstrating thermal efficiencies greater than 30% over a range of cycle temperature ratios and heat rejection temperatures. A system specific mass of

Technological advances are needed for large deployable solar concentrators and secondary concentrators, high temperature heat receivers with thermal energy storage capability, and advanced lightweight heat rejection sub-systems. For Brayton power, advances are needed in ceramic high temperature turbine technology, high efficiency compressors matched to turbine performance, high efficiency alternators, lightweight carbon composite heat exchangers and recuperators.

For Stirling, advances required are: high frequency, low inductance linear alternators, low mass displacer, hot-end materials and structures, efficient cold-end thermal integration with lightweight radiators, high efficiency low mass controllers, and regenerators.

For power management and distribution systems, areas of emphasis include: high reliability, light weight, radiation-hardened power electronic components (semiconductor switches, diodes, capacitors, and transformers); high voltage switching contactors (>100Vdc) tolerant to corona discharge; and high efficiency (>95%) modular DC converters for boost and buck conversion. Concepts for monitoring power system status, fault tolerance, redundancy, and energy management. Advanced power cabling including high voltage, superconductors, carbon nanotube, and cable mbedded with structural elements. Also of importance are, intelligent and modular distribution switchgear and power management that can autonomously reconfigure in response to faults and changing loads.

Research for Wireless Power Transmission (WPT) technology development, to reduce the cost of electrical power and to provide a stepping stone to NASA for delivery of power between objects in space, between space, and surface sites, between ground and space, and between ground and air-platform vehicles. WPT can involve lasers or microwaves along with the associated power interfaces. Microwave and laser transmission techniques have been studied with several promising approaches to safe and efficient WPT identified. These investigations have included microwave phased array transmitters, as well as visible light laser transmission, and associated optics. There is a need to produce "proof-of-concept" validation of critical WPT technologies for both the near-term as well as far-term applications. These investments will be harvested in near-term, beam-safe demonstrations of commercial WPT applications. Proposals are sought that include such activities as the technology elements, architecture, and demonstration programs for wireless transmission of power. Receiving sites (users) include
ground-based stations for terrestrial electrical power, orbital sites to provide power for satellites and other platforms, future space elevator systems, and space-based sites for spacecraft and space vehicle propulsion.

X3.02 Energy Storage

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

All exploration missions require advanced primary and rechargeable energy storage devices that are high-density, have long-life capability, and have the ability to function at extreme temperatures. The energy storage requirements vary significantly from a few watt-hours (astronaut equipment) to hundreds of kilowatt-hours (human outposts), depending on the mission. Similarly, power requirements also vary from a few watts (astronaut equipment) to several kilowatts, depending on the mission (human rovers, human outposts, and crew exploration vehicles).

Advanced energy storage devices, such as primary batteries, rechargeable batteries, fuel cells, and flywheels are required to enable future robotic and human exploration missions. Advanced primary batteries are required for applications such as astronaut equipment, communication devices, \textit{in situ} resource utilization systems, sensor networks, etc. Advanced rechargeable batteries are required for solar powered landers and rovers, solar powered human outposts, astronaut equipment, and spacecraft. Primary fuel cells are required for crew exploration vehicles and rovers. Regenerative fuel cells provide an enabling, mass-efficient solution for surface electrical energy storage for future long-duration human exploration of the lunar and Mars surfaces. Flywheels provide an effective solution to meeting peak power requirements when used in hybrid systems with battery or fuel cell systems providing the base power, and offer the capability of integrated power and attitude control.

Energy Storage devices are needed for EVA and EVA accessory applications as well as vehicle and base back-up or peaking power applications. Areas of emphasis include advanced battery materials and cell designs with the potential to achieve the performance and safety advancements required for manned applications. Hybrid systems consisting of fuel cells, batteries, flywheels, and/or ultra capacitors are of interest. Also sought are high energy density fuel cell reactant storage innovations compatible with the performance and safety goals specified herein. Micro and nano-engineered materials are an area of emphasis for all of these applications. Proposals addressing micro-batteries, and integrated power generation and storage are sought.

Primary and rechargeable lithium-based batteries with advanced anode and cathode materials and advanced liquid and polymer electrolytes and solid-state systems are of particular interest. Technology advancements that contribute to the following performance goals are sought: specific energy >180 Wh/kg, calendar life (>15 years), and a wide operating temperature range (-60°C to 60°C). Primary batteries with the following performance targets are of interest: low temperature operation capable of delivering >30% of their ambient temperature capacity at temperatures as low as -100°C, specific energy: >400 Wh/kg, long calendar life >15 years, and high rate capability >C/10.

Fuel cell (FC) and regenerative fuel cell (RFC) systems with power capabilities in the range of 100-1000 watts and 2-10kW are of interest. Technological advances are sought that FC/RFC based systems with the following characteristics: specific energies: FC >1500 W/kg, RFC >600 Wh/kg. Efficiencies: FC>70% at 1500 W/kg, RFC >60% at 600 Wh/kg, and lifetimes: FC >10,000 hours, RFC >1500 cycles. Concepts that incorporate passive
operation and advanced reactant storage options (example: \( \text{H}_2, \text{O}_2 \)) are sought.

Advanced fuel cell development should include proton exchange membrane fuel cells (PEMFC - high and low temperature), regenerative fuel cells (RFC), and solid oxide fuel cells (SOFC). PEMFC areas of emphasis include long-life stacks and systems with emphasis on gravity-independent water management within the stack or elsewhere in the system, passive water separators, and passive reactant recirculation devices. RFC areas of emphasis include long-life, high-efficiency PEMFCs and electrolyzers. SOFC areas of emphasis include the capability to utilize CO/CO\(_2\) and methane fuels for power generation.

Flywheel technology areas of interest are: system configuration concepts for high specific energy (>100Wh/kg for systems >500Whr and >50Wh/kg for systems 600 Wh/kg, and/or concepts that integrate energy storage, momentum storage, and spacecraft structure are sought.

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**X3.03 Cryo & Thermal Management**

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

This subtopic includes technologies for waste heat management, movement, and rejection; technologies including lightweight and/or high-temperature radiators, heat pipes, heat sinks, etc. Also includes cryo-coolers and related low-temperature systems. These technologies will impact space solar power systems, spacesuits and habitation systems, robotics, and surface systems.

Spaceport operations, both on Earth as well as extraterrestrial, are heavily dependent upon a wide range of cryogenic systems, including liquid oxygen, liquid nitrogen, liquid helium, and supercritical breathing air. Each above application has unique performance requirements that need to be met. Sizes of these systems range from the small (3400 m\(^3\) for LOX and LH\(^2\) ground propellant storage). Advanced cryogenic technologies are being solicited for all these applications. Proposed technologies should offer enhanced safety, reliability, or economic efficiency over current state-of-the-art, or should feature enabling technologies to allow NASA to meet future space exploration goals. Technology focus areas are divided as follows: passive systems, storage and distribution components, refrigeration systems, advanced instrumentation, and advanced operational concepts.

Cryogenic propellants such as hydrogen, methane, and oxygen are required for many current and future space missions. Operating efficiency and reliability of these cryogenic systems must be improved considering the launch environment, operations in a space environment, and system life, cost, and safety. Innovative concepts are requested for cryogenic insulation systems, fluid system components, and instrumentation. Although this subtopic solicits unique and innovative concepts in the cryogenic components and instrumentation areas, there is an emphasis at this time for:

- Advanced thermal switches to isolate heat transfer from a de-powered cryocooler;
• Advanced low-gravity submersible pumps designed specifically for moving cryogen heat that enters the tank wall to the heat exchanger coupled to the cryocooler;

• Advanced tank support systems capable of supporting tanks during the launch environment, but decoupling on-orbit to minimize thermal loads;

• Advanced cryocoolers which are reliable, lightweight, and capable of removing significant heat at liquid hydrogen temperatures;

• Low heat leak cryogenic quick disconnects capable of sealing against the vacuum of space;

• Long-life, low power valves capable of sealing at cryogenic temperatures and being cycled many times without consuming pressurant gas;

• Liquid acquisition devices capable of preventing gas ingestion into engine feed lines in low gravity;

• Methods for cryogenic fluid acquisition and transfer in zero gravity;

• Methods of determining liquid remaining in propellant tanks in low gravity;

• High accuracy differential pressure transducers, which can be read submerged in liquid cryogen;

• On-orbit leak detectors;

• Lightweight, low-power temperature sensors which can be placed internally to the storage tank with a minimum number of feed-throughs;

• New technology valves for cryogenic applications, including LOX, LH\textsuperscript{2} and LHe, that minimize thermal losses and pressure drops. Components include shutoff and flow-control valves. Valves should be adaptable to electromechanical actuation and range in size from ½ to 6 inches;

• Integrated heat exchangers in large-scale storage systems designed to provide for zero boiloff and densification of liquid hydrogen and liquid oxygen;

• Advanced low-temperature materials for cryogenic containment;

• Insulation materials capable of retaining structural integrity while accommodating large operating temperatures ranging from cryogenic to elevated temperature conditions.

Thermal management systems are needed for the rejection of heat to hot environments for daytime operations on the lunar surface, large space radiators to dissipate heat from power and propulsion systems, thermal control for mobile systems, cryogenic propellant storage and handling for in-space refueling, and long-term cryogen storage for propellant depots.

Thermal management concepts include advanced heat sinks, heat pipes, and interface materials with high thermal conductivity that are electrically isolative. Innovative methods of increasing the specific thermal capacitance of the power systems are also sought:

• Qualified heat pumps to reject heat to hot environments;

• Multi-zone thermal control systems for spacesuits and mobile systems;
• Lightweight deployable low temperature radiators for use on the lunar surface;

• Concepts for the thermal management of advanced power system component designs for operation in deep space, lunar, and Martian environments.

Advanced Studies Concepts and Tools (ASCT) Topic X4

The goal of this topic is to develop ESR&T (Exploration Systems Research and Technology) tools that advance the SOA (State-Of-Art) for: the study of revolutionary exploration system advanced concepts, system technologies, and architectures; the prioritization of mission enabling technologies; systems engineering analysis, which reduces mission risk; systems design and analysis; and the conduct of exploratory research and development for emerging technologies. The projects to be selected are expected to challenge SBIR companies to take on research projects with higher technology development risk and higher potential payoff than they would, otherwise; and, in addition, are judged to be likely to provide new capabilities to meet NASA’s strategic goals and objectives for Exploration Systems. Projects must press the state-of-the-art, display a high degree of innovation, and involve significant technical challenges. Projects must be technically feasible, but the proposer should not assume that the lower the technical risk in a project, the greater the probability that it will be funded. Component-related, system-related, and process-related projects are all of interest. Subtopics of this ASCT topic area include: Technology Systems Analysis Tools - this subtopic includes the development of advanced tools to support: advanced concept analysis; systems architecture analysis; emerging systems technology analysis; technology portfolio assessment and forecast analysis; campaign analysis; technology databases; advanced concept development risk and cost modeling; etc. This subtopic encompasses support for technology road map definition. Systems Design and Analysis Tools - this subtopic includes the development of advanced tools for implementing: an advanced modeling and systems simulation environment; integrated analysis for assessing potential system engineering impacts of new technologies; design and analysis databases; system engineering models; engineering discipline analysis; system level risk analysis; probabilistic risk analysis (PRA); reliability, maintainability, and availability analyses; human factor analysis; life cycle cost analysis; and other systems engineering Figures of Merit (FOM) analyses. This ASCT topic is currently focusing on developing advanced tools, which enable the following:

• Study of revolutionary exploration system advanced concepts, technologies, and architectures;

• Exploratory research and technology in the full range of technical fields related to space exploration;

• Integrated modeling and simulation of exploration systems and mission risk.

Sub Topics:

X4.01 Technology Systems Analysis

Lead Center: GRC

Participating Center(s): JPL

The goal of this subtopic is to develop new tools to ensure that advanced technology investments are guided by
appropriate analyses. These analyses are needed in areas involving all of the various element programs within ESR&T. The analyses will support the definition of technology road maps for ESR&T.

The scope of Technology Systems Analysis Tools includes the development of advanced tools to support technology systems analyses, such as: portfolio analysis; campaign analysis; system technology architecture impact analysis; advanced concept analysis; sensitivity analysis; verification and validation analysis; development cost analysis; and the population of advanced technology databases and information systems. The ASCT analyses planned will be performed using low-fidelity/high-level techniques. They will focus on entry level technologies and notional architectures. Higher fidelity assessments will be performed using ESMD (Exploration Systems Mission Directorate) Simulation Based Acquisition (SBA) resources.

This Technology Systems Analysis Tools subtopic is currently focusing on developing advanced tools which enable the following:

- Conducting exploratory research and development of emerging technologies and advanced concepts with high potential payoff;
- Performing architecture, campaign, and technology analyses to identify and inform portfolio development for relevant exploration applications;
- Technology analysis to identify and prioritize mission enabling technologies;
- Architecture, mission, advanced concept, and technology risk analysis;
- Technology databases, roadmaps, and portfolio development;
- Exploration and implementation of different advanced concepts development methodologies and techniques to enable more effective and efficient study development;
- Development of advanced concepts analyses and sensitivity analyses that can incorporate the full range of technical fields related to space exploration;
- Analysis of advanced concepts, advanced technologies, and portfolio analysis;
- Campaign analysis including the synthesis and analysis of many missions, architectures and competing capabilities and technologies against FOMs;
- Technology analysis that identifies SOA and levels of performance metrics associated with cost- and risk-dependent chronologies (technology datasheets);
- Advanced concept and system technology verification and validation;
- Effective techniques for presenting tradeoffs and recommendations to decision-makers.
The goal of this subtopic is to maximize the credibility of the integrated systems analysis efforts being performed within ASCT by providing validated systems design, system analysis, and systems engineering tools. This will include the development of tools to produce: a modeling and simulation environment, design and analysis databases, system engineering models, engineering discipline analysis, parametric-based risk analysis, and probabilistic risk analysis (PRA), etc. This effort will closely coordinate with and support the development of the Simulation Based Acquisition (SBA) system in support of Exploration System Mission Directorate (ESMD) program acquisition and analysis.

The scope of System Design and Analysis Tools includes tool development activities in the following areas: advanced systems simulation modeling environment; design and analysis databases and system models; performance and structural sizing; SBA advanced systems engineering tools for mid-technology level simulation and visualization of life cycle cost, risk, reliability, supply chain logistics, maintainability, availability, and other system engineering Figures of Merit.

This subtopic is currently focusing on the following technology areas:

- Systems engineering tools and discipline analysis tools in support of Simulation Based Acquisition. See ESMD-RQ-0025, ESMD-RQ-0026 and SBA Strategy in the Crew Exploration Vehicle Procurement Bidder's library (http://exploration.nasa.gov/acquisition/cev_procurement.html [1]) for additional information.
- Advanced engineering tools that integrate performance, risk, and cost modeling.
- Development of system engineering tools that implement new analytical methodologies and techniques in support of both ESR&T and SBA activities.
- Advanced systems simulation modeling environment that includes database technologies and data collection tools.
- Seamless integration of design tools, modeling tools, simulation tools, and other systems engineering tools via standards-based software interoperability.
- Novel approaches to assessing the performance, cost, or risk of proposed mission architectures.
- Techniques for characterizing and optimizing investments in Modeling and Simulation.
- Methods to extend and reuse models and simulations over the program lifecycle.
- Model-based techniques for optimizing designs in distributed, multi-organization, multi-contract design teams.
This SBIR Topic seeks innovative concepts for technologies that will reduce life-cycle mission costs by providing high-confidence design of onboard autonomy, including safe and reliable human autonomy interaction. NASA is preparing for human-robotic exploration of the Moon and Mars. Traditional means of providing system information, such as inspections and preventive maintenance, have limited utility for exploration missions. Other solutions, such as telemetry data, become less useful as communication bandwidth shrinks and communication delays increase. Under these circumstances, increasing the autonomy of the onboard systems provides the best means of managing system operations. Autonomous onboard system technologies involve the use of goal-oriented operations, requiring means for sensing the environment and making intelligent choices with regard to resources, procedures, health and safety, logistics, and configuration. The Software, Intelligent Systems and Modeling (SISM) Element program will develop and test reliable software, autonomous and human-robotic systems, and model-based methods for design, analysis, and operations. SISM is being formulated in collaboration with several ESRT Technology Maturation Program elements (for example, Advanced Space Operations, Lunar and Planetary Surface Operations, and Advanced Space Platforms and Systems), as well as the Human-Systems Integration Program in HSRT. In addition, this Element Program is cognizant of on-going FY04 SBIR tasks in related areas, such as advanced modeling and simulation. To focus the role of this SBIR Topic within the overall scope of SISM, there will be an emphasis on concepts that reduce life-cycle costs by increasing the usability of key classes of advanced design methods and tools. The key classes of methods and tools are defined by the two subtopics, Software Engineering (X5.01) and Human-Autonomy Interaction (X5.02). These kinds of design and test technologies have made great advances during the past ten years, but the usability of the technologies, and therefore their actual impact, has lagged behind their potential impact.

Sub Topics:

**X5.01 Software Engineering**

*Lead Center: ARC*

*Participating Center(s): GSFC, JSC*

The objective of this subtopic is to bring to fruition software engineering technologies that enable engineers to cost-effectively develop and maintain NASA mission-critical software systems. Particular emphasis will be on software engineering technologies for sustaining engineering: achieving affordable reliability over successive spirals of mission software development, maintenance, and upgrades for Crew Exploration Vehicle and Project Constellation. A key requirement is that projects address the usability of software engineering technologies by NASA (including NASA contractors) engineers, and not only specialists.

Many of the capabilities needed for successful human exploration of space will rely on software. In addition to traditional capabilities, such as GNC (guidance, navigation, and control) or C&DH (command and data handling), new capabilities are under development: integrated vehicle health management, autonomous vehicle-centered operations, automated mission operations, and mixed human-robotic teams to accomplish mission objectives. These capabilities will be needed in exploration spirals 2 and 3, including the extended lunar missions. Ensuring that these capabilities are reliable and can be developed and maintained affordably, will be challenging but critical to both the lunar missions and the subsequent Martian missions. Proposals should clearly indicate how the technology is expected to address the challenge of reliability and affordability. Mission phases that can be addressed include not only the software life-cycle (requirement engineering through verification and validation) but also upstream activities (e.g., simulation-based acquisition for software capabilities; mission planning that incorporates trade-space development of software-based capabilities) and post-deployment (e.g., new approaches for computing fault tolerance; rapid reconfiguration, and certification of mission-critical software systems).

Software engineering tools and methods that address reliability for exploration missions are sought. Projects can address technology development and maturation that provide for the following and related capabilities:
Software-based radiation fault tolerance for computation;

Methods and tools for development and validation of autonomic software systems (systems that are self protecting and self healing);

Automated software generation methods from engineering models that are highly reliable;

Scalable verification technology for complex mission software, e.g., model-checking technology that addresses the 'state explosion' problem and static-analysis technology that addresses mission-critical properties at the system level;

Automated testing that ensures coverage targeted both at the system level and software level, such as model-based testing where test-case generation and test monitoring are done automatically from system-level models;

Technology for calibrating software-based simulators and test-beds against high-fidelity hardware-in-the loop test-beds in order to achieve dependable test coverage; and

Technology for verifying and validating autonomy capabilities including intelligent execution systems, model-based diagnosis, and adaptive control.

A requirement for a sustainable and affordable human exploration presence in space is the need for modular, reusable elements and subsystems. Major subsystems (e.g., integrated vehicle health management) will present challenges in terms of software-based reconfigurability needed over a long sequence of missions. Projects can address technology development and maturation that provide for the following and related capabilities:

Software reuse for mission-critical, real-time applications;

Architectures that facilitate reconfiguration with upgraded components;

Affordable verification, validation, and certification of upgraded components and sub-systems within a system (or system-of-systems) context;

Intelligent management of software assets;

Middleware that enables software platforms to migrate to new hardware platforms (e.g., middleware that enables command and control software to be transparently ported to distributed grid and cluster computer platforms).

X5.02 Human Autonomy Interaction

Lead Center: JSC
Participating Center(s): ARC, GSFC
Autonomous and automated operations will be required for systems fulfilling the Vision for Space Exploration. This subtopic addresses the need for modeling and analysis tools and technologies for design, test, and evaluation of human-autonomy interaction systems. The tools will support analyses of scenarios, tasks, information, and communication. They can validate and build confidence in human-autonomy interfaces and interaction support by identifying and mitigating risks (e.g., workload, situational awareness, and error). The technologies will interoperate with models and tools for design, evaluation, and certification of hardware and software systems, and will support understanding by engineers and planners who are not experts in human-system design or human factors. They will be cost-effective to use and be easily updated and reconfigured to reflect changes in designs and plans.

The human-autonomy modeling and analysis technology will be applied to astronaut crew-autonomy and ground-crew-autonomy interactions in space missions. Autonomous systems can include exploration vehicles and subsystems, science stations, robots, robotic manipulators, rovers, and communications satellites. Autonomous operations can include rendezvous, proximity operations, mating of on-orbit elements, in-space assembly, maintenance, and robotic operations, including inspection, material transport, and sampling. These operations can be nominal, off-nominal, or contingency operations. Autonomy will be essential to ensure safe robot operation in the proximity of critical systems and humans. Autonomous functions can include science traverse and path planning, crew and resource scheduling, procedure execution, and control of subsystems such as power, thermal, propulsion, and communications.

Innovative human-autonomy modeling and analysis technologies are needed to address unique challenges of space missions. These include multi-modal interfaces, asynchronous communication with long delays and long blackouts, unanticipated problems, and rare crew interactions by exception. Human-autonomy interactions can include supervisory control, communication, and coordination in shared planning and operations. They can include interactions to adapt, modify, and maintain systems to respond to emerging requirements and challenges. The interactions can also include dynamic control and adjustment of level of autonomy or supervision, type of coordination, and type of communication.

This subtopic seeks projects that will demonstrate innovative technologies for use by engineering and operations teams for analyzing human-autonomy interactions and risks and for evaluating proposed mitigations of these risks, within the constraints of an affordable and timely mission design and planning process.

Advanced Space Operations (ASO) Topic X6

This Topic covers a range of key technology options associated with future space exploration systems and architectures that involve a variety of combinations of advanced robotic and human capabilities, ranging from remotely telesupervised robotic systems, through locally-teleoperated systems, to focused human presence (with robotic agent assistance). Technologies that enable in-space assembly, maintenance, and servicing are also included. Key objectives derive from the goals of safe/reliable, affordable, and effective future human and robotic space exploration in support of the U.S. Vision for Space Exploration. These efforts will be closely coordinated with
spacecraft subsystem, system, and related R&D within the Advanced Space Platforms and Systems Topic.

Sub Topics:

**X6.01 Intelligent Operations Systems**

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

The goal of this subtopic is to develop intelligent systems and technologies that could dramatically improve the affordability and productivity of long-duration human space operations, while preserving the high degree of safety and flexibility offered by state-of-the-art approaches. The current operations models used for the Space Shuttle and International Space Station, which require large ground teams continuously managing the daily operation of the spacecraft and the activities of the crew, are a major cost driver for these programs. As the human exploration campaign ventures farther into deep space, the communications time delays and longer-duration missions will require greater crew autonomy from Earth-based support. To achieve NASA's exploration goals, technologies are needed that can enable a new paradigm for human space operations.

### Intelligent Planning and Execution Systems for Crew Autonomy

Greater autonomy from Earth-based support implies that crewmembers will need to manage their exploration missions holistically. This will be possible only if automation helps the crew to integrate the complex interactions among many spacecraft subsystems efficiently and to manage and prioritize human and automated activities. Intelligent systems will need to be seamlessly integrated with operational procedures so that all the information required to make key decisions is continuously updated and presented to the crew in a rapidly comprehensible fashion. Crew interfaces (e.g., displays, voice recognition, etc.) will need to be intuitive and reliable. Validated, automated systems are needed that help a spacecraft/habitat crew coordinate and prioritize plans and execute nominal/off-nominal procedures in accordance with codified mission rules and objectives. These systems should improve upon capabilities already demonstrated in human space exploration missions (e.g., Space Shuttle and International Space Station).

To evaluate proposed intelligent systems technologies, it is important to identify measurable performance objectives. Such performance measures include: (1) the speed and ease by which astronauts can plan and schedule future activities and understand the consequences of exercising various planning options; (2) the reliability, speed, and ease by which astronauts can maintain comprehensive situational awareness of a complex spacecraft/habitat without cognitive overload; (3) the reliability, speed, and ease by which astronauts can derive (on demand, or in response to detection, of an off-nominal condition) sufficiently detailed knowledge of the spacecraft/habitat, to issue commands that isolate anomalies, perform recovery procedures, and make other safety/mission-critical decisions.

Modular designs that employ open architectures and interface standards are very important to assure cost-effectiveness and flexibility of intelligent operations systems. These architectures should promote extensibility/evolvability and accommodate future system upgrades. Such designs could include standalone tools that capture and manage corporate knowledge about manned spacecraft operations.

Also of interest, though of lesser priority, are innovative technologies that can significantly enhance ground operational efficiency and performance.

### Intelligent Modular Training Systems

Intelligent training systems are needed that enable flight crews to operate complex spacecraft safely and
effectively, retain proficiency during long-duration missions, adapt easily to an evolving and expanding set of flight systems during the course of the exploration campaign, and achieve flight certification faster and more cost-efficiently than is possible with existing systems. Plug-and-play crew training systems that employ open architectures and interface standards are very important. These architectures should promote extensibility/evolvability and accommodate future system upgrades. The intelligent training systems should enable connectivity with models from various sources, with simulated or flight data (real-time and archived), with students and teachers at multiple locations, and with various platforms including ground-based/desktop environments and in-space, zero-g/partial-g portable or control station systems. When integrated with an operational environment, these systems must demonstrate effectiveness while ensuring that the performance of the vehicle or facility is unaffected.

Focus should be on the following applications:

- Intelligent onboard technologies for human space exploration; and
- Intelligent human space exploration mission control technologies.

Note: Related technologies of interest but covered under other SBIR subtopics include:

- X5.01 Software Engineering;
- X5.02 Human Autonomy Interaction;
- X6.03 Launch Site Technologies (Launch site command and control system technologies); and
- X8.01 Vehicle Health Management Systems.

X6.02 Space Assembly Maintenance & Servicing

Lead Center: GSFC
Participating Center(s): JSC

The goal of this subtopic is to develop technologies that enable reliable and affordable in-space assembly, maintenance, and servicing for human and robotic exploration missions in Earth orbit and beyond. Systems that enhance crew safety and mission reliability by automating these functions (whether robotically, tele-robotically, or with integrated human/robotic teams) are needed. Technologies that enable robust and reliable Earth-orbit assembly of spacecraft components (both modular and non-uniform), and thus alleviate the difficulties of launching larger, pre-integrated payloads, are of particular interest. Long-duration maintenance and servicing systems that are modular and generically applicable to a variety of orbital or transfer exploration spacecraft are also of interest.

Focus should be on the following applications:
Earth-orbit assembly of large spacecraft systems (e.g. heat shields, propellant stages);

Autonomous inspection of spacecraft systems using either small free-flying inspection spacecraft or attached, highly-mobile inspection robots; and

Autonomous removal and replacement of failed spacecraft systems.

Specific technologies of interest in addressing these challenges include:

- Self-contained collision prevention/avoidance systems for robots (free-flying or attached) in close proximity to spacecraft, instruments, astronauts, etc.;

- Dexterous robotic end-effectors/manipulators for robotic assembly and maintenance, including systems that accommodate instability between robotics and target surfaces;

- Robotic non-destructive structural inspection technologies;

- Advanced robotic control systems (e.g., systems that provide active damping of robotic arms to reduce un-commanded motion, high degree-of-freedom (DOF) systems, systems that function in multiple mission environments, and systems that incorporate intuitive man-machine interfaces and/or virtual reality simulation);

- Robotic tele-operation control systems that accommodate latency and enable "real time" robotic operations;

- Vision systems for both autonomous and tele-robotic operations, including systems that demonstrate: autonomous and rapid object recognition, affordable zoom/focus lens control, robust spatial perception of working environments, ability to operate under various lighting conditions, economical video compression and 3-D mapping techniques, and low power autonomous visual inspection systems;

- Roboticall operable structural/precision interface attachment systems;

- Modeling of contact dynamics in zero gravity for capture and manipulation;

- Test beds to validate robotic systems, including 6-DOF simulated weightless testing; and

- Orbital mechanics optimization of libration point rendezvous for assembly and servicing.

Note: Related technologies of interest but covered under other SBIR subtopics include:

- Robot-mounted sensors for on-orbit assembly/construction (X1.03 Sensing and Imaging), and

- Plug-and-play avionics and attachment technologies for autonomous rendezvous and docking (X8.02 Intelligent Modular Systems).
X6.03 Launch Site Technologies

Lead Center: KSC

Participating Center(s): GSFC, MSFC

The purpose of this subtopic is to develop technologies and concepts that will improve launch processing safety through the use of automated systems with limited human contact; make launch operations more cost- and time-efficient through standardization, commonality, and interoperability of launch systems and spaceport infrastructure; and improve the flexibility and adaptability of spaceport infrastructure in order to accommodate multiple vehicle types and diverse missions. Improvements in launch site operations can enable airport-like efficiencies at reduced cost and shortened processing turnaround time, thereby contributing significantly to the goal of a sustained and affordable space exploration program. Additionally, advanced launch operations technologies and concepts that may significantly improve launch vehicle specific energy or otherwise improve launch performance, affordability, and sustainability for space exploration missions are of interest. Topic areas that will be emphasized for improvements in launch site operations include:

- Propellant handling systems: autonomous propellant loading; automated umbilicals; improved control of cryogenic mass loss; hazardous leak and flame detection; and improved cryogenic cooling, insulation, and sealing technologies;
- Common integrated command and control system technologies for launch site operations: ground integrated health management systems, work control, configuration management, and other support systems;
- Test equipment: universal avionics test equipment and automated and wireless built-in test equipment that reports launch vehicle and/or payload status;
- Launch acoustic modeling and mitigation systems; and
- Payload and launch vehicle systems handling equipment.

Modular designs that employ open architectures and interface standards are very important to assure cost-effectiveness and flexibility of launch site technologies. These architectures should promote extensibility/evolvability and accommodate future system upgrades. Topic areas related to advanced launch operations technologies and concepts include:

- Horizontal launch assist ground systems, including systems that preclude the need for vehicle take-off gear. Specific technology areas of interest include: vehicle acceleration mechanisms, vehicle structural support or levitation systems, control and stabilization systems, separation mechanisms, runway or track stability and maintenance systems, and energy storage and delivery systems; and
- Other novel launch operations technologies and concepts.
Focus should be on the following applications:

- Earth-based launch site systems for human and robotic space exploration missions.

Note: Related technologies of interest but covered under other SBIR subtopics include:

- X6.01 Intelligent Operations Systems.

High Energy Space Systems (HESS) Topic X7

This Topic covers a range of key technology options associated with future space exploration systems and architectures that are 'energy rich'-including high power space systems, highly efficient and reliable space propulsion systems, and the storage, management, and transfer of energy/propellants in space. It also addresses high-energy maneuvering including aero-entry, aero-braking, and other aero-assist related R&D. The affordable deployment of systems and logistics beyond low Earth orbit will depend on high-power space transportation. In addition, a broad range of future systems and technologies will be constrained or enabled by the availability (or lack) of significant power at an affordable cost.

Sub Topics:

**X7.01 Chemical Propulsion Systems and Modeling**

**Lead Center:** MSFC

**Participating Center(s):** AFRC, GRC

The goal of this subtopic is to develop innovative chemical propulsion systems and system concepts as well as modeling tools and capabilities that support chemical propulsion system design and analysis. Applications of interest include earth-to-orbit and in-space transportation, with a particular focus on versatile, multi-use in-space cryogenic engines with exceptionally high reliability, space-based reusability (i.e. capability for many restarts with little to no maintenance), and deep-throttling capability. These are needed for all phases of exploration missions, including trans-lunar injection, decent to the lunar surface, ascent to lunar orbit, and return to Earth. Also of interest are safe and affordable earth-to-orbit systems that enable high overall vehicle payload mass-to-liftoff mass ratios, with improvements in thrust-to-engine weight ratio, trajectory-averaged specific impulse, and overall reliability.

Specific areas of interest for technology advancement and innovations include:
Propulsion system design concepts that address LOX/LH$_2$, as well as LOX/CH$_4$ and other LOX/Hydrocarbon engine and main propulsion systems integration issues;

- Integrated chemical propulsion system concepts that integrate primary propulsion and reaction control system elements;

- Design and analysis tools that significantly enhance the overall systems engineering evaluation of advanced chemical propulsion system concepts. These include tools for sensitivity analysis, quantification of system benefits to changes, propulsion system operability, "bottoms up" weight estimating, cost estimating, and reliability prediction for propulsion systems;

- Manufacturing techniques that allow for significant reduction in the cost and schedule required to fabricate engine and main propulsion system components. These techniques can use current or emerging processes and manufacturing technologies to develop engine and main propulsion system components that will reduce complexity, increase reliability, and that are easier to assemble, install, and test when integrated onto the vehicle;

- Concepts for solid or hybrid rockets that increase mass fraction, decrease the need for thermal insulation, and reduce or eliminate the need for staging; and

- High-performance advanced propellants (as indicated by high specific impulse and high specific impulse density) and non-toxic propellants that can significantly improve safety and cost of propulsion systems operations.

Note: Related technologies of interest but covered under other SBIR subtopics include:

- X7.02 Chemical Propulsion Components
- X8.01 Vehicle Health Management Systems

**X7.02 Chemical Propulsion Components**

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

The goal of this subtopic is to develop innovative chemical propulsion component technologies that improve the safety, operability, reliability, and performance of propulsion systems required for human and robotic exploration missions. Components should be applicable to earth-to-orbit or long-duration in-space transportation systems (both primary propulsion and reaction control systems) for a variety of exploration mission phases, including trans-lunar injection, decent to the lunar surface, ascent to lunar orbit, and return to Earth.

System masses will be critical in these far-reaching missions, dictating the use of lightweight components and the use of propellants harvested or manufactured on the surface of the Moon, Mars, or other destinations-an approach known as *in situ* resource utilization (ISRU). Candidate ISRU propellants include hydrogen, oxygen, carbon monoxide, carbon dioxide, methane, various other hydrocarbons, and compounds derived from these materials.
In some scenarios, one propellant may be manufactured *in situ* while its oxidizer or fuel is brought from Earth. Because the use of ISRU propellants represents a departure from the state-of-the-art and from the existing base of engines and technologies, a new suite of propulsion system and component technologies will be required.

These new in-space propulsion systems are expected to encounter conventional challenges such as regulator leakage, valve leakage, valve heating (on pulsing engines), solubility effects (such as combustion instabilities caused by gas bubble evolution in liquid propellants), and propellant acquisition (i.e., extracting gas-free propellant from the tank and delivering it to the engine). In-space chemical propulsion systems that incorporate long-term use of cryogenic propellants such as hydrogen, methane and oxygen present new challenges, including efficient, reliable, and durable propellant cryocooling, storage, acquisition (from tanks), transfer (through feed lines), gauging and flow measurement; however, these particular challenges are addressed by a separate sub-topic, X3.03 Cryo and Thermal Management.

Chemical propulsion component technologies that demonstrate improved capabilities using a variety of propellant combinations are of interest, including:

- Advanced turbopumps with wider throttle range and improved cavitation control, plus specific turbomachinery components such as bearings, turbines, and impellers that demonstrate greater reliability and lifetime;
- Injectors with low thermal mass and long-duration reliability (e.g. for high duty-cycle attitude control thrusters);
- Long-life combustion chambers (e.g., based on use of advanced materials);
- Innovative thruster valve designs that tolerate high thermal loading due to heat soak-back during pulse mode operation;
- Innovative concepts for fast acting valves to enable use of larger thrusters for small impulses (i.e. spacecraft fine pointing);
- Highly-reliable long-duration seals;
- Long-life, high-reliability ignition systems;
- Lightweight, highly reliable gas compressors for pumping gaseous propellant into pressure vessels either in-flight or on a terrestrial surface;
- Novel pressurization approaches that minimize dissolution of pressurant gas in storable propellants (e.g., nitrogen tetroxide, hydrazine, and hydrazine derivatives)
- Novel concepts that increase performance or decrease mass of pressurization systems;
- Development of advanced materials that exhibit high compatibility with gaseous oxygen;
- Propulsion components based on microelectromechanical systems (MEMS) technology;
- Advanced nozzle concepts for in-space propulsion systems;
• Reaction control system thrusters that burn *in situ* and non-toxic propellants;

• Innovative thruster designs that minimize or prevent high heat soak-back during pulse mode operation;

• Highly reliable, lightweight compressors for use in gaseous propellant storage and distribution systems;

• Advanced lightweight multi-use positive expulsion devices for storable propulsion systems; and

• Other innovative chemical propulsion system components that improve system safety, affordability, or effectiveness.

Note: Related technologies of interest but covered under other SBIR subtopics include:

• X3.03 Cryo and Thermal Management

• X7.01 Chemical Propulsion Systems and Modeling

• X8.01 Vehicle Health Management Systems

**X7.03 High-Power Electric Propulsion**

*Lead Center: GRC*

*Participating Center(s): JPL, JSC*

The goal of this subtopic is to develop innovations in high-power (100 kW to MW-class) electric propulsion systems. High-power (high-thrust) electric propulsion may enable dramatic mass and cost savings for lunar and Mars cargo missions, including Earth escape and near-Earth space maneuvers. At very high power levels, electric propulsion may enable piloted exploration missions as well. Improved performance of propulsion systems that are integrated with associated power and thermal management systems and that exhibit minimal adverse spacecraft-thruster interaction effects are of interest. Innovations are sought that increase system efficiency, increase system and/or component life, increase system and/or component durability, reduce system and/or component mass, reduce system complexity, reduce development issues, or provide other definable benefits. Desired specific impulses range from a value of 2000 s for Earth-orbit transfers to over 6000 s for planetary missions. System efficiencies in excess of 50% and system lifetimes of at least 5 years are desired. Specific technologies of interest in addressing these challenges include:

• Long-life, high-current cathodes (100,000 hours);

• Electric propulsion designs employing fuels that are more readily available (whether from Earth or *in situ* space resources) and easy to store/handle;

• Electrode thermal management technologies;
- Innovative plasma neutralization concepts;
- Metal propellant management systems and components;
- Cathodes for metal propellants;
- Low-mass, high-efficiency power electronics for RF and DC discharges;
- Lightweight, low-cost, high-efficiency power processing units;
- Low-voltage, high-temperature wire for electromagnets;
- High-temperature permanent magnets and/or electromagnets;
- Application of advanced materials for electrodes and wiring;
- Highly accurate propellant control devices/schemes;
- Miniature propellant flow meters;
- Lightweight, long-life storage systems for krypton and/or hydrogen;
- Fast-acting, very long-life valves and switches for pulsed inductive thrusters;
- Superconducting magnets;
- Lightweight thrust vector control for high-power thrusters; and
- High fidelity methods of determining the thrust of ion, Hall, and advanced plasma engines without using conventional thrust-stands.

Note: Related technologies of interest but covered under other SBIR subtopics include:

- Low- to medium-power solar electric propulsion for planetary science missions (S8.04 Spacecraft Propulsion).

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**X7.04 Aeroassist Systems**

**Lead Center:** JSC

**Participating Center(s):** AFRC, ARC, LaRC

The goal of this subtopic is to develop innovative human-rated aeroassist systems for missions including lunar return to Earth and precursor missions for human Mars exploration. Systems are needed to support the following flight regimes: aerocapture, entry interface to subsonic speeds, and Mach 5 to subsonic speeds. Systems must be capable of controlled flight and be compatible with pinpoint, soft landing systems, which achieve landing accuracies of 10s of meters at touchdown or powered descent initiation. These systems must be compatible with launch vehicles and transit vehicles and capable of safely discarding unneeded and constraining hardware on landing and
providing surface access. Technology needs include aeroassist system design, Thermal Protection System (TPS) designs, modeling capabilities, sensor systems, and navigation technologies that support reliable aerocapture or aerobraking of multi-metric-ton-class piloted or cargo spacecraft. In particular, this subtopic seeks innovations in the following areas:

- **Innovative aeroassist system designs.** This includes low-mass, rigid aeroassist systems based on robust, high-temperature structures and adhesives, modular or deployable/inflatable aeroshells with large surface area, and inflatable ballutes;

- **TPS designs for human-rated aeroassist vehicles returning to Earth from the Moon and Mars, and for Mars aerocapture and Entry, Descent and Landing (EDL).** Innovative TPS concepts are solicited to reduce current TPS mass fractions by 25% to 50% and to reduce TPS costs;

- **Ablative and reusable TPS materials and concepts that significantly enhance performance and reduce mass.** This includes development and characterization of single- and multi-use TPS materials, TPS for rigid aeroshells, and flexible TPS materials for deployable aeroshells. Thermo-chemical and mechanical properties data for probabilistic design, spallation characteristics, and accurate simulation tools to predict material behaviors and material compatibility are required. Innovative TPS concepts are solicited to reduce current TPS mass fractions by 25% to 50% and to reduce TPS costs;

- **Aerothermodynamic modeling tools with greater accuracy and less uncertainty:** (1) Innovative and accurate computer modeling of fluid structure interactions, including flow stability and surface deflections under dynamic conditions for decelerator deployment and inflation; (2) Modeling and simulation of convection/radiation/ablation coupled three-dimensional flow fields, for both optically thick and thin shock layers and highly ionized flows; (3) Accurate prediction of wake heating including radiative heating components; (4) Accurate prediction of single and multiple rocket plume effects (e.g., reaction control system thrusters) on the vehicle aerodynamics and heating;

- **Innovative sensor systems which are capable of providing real-time or near real-time updates to atmospheric pressure, temperature, density, and winds to support the guidance systems used on aeroassist vehicles;**

- **Innovative sensor systems for inflatable aeroassist vehicles capable of providing real time aerosurface temperature, strain, deflection, flight loads and other significant parameters; and**

- **Lightweight flexible materials that will reduce the mass and increase the strength and thermal characteristics for applications to deployable aeroshells and supersonic deployed decelerators.**

Focus should be on aeroassist systems applied to the following mission classes:

- **Earth return of piloted spacecraft from the Moon.** Return-to-Earth scenarios for human lunar missions include: (1) short-range direct entry and landing; (2) extended-range entry using a skip out of the atmosphere with subsequent EDL to the Earth's surface; and (3) aerocapture into a low-energy Earth orbit followed by EDL. Inertial arrival speeds of approximately 11 km/s (up to 12 km/s for some abort scenarios) with entry masses of at least 5 metric tons are expected for normal lunar return. Acceptable sustained loads for these piloted missions are limited to about 5 gs perpendicular to the human spine in the "eye balls in" direction; and

- **Mars precursor missions for human exploration.** These include robotic missions designed to deliver pre-deployed cargo or to conduct technology demonstrations in anticipation of follow-on human Mars missions.
Candidate human mission scenarios for Mars include human and cargo aerocapture into a Mars orbit followed by EDL to the Mars surface and return to Earth. Mars aerocapture missions are expected to have arrival speeds of 6 to 8 km/s and aerocapture mass on the order of many 10s of metric tons. Return-to-Earth scenarios for human Mars missions are similar to those for lunar missions, except for higher arrival speeds (11.5 - 12.5 km/s, up to 14 km/s for some off-nominal scenarios).

Note: Related technologies of interest but covered under other SBIR subtopics include:

- Inflatable and other innovative structures (X2.02 Structures and Habitats); and
- Aeroassist systems for deep space robotic science missions (S5.01 Low Thrust and Propellantless Propulsion Technologies).

Advanced Space Platforms and Systems Topic X8

This Topic covers a range of key technology options associated with future space exploration systems and architectures that are resilient, reliable, and reconfigurable through the use of miniaturization, modularization of key functions in novel systems approaches. Platforms technologies that support self-assembly and in-space assembly, as well as in-space maintenance and servicing, are included. These efforts are coordinated with in-space assembly and related R&D within the Advanced Space Operations Topic (e.g., involving extra-vehicular activity (EVA) systems, robotics, etc.).

Sub Topics:

**X8.01 Vehicle Health Management Systems**

**Lead Center:** ARC

**Participating Center(s):** JSC, MSFC, SSC

In order to meet the automation and autonomy requirements of the Vision for Space Exploration, innovative health management technologies are required throughout the system lifecycle including design, development, test, validation, integration, operation, maintenance, and disposition. Traditional means of supporting vehicle health such as invasive inspections are extremely limited in their utility for exploration missions. Other solutions such as ground-based monitoring of telemetry data become less useful as communication delays or bottlenecks increase. Under these circumstances, autonomous and automated solutions to systems health management provide the best means of increasing crew safety and mission success probability for future space exploration missions.

Another significant concern is in mission operations. Operations models that require large numbers of ground controllers and other mission support staff will be cost prohibitive in the future. Future systems must provide appropriate levels of safety and mission success factors while reducing support staff on the ground. In addition, future space missions will have to maintain a healthy balance and seamless transition between crewed and robotic operations.
Proposals should be responsive to the overall goals and objectives of the Exploration System-of-Systems as defined in Project Constellation requirements. Proposals may address specific vehicle health management capabilities required for exploration system elements (crewed spacecraft, launch systems, habitats, rovers, etc.). In addition, projects may focus on one or more relevant subsystems such as propulsion, structures, thermal protection systems, power, avionics, life support, and communications. Proposals that involve the use of existing NASA health management test beds (power, propulsion, systems integration, life support, diagnostics, networking, etc.) for technology validation are encouraged.

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

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

- Health monitoring and management technologies to enable situational awareness of system health, safety, and margins. Solutions may include novel approaches to fault detection and isolation, diagnostics, and mitigation of system degradations and failures. Solutions may also include innovative health management system architectures that are robust to single point failures and are scalable, modular, and expandable without costly redesigns;

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

- System-of-systems health management concepts to provide robust cooperation of multiple Exploration elements, e.g., spacecraft constellations or rendezvous and docking operations;

- Prognostic techniques able to anticipate system degradation and enable further improvements in mission success probability, operational effectiveness, human-machine teaming, and automated recovery of function;

- Real-time data analysis methods for structural sensing, including detection, localization, damage assessment, and automated assessment of thermal protection system integrity;

- Crew-automation interfaces that are capable of reporting quantitative/qualitative sensor readings, assessing system status, explaining current conditions, predicting likely system behaviors, and proposing corrective actions in a manner that does not exceed the capacity of human understanding, especially in high-risk situations requiring rapid human response. Innovative ways for the health management system to convey a wealth of information quickly and effectively are desired; and

- End-to-end health management system architectures that are integrated with and validated on spacecraft subsystems on ground-based (or virtual) test beds.
X8.02 Intelligent Modular Systems

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

This subtopic will involve development and demonstration of a range of technologies for reconfigurable, intelligent, modular space subsystems, systems, and systems of systems. Technologies should focus on establishing the validity of new approaches to Earth-Moon human and robotic operations, with a view toward longer-term applications for the inner Solar System (e.g., Mars) exploration missions. Many of these future missions, systems, and capabilities imply the need for the development of large and complex systems and infrastructures in space. But, the size-constraints, mass-capability, and cost of launching large monolithic payloads into space limit the development and realization of these capabilities. If a different design approach using intelligent modular systems rather than monolithic payloads is used, these large space systems become more tractable. Also, intelligent modular systems include low system impact of a single launch vehicle loss, since modular systems are launched on multiple vehicles at multiple times. Replacement of modules over the system lifetime is, in many cases, a more reasonable approach to maintaining a system; and, graceful degradation of the system capability can be more readily managed with modular units. Hardware costs of multiple identical units can be reduced through economies of scale, and modular approaches can accommodate cost-phased programs that develop and fly a “pilot” system, which can initially prove a capability, and then be added to later as demand for capability increases. Technologies of interest include:

Modular Structures (MSFC)

Structural technologies of interest include inflatable, erectable, deployable, or easily connected modules to create large space structures. Assembly technology of interest may include approaches for integrating deployable modular units with larger structures such as habitation modules or propellant tanks, and approaches for assembly of erectable modules that form backbones or support trusses. Attachment technologies such as autonomous rendezvous and docking, innovative connectors and joining, bonding techniques, and module positioning and alignment systems are also of interest.

Adaptable and Reconfigurable Modular Systems (GSFC)

Integrated, reconfigurable modular systems incorporating multiple elements such as solar collection arrays, radiators, power, data, utility lines, science instruments, plug and play avionics, and integrated inspection and verification techniques are solicited, including modular structures using embedded sensors and actuators.

Human-Robotic Modular Systems (JSC)

Multi-functional robotic hardware and software systems are of interest to aide in surface and in-space operations. Robotic surface operations including exploration, assembly, fabrication, construction and transportation operations are of interest as well as similar systems for in-space operations. In addition, techniques are solicited for effective, efficient, and intuitive operation and control of robotic hardware through design and development of advanced human-computer interfaces.
This Topic covers a range of key technology options associated with future lunar and planetary surface exploration and operations for a range of increasingly-ambitious human and robotic mission options through the development of in situ resource utilization technologies, highly-capable surface mobility systems, and various supporting infrastructures. Key objectives are derived from the goals of safe/reliable, affordable and effective future human and robotic lunar and planetary surface exploration in support of the U.S. Vision for Space Exploration.

Sub Topics:

X9.01 In-Situ Resource Utilization & Space Manufacturing

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

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

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

In Situ Resource Extraction and Separation

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

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

**In Situ Resource Processing and Refining**

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

- Technologies, processes, and systems for robotic precursor and early human missions to the Moon in the areas of processing of lunar resources into oxygen, propellants, and feedstock for in situ manufacturing or surface construction;
- Technologies, processes, and systems for robotic precursor missions or eventual human missions to Mars, which produce mission critical consumables, such as oxygen, propellants, life support gases, fuel cell reagents, and in situ manufacturing feedstock. Robotic and human missions to Mars that consider initial or evolutionary use of ISRU consumables currently assume the use of liquid oxygen and hydrocarbon fuel (methane, propane, methanol, ethanol, or low freezing point mixtures) propellants for propulsion systems and mobile fuel cell power systems; and
• Developing and evaluating seals for high temperature multi-temperature and operation cycle regolith processors, water electrolysis and carbon dioxide electrolysis units; developing and evaluating low gas loss regolith inlet and outlet units (seals, augers, hoppers) for regolith processing; and developing and evaluating 0-g water separation, and separation of nitrogen from carbon dioxide are of particular interest for lunar and Mars resource processing.

Surface Manufacturing w/In Situ Materials

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

• Additive Manufacturing Techniques;
• Subtractive Manufacturing Techniques;
• Formative Manufacturing Techniques; and
• Part Assembly/Integration.

Manufacturing Support Processes

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

Surface Construction w/In Situ Materials

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

• Construction techniques for robotic precursor and early human missions that support site planning and preparation and the use, manipulation, and placement of raw materials and expected feedstock materials
from *in situ* Resource Processing and Refining for lander plume debris, meteorites, and solar/galactic radiation shielding:

- Construction techniques for robotic precursor and early human missions that support bunker and habitat structure construction using and manipulating raw and expected feedstock;

- Construction techniques that can be demonstrated on robotic precursor missions that demonstrate dust mitigation concepts for surface mobility around landing pads, habitats, dust-sensitive instruments, and airlocks; and

- Lunar *in situ* fabrication techniques that can be demonstrated on robotic precursor missions that enable growth in solar power generation, storage, management, and distribution capabilities using raw materials, expected feedstock. Demonstrations can initially assume use of Earth supplied consumables in small amounts.

**Point of Departure Mission Information for Proposals**

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

Excavation, separation, and processing needs for lunar missions depend on the resource of interest, location, and concentration of the resource and the processing technology considered. Mars sample return missions that incorporate *in situ* propellant production require atmospheric carbon dioxide collection and possibly atmospheric or regolith water extraction to support the production of 300 kg to 2000 kg of propellant depending on the size of the sample and whether the mission is a Mars orbit rendezvous or direct Earth return mission. Breathing rates for astronauts are approximately 0.07 kg of oxygen (O\(_2\))/person/hour in habitats and 0.1 kg O\(_2\)/person/hour for Extra-Vehicular Activities (EVAs). Early human lunar mission surface durations may vary from 3 to 45 days and can include from 2 to 6 crewmembers. Lunar human landers require approximately 5000 to 8000 kg of propellant for ascent and approximately 15,000 to 25,000 kg for landing and ascent combined. Mars mission surface durations are 30 to 90 days for opposition class missions and 450 to 600 days for conjunction class missions. Mars human ascent vehicles typically require 20,000 to 30,000 kg of propellant. Fuel cell reagent consumption rates depend on the power required for the application, the reagents, and the fuel cell technology used. EVA suits and small rovers can require 500W to 1 KW of power/hour, unpressurized rovers can require 3 to 6 KW of power/hour and pressurized rovers can require 10 KW/hour and above.

**X9.02 Surface Mobility/Mechanisms**

**Lead Center:** JPL

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

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

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

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

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

Crew Mobility Systems

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

Prometheus Technologies Topic X10

The primary goal of the Prometheus Nuclear Systems and Technology (PNS&T) Theme is to mature technology and develop systems to overcome current limitations of space power and propulsion in support of the Vision for Space Exploration. Developing and demonstrating safe and reliable nuclear fission-based spacecraft power and propulsion systems will enable human and robotic exploration, enhance scientific capabilities, and facilitate unprecedented levels of exploration and scientific return. Potential benefits of space nuclear power include very high total energy and total power capability, and high delta-V nuclear-electric propulsion that can enable a wide range of solar system exploration missions not possible today. To meet the goals of the Vision for Space Exploration, new exploration missions would have requirements exceeding what current power and propulsion systems can provide, particularly for surface and outer planet applications. Prometheus nuclear systems can provide a viable, enabling, alternative for those missions that have no other practical solution. The PNS&T Theme is comprised of two programs - the Nuclear Flight Systems program and the Advanced Systems and Technology program. The Nuclear Flight Systems program is focused on developing the first Prometheus demonstration of nuclear fission power in space, including development of nuclear reactor power, electric propulsion and other
associated spacecraft systems. The Advanced Systems and Technology program is focused on conducting research and development of advanced systems and technologies beyond those needed for the first demonstration mission including research for advanced power and propulsion systems, materials development, integrated spacecraft systems, and other capabilities. This advanced technology development will be necessary to support NASA's goal of more distant, more ambitious, and longer duration human and robotic exploration of Mars and other destinations. Five key program research areas include advanced nuclear electric propulsion, advanced fission-based power systems, advanced nuclear propulsion systems, advanced nuclear vehicle and spacecraft systems, and long-range nuclear reactor systems technology development. The five PNS&T subtopics are focused on these Advanced Systems and Technology program areas.

Sub Topics:

X10.01 Long-Life Validation and Flight Qualification of Nuclear Space Systems Hardware Prior to Flight Use

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

Nuclear space systems are expected to be an integral part of the national Vision for Space Exploration. Nuclear electric power would allow human and robotic exploration to reach beyond the constraints of solar power systems and is expected to be crucial for long-duration habitation and exploration of the Moon and Mars. Nuclear propulsion systems offer the potential for significantly higher specific impulse and/or significantly higher delta-V than chemical engines, reducing the amount of propellant and associated costs needed to perform a given mission. Nuclear thermal propulsion (NTP) systems up to several hundred megawatts and nuclear electric propulsion (NEP) systems from 30 kW to hundreds of kilowatts and more, are being considered for the economical delivery of lunar and Mars cargo, rapid crew transit to Mars, and, in the case of nuclear electric propulsion, robotic exploration of the solar system and beyond. However, the long-duration performance and life testing of these high power nuclear space systems can be very expensive and poses several unique and significant challenges. The intent of this solicitation is to elicit new or significantly improved approaches that accelerate or simplify the long-life validation and flight qualification of high power nuclear space systems hardware.

While the testing of nuclear reactors is clearly beyond the scope of this solicitation, proposals are invited for innovative methods that simplify, accelerate, reduce the cost, or otherwise improve upon current techniques to ground test and validate the life and performance of non-reactor high power space nuclear power and propulsion components, subsystems, and systems. Also invited are proposals that address new and innovative approaches to seamlessly integrate high power space nuclear power and propulsion hardware elements into complete systems of systems, with corresponding methods for flight qualification prior to flight use.

Sample high power space nuclear power and propulsion areas that could benefit from accelerated or simplified performance and life validation include, but are not limited to: electric power conversion systems for in-space or planetary surface power; electric power management and distribution systems; accelerated testing of pulsed or steady-state high power electric thrusters or thruster arrays under appropriate vacuum and thermal conditions; performance and life testing of component materials and structures under simulated NTP hot hydrogen flows; the simulated operation, shut-down, and restart of NTP system components over simulated mission profiles in relevant vacuum, thermal, and radiation test environments; other space nuclear power and propulsion hardware elements that must operate in extreme environments over extended mission durations; and simplified or accelerated techniques for hardware integration and flight qualification of a complete system of systems prior to flight use. Proposed methods should substantially and demonstrably reduce the time and expense to validate the life and performance of space nuclear power and propulsion technologies compared to state of the art techniques.
NASA is interested in the development of critical technologies for first in-space applications of solid core nuclear thermal propulsion (NTP) systems for use in a variety of future exploration missions. For short, round trip, human missions to Mars, NTP systems may be enabling. It can potentially also help reduce launch mass or increase payload delivery for cargo and crewed missions to the Moon and other destinations. The first anticipated in-space application of solid core NTP systems could occur in the time frame of 2025 to 2030 and could be based on a high-thrust/high-Isp (~850 - 950s) NTP system that uses a fission reactor with U-235 fuel as its source of thermal energy. During the short primary propulsion maneuvers of a typical conceptual mission, large quantities of thermal power (100s of MWt) would be produced within the NTP system and removed using LH$_2$ propellant that is pumped through the engine's reactor core. The superheated hydrogen gas is then exhausted out the engine's nozzle to generate thrust. Recent NASA studies have shown that small engines (~15-25 klbf), used individually or in clusters, could support a broad range of mission types. Representative ranges of engine performance include: 1) hydrogen exhaust temperatures ~2500-2900 K; 2) propellant flow rates ~7-13 kg/s; 3) chamber pressures ~500 -1500 psi ; and 4) nozzle expansion area ratio ~200:1-500:1.

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

- High temperature, radiation tolerant instrumentation and avionics for engine health monitoring. Non-invasive designs for measuring neutron flux (outside of reactor), chamber temperature, operating pressure, and H$_2$ propellant flow rates over wide range of temperatures are desired;
- Long-life, lightweight, reliable hydrogen turbopump designs and technologies;
- Lightweight, long-life, high heat flux thrust chambers, regenerative-cooled nozzles and radiation-cooled skirt extensions that are compatible with hot hydrogen;
- Radiation tolerant materials compatible with above engine subsystem applications and operating environments;
- High temperature, low-to-moderate burn-up carbon- and ceramic-metallic (cermet)-based nuclear fuels for use in NTR and BNTR engines;
- Improved chemical vapor deposition (CVD)/coating techniques for heritage "Rover/NERVA" type carbon-based fuels that reduce and/or prevent cracking, fuel element erosion via H$_2$ attack, and release of fission product gases into the engine's H$_2$ exhaust stream;
- Mass-optimum neutron and gamma radiation shielding materials and designs that minimize exposure/damage to key engine components and subsystems (e.g., LH$_2$ turbopumps) and provide radiation protection for the crew; and
- Dual-use shielding materials and designs that also provide habitat protection against galactic cosmic rays and solar flares are also encouraged.

Note that any associated NTP simplified test approaches, power systems, and thermal management/heat rejection systems technologies should be submitted to subtopic areas X10.01, X10.03, and X10.04, respectively.
NASA is interested in the development of highly advanced systems, subsystems, and components for use with high-power, fission power systems for a variety of future robotic and manned exploration missions to the Moon, Mars, and beyond. Anticipated electric power levels range from 30 to 100s of kilowatts for the nearer-term and possibly up to multi-megawatts for the far-term. Fission-based systems are anticipated to enable long duration stays of approximately 45 to 90 days over the lunar night and may have in situ resource utilization applications. Power levels needs are anticipated to be between 30-50 kWe for these early exploration missions.

Potential Mars-surface human outpost applications for high-power space nuclear power systems could include habitats, resource processing, propellant production/liquefaction/maintenance, and excavating and mining equipment. These potential Mars surface human mission activities could require power in the 100 kWe range. Also, space nuclear power systems could be needed for robotic outposts as a precursor to human Mars surface exploration with 50-500 day stays. Power levels of about 30-50 kWe may be needed to support these initial robotic outposts and other science applications such as: deep drilling, resource production demonstrations, rovers, weather stations, etc.

Potential electric propulsion applications include high power space nuclear power systems for primary electric propulsion, vehicle housekeeping, cryogenic propellant maintenance, orbiting power assets and science payloads. Power levels in the 100-200 kWe range are envisioned for robotic vehicles. Far-term vehicles for human missions may also be needed and could require about 1-2 MWe for high-mass cargo vehicles to the Moon or Mars and the low 10s of MWe for piloted electric propulsion vehicles. Nuclear thermal propulsion systems could also be designed to produce electric power and power levels of about 50 kWe could be needed to meet crew habitat, propellant boil-off, and other spacecraft power requirements.

Proposals are sought in the following specific technologies areas:

- Advanced, high-efficiency, high-temperature high-power conversion >20%, 30-200 kWe for the nearer-term, and up to MWe-unit size for the far-term (with technical issues of scaling to high power unit);
- Electrical power management, control and distribution in the 1000-5000 V range;
- Deployment systems/mechanisms and innovative methodologies for surface mobility systems for remote emplacement of power systems and for use of indigenous shielding materials;
- Material compatibility with local environments;
- Systems/technologies to mitigate lunar and planetary surface environments including dust accumulation, lunar surface temperature extremes, wind, planetary atmospheres (CO₂, corrosive soils, etc.);
- Power system design considerations for long life (>10 years), autonomous control and operation, including sensor technologies; and
- Radiation tolerant systems and materials (including lunar, Mars and in-space environments) for robust,
In addition to reducing overall system mass, volume and cost, increased safety, and reliability are of extreme importance. It is envisioned that these high power space nuclear power system technologies could be used on robotic and human exploration missions and it is to NASA's advantage to develop those technologies that evolve from robotic to human exploration mission requirements with a minimum of redesign. Technologies that enable challenging missions such as, nuclear electric propulsion, planetary surface power, and in-space electric power generation are of particular interest. Technologies that easily and efficiently scale in power output and can be used in a host of applications (high commonality) are desired.

Proposals for thermal management systems and innovative materials computational engineering should be proposed to X10.04 and X10.05, respectively.

X10.04 Heat Rejection Technologies for Nuclear Systems

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

NASA is interested in the development of advanced heat rejection subsystems for use with high-power, fission-based power and propulsion systems for a variety of future robotic and manned exploration missions to the Moon, Mars, and beyond. Anticipated electric power levels for these high-power, space nuclear systems could range from 30 to 100s of kilowatts for the nearer-term and possibly up to multi-megawatts (2-20 MWe) for the far-term. Potential applications include in-space transfer vehicles and planetary orbiters, and surface bases with global site capability on the lunar and Mars surface. The heat rejection sub-systems for any of the possible high power space nuclear power plant choices would need to be matched with the thermodynamic cycles of the power plants in a manner that will maximize space nuclear power system performance while keeping heat rejection subsystem and overall power system specific mass (kg/kW) to a minimum. The levels of heat rejection could be from about 100 kilowatts to many megawatts, and the task could be even more challenging by the long life requirements imposed by deep space missions, the extreme radiation environments possibly encountered, and the unique challenges imposed by surface missions including the effect of an atmosphere, elevated sink temperature, and particle contamination. The radiator operating temperature range can vary greatly depending on the mission, but temperatures as low as 400K and in excess of 1000K are possible.

Typical heat rejection systems usually include a) a heat transport loop carrying heat to radiator surfaces for rejection to space, and b) a space radiator, which accomplishes the final heat rejection to space by thermal radiation. If the cycle working fluid is different from the radiator heat transport fluid, a "heat sink" heat exchanger and a fluid-circulating pump also need to be included in the design.

Proposals are sought in the following critical technologies areas:

- Low areal density heat rejection radiators (2);
Innovative heat transfer approaches between heat transport loop and radiating surfaces;

Development of light weight, radiation tolerant, thermally stable, high-performance components and pump loop systems including heat pipes and pumps in the low to intermediate temperature ranges (300K to 500K), intermediate temperature ranges (450K to 650K), and intermediate to high temperature ranges (700K to 1000K and higher);

Pumped loops that take advantage of the abundance of waste heat and transport some of it to the spacecraft and payload components for thermal management. Waste heat source to spacecraft radiator distances will likely be too large for passive technologies, and pumped loops may offer a possible solution. Since rejection of megawatts of waste heat could require large radiating surfaces, loop heat pipes may provide a lightweight solution to distributing this heat over long distances. Specific areas of interest for this area include:

- Long term material/working fluid compatibility, lightweight material integration, and working fluid performance for the various temperature ranges; and
- High temperature, long-life pump technology, single- and two-phase systems, and thermal bus concepts involving multi-evaporators and condensers.

High temperature, lightweight heat rejection system materials. Such materials may include those to enable lightweight radiators and heat pipes. Work in this area should address harsh radiation environments, launch/landing loads, and long life issues;

Durable low-absorptivity/high-emissivity and variable emissivity coatings for radiating surfaces;

Novel and efficient deployment systems/mechanisms for radiators in zero gravity and/or non-zero gravity fields to minimize mass, complexity, and stowed area/volume;

Systems and technologies to mitigate adverse effects of planetary surface operating environments, such as cosmic and fission process induced radiation, dust accumulation, wind loading, planetary atmospheric effects due to CO$_2$, and variable sink temperatures;

Design considerations for heat rejection subsystems should include long service life (>10 years) and autonomous operation;

Development of advanced, high temperature heat pump technologies based upon conventional vapor compression cycles, absorption/adsorption cycles, and advanced thermoelectric and/or thermo-acoustic technologies;

Advanced eutectic working fluids capable of extended duration use that would mitigate design issues related to the freezing and subsequent reuse of thermal management coolants; and

Alternate cooling technologies for the rejection of waste heat from large capacity planetary or surface nuclear power systems. Such systems may include, but are not limited to, deployable cooling towers and/or optimized radiators.

In addition to reducing overall system mass, volume, radiator area, and cost, increased safety and reliability are of prime importance. Technologies are desired that readily scale in heat rejection capability for various power plant outputs, and thus can be used in a range of applications.
X10.05 Computational Material Science Tools for Space Nuclear Systems Design

Lead Center: GRC
Participating Center(s): MSFC

NASA is interested in the development of highly advanced systems, subsystems, and components for use with high-power, fission power and propulsion systems for a variety of future robotic and manned exploration missions, including in-space, lunar-surface, and Mars-surface applications. Advanced high-power space nuclear power and propulsion systems for robotic and human exploration missions involve a range of specialized materials for the reactor, heat transfer system, energy conversion system, propulsion system, and other nuclear vehicle systems. These materials may include carbon-carbon, super alloys, refractory alloys, structural ceramics, ceramic matrix composites, and other high-temperature space nuclear systems materials. Long-term stability greater than 10 years is critical for long-life space nuclear power system applications. Materials would be subjected to fission process radiation while exposed to in-space (plasma, out-gassing, etc.) and/or planetary operating environments.

This subtopic is focused on the development of computational materials science tools to develop and select these specialized space nuclear systems materials. Many considerations go into selection of materials for demanding applications. These include strength, creep resistance, phase stability, oxidation/corrosion resistance, nuclear capture cross-section, and radiation tolerance. In recent years computational materials science has assisted with not only the selection of existing materials with a given set of properties but also with the development of new materials with those properties. These tools include first principles calculations of phase equilibria, computational thermodynamics (the CALPHAD technique), and creep modeling.

Proposals are sought for the specific technologies areas:

- A computational ‘toolbox’ for material selection with particular emphasis on space nuclear power and propulsion systems requirements;
- Computational tools to address particular issues in mechanical property degradation in space nuclear power and propulsion systems over long times. This includes, but is not limited to, long-term creep modeling;
- Computational tools to predict long-term oxidation/corrosion and flow-induced erosion issues in the high temperature portions of these systems, including the heat transfer system. This includes thermodynamic modeling of heat transfer media attack of alloys;
- Computational tools to predict long term stability of various joining techniques used in these space nuclear systems. This includes diffusion modeling in alloys; and
- Computational tools to predict interaction of the radiation environment. This includes effective capture cross-section for complex materials systems and production of secondary energy and potential impact on components.

It is anticipated that Phase 1 will focus primarily on the new computational tools for material selection and development with some limited experimental verification. Later phases should involve more extensive verification, to the point where these tools could be readily utilized for the design of space nuclear systems.
The crews that leave the Earth for exploration destinations must keep healthy to perform their mission and to return safely back to Earth. The subtopics seek innovative technologies that will enable crew health and performance, and that will assure there will be no unacceptably long-term consequences after returning while supporting healthy and productive sustained human presence. Proposals for technologies that will enable human space exploration are sought in the areas of Radiation Health and Radiation Shielding; Human Health Countermeasures including artificial gravity, exercise, pharmacology and nutrition, cell and tissue-based analog systems, and physiological countermeasures; Exploration Biology, including the science, spaceflight systems, and technologies that support human exploration; Autonomous Medical Care including technologies of prevention, monitoring, diagnosis, and treatment of human medical problems. Research should be conducted to demonstrate technical feasibility during the Phase 1 contract and show a path toward a Phase 2 specific deliverable. The contractor will then, when appropriate, deliver a demonstration unit of the instrumentation for NASA testing before the completion of the Phase 2 contract.

Sub Topics:

X11.01 Radiation Health

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

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

Ground-Based Heavy Ion Accelerator Research Support Equipment

NASA utilizes facilities at Brookhaven National Laboratory (BNL) to conduct fundamental radiobiology and shielding experiments. However, the facilities at BNL were not developed with NASA's high number of investigators in mind, thus there are areas where technology developments can improve efficiency and throughput. Technologies of specific interest include, but are not limited to, the following:

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

- Controlled beam line access that provides safe, but rapid and reliable human access to the beam target areas and lockout during specimen exposure; and

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

High Throughput Genomic Analysis Techniques

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

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

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

Radiation Shielding and Fabrication

The NASA Space Radiation Research Program uses the NASA Research Announcement (NRA) as the primary means of soliciting research to conceive and radiation-test new radiation shielding materials concepts. The materials concepts include new and innovative lightweight radiation shielding materials to shield humans in crew exploration vehicles, large space structures such as space stations, orbiters, landers, rovers, habitats, and spacesuits. The materials emphasis is on non-parasitic radiation shielding materials, or multifunctional materials, where one of the functions is the radiation shielding, but also serves as structural and other functional components of flight and/or habitat systems. The specific areas in which SBIR-developed technologies can contribute to NASA's overall mission requirements for advanced radiation shielding materials technologies are:

- Characterization of the physical, chemical and relevant functional properties and the validation and qualification of such multi-functional radiation shielding materials;

- New and innovative manufacturing techniques for producing quality-controlled advanced radiation shielding products and structural components, including innovative scale-up methods for producing quality-controlled viable quantities of advanced radiation shielding materials;

- New and innovative processing methods for producing quality-controlled advanced radiation shielding materials of all forms - resins, fibers, fabrics, composites and fiber-reinforced composite materials;

- New and innovative fabrication techniques for fabricating advanced radiation shielding materials into useful products and structural components; and

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

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

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

- Advanced spaceflight detector systems to provide reliable environment data for a specific spectrum of energies, including: real time dosimetry providing dose and particle types and energies and cumulative dosimeters for characterizing space environments for use onboard spacecraft and planetary surfaces as well as alarm systems for Solar Particle Events; and

- Microdosimetry for operational and research applications, including implantable dosimeters for biological studies, that translate particle counts into biologically relevant dose or damage.

**X11.02 Human Health Countermeasures**

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

In order for humans to live and function safely and efficiently in space or in the hypogravity of the Moon (1/6g) or Mars (3/8g), a good understanding of the effects of micro- and hypogravity and other factors associated with the space environment on human physiology and human responses to the space and extra planetary environments is required. A variety of countermeasures must be developed to oppose the deleterious changes that occur in space and upon subsequent exposure to other gravitational fields. The ability to monitor the effectiveness of countermeasures and alterations in human physiology during space exploration missions, particularly when several countermeasures are used concurrently, is equally important. This subtopic seeks innovative technologies in several very specific key areas. Since launch costs relate directly to mass and volume, instruments and sensors must be small and lightweight with an emphasis on multi-functional capabilities. Low power consumption is a major factor, as are design enhancements to improve the operation, design reliability, and maintainability of these instruments in the environment of space and on planetary surfaces. As the efficient use of time is extremely important, innovative instrumentation setup, ease of usage, improved astronaut (patient) comfort, noninvasive sensors, and easy-to-read information displays are also very important considerations. Extended shelf life and ambient storage conditions of consumables are also key necessities. Ability to operate in 0g, 1/6g, and 3/8g becomes more important as we march towards human Moon and Mars missions.

**Exercise and Related Hardware**

Development of an immersive visual display system is required to be interfaced with treadmill exercise devices. This system may not be head-mounted but could be free standing and provide at least a 180° field of view. This visual display would allow visual flow patterns to be displayed to a non-encumbered subject during in-flight or on-surface treadmill exercise. In addition, miniaturized exercise hardware (treadmill or resistance exercise);
physiological monitoring devices; and metabolic gas (carbon dioxide and oxygen) analysis systems for use with exercise and miniaturized interactive feedback and entertainment systems.

A tool or toolkit should simulate and visualize the exercise device design and performance. A comprehensive, scaled 3D/virtual human model interface would be valuable to show biomechanical and kinetic effects of the exercise device. Relative physiological data from anthropometry to stress/fatigue to trauma/insult onset should be targeted. If in-flight/on-orbit micro gravitational and planetary surface gravitational forces can be simulated, this could help produce germane simulations with which to implement new designs and products. A time-delay algorithm would be advantageous in helping provide for latency-moderated haptics (force-feedback) and long-distance teleoperative control. This will allow remote teleoperation with force-feedback despite the high latencies involved.

Noninvasive Pharmacotherapy and Monitoring

Development of innovative technologies resulting in noninvasive methods for diagnosis, treatment, and therapeutic drug monitoring is needed to facilitate effective pharmacotherapy of humans in space. Many questions remain about the effectiveness of pharmaceuticals in micro- and hypo-gravity environments, which may interfere with their activity by sensitizing or desensitizing the crewmember or interfering in other ways with the desired physiological effect. Micro-encapsulation of drugs, radio contrast agents, crystals, and development of novel drug delivery systems wherein immiscible liquid interactions, electrostatic coating methods, and drug release kinetics from microcapsules or liposomes can be altered under microgravity. Devices for continual monitoring of physiology during pharmacotherapy would also be advantageous to ensure that on-orbit expression of therapies relates to on-Earth histories.

Device for Providing Increased Neuromuscular Activation during Spaceflight

Astronauts returning from spaceflight exhibit post-flight postural and gait instabilities that are a result of neural adaptation to microgravity. A small, lightweight countermeasure device is required to stimulate somatosensory receptors on the plantar surface of the feet during in-flight exercise with the goal of increasing neuromuscular activation and enhancing sensorimotor integration. This system would integrate with in-flight exercise hardware and coupled with visual stimulation systems would allow a more complete sense of immersion to enhance in-flight postural and locomotor training.

Device for Measuring Body Fluid Shift

A body impedance device to measure fluid shifts in four segments of the body associated with a short-radius centrifuge. The device should measure the following parameters, namely, resistance, change in resistance and rate of change of resistance and reactance. The device should withstand g forces (5g) produced by centrifugation and meet safety standards such as subject isolation.

MEMS-Based Human Blood Cell Analyzer

Development of a small, automated and micro- and hypo-gravity capable instrument that will analyze micro liter quantity of human whole blood and provide a complete blood cell count (RBC, WBC, platelet, hemoglobin concentration, hematocrit, WBC differential, and calculated RBC indices) that correlates with traditional ground-based impedance or light-scattering technologies is needed. Likely devices based on MEMS will employ a biocompatible combination of micro fluidics, micromechanics, micro-optics, microelectronics, and data telemetry capabilities in an integrated handheld package with a user-friendly operator interface.
Cell/Tissue Analog Studies

Cell/Tissue analog studies in ground-based, microgravity-analog bioreactors allow us to understand the ill-effects of microgravity and radiation on human tissues—especially, bone, muscle, and cardiac and immune response. Technologies that allow automated biosampling, lyophilization of mammalian cells, miniaturized protein microarray analyzer, tools derived from Bionanotechnology relevant to the understanding are of interest.

X11.03 Autonomous Medical Care

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

Exploration missions require a healthy, well-performing crew supported by a robust infrastructure for the monitoring, diagnosis, and treatment of medical conditions. Since return time to Earth and communications delays during such missions will greatly reduce the effectiveness of Earth-involvement, the crew must be capable of performing the majority of medical activities independently. Therefore, this system of autonomous medical care must provide the capability for patient care as well as measure and assess fitness levels for duty during a mission with little or no real-time support from Earth. The objective of this subtopic is to sponsor applied research leading to the development of such an infrastructure with the associated medical devices and procedures that will mitigate crew health, safety, and performance risks during future flight missions to the Moon and Mars. Medical diagnostic, treatment, and monitoring devices are critical for providing health care and medical intervention during missions, particularly extended-duration spaceflight to the Moon and Mars. Of particular interest are devices with minimized mass, volume, consumables, and power consumption that are capable of multiple functions in both micro-g and sub-g environments. Design enhancements that improve the operation, reliability, flexibility, and maintainability of medical devices in the space environment are also sought. Additional considerations include innovative approaches to human-device interactivity and interface, automation of device functions, improved ease of use, and astronaut comfort.

Device for Body Chemistry Assessment

Development of an integrated, adaptable laboratory analysis system/sensor system for in-flight assessment of body fluids (including blood) and solids is desired. This system would be used to obtain quantitative measurement of dissolved gases, calcium ions, and other electrolytes, proteins, lipids, hormones, carbohydrates, vitamins, minerals and clinical drug levels with minimal or no consumables usage or specimen preparation skill. Likely candidates will be based on MEMS technology and will employ a biocompatible combination of micro fluidics, micromechanics, micro-optics, microelectronics, and data telemetry capabilities in an integrated handheld package with a user-friendly operator interface.

Voice- and Gesture-Actuated Interactive Procedures

Astronauts working in space or on the lunar or Martian surface will require a hands-free, interactive, step-by-step environment for performing flight medical procedures. This system should have the capability to utilize links, prepare textual or graphical indication of progress through a procedure, return to previous steps, page forward/page backward, and automatically annotate verbal input relative to subject response during procedure or treatment. An inventory capability must exist for obtaining and stowing required items (including medications) as well as a mechanism to assess the resulting consumables status after a procedure has been completed. Ground-
monitoring capability is also required, at least in the early stages.

**Closed Loop Medical Respirator**

A closed loop flight and human certified medical respirator with real-time remote monitoring and remote control capability is required. This respirator must incorporate a function to limit the amount of $\text{O}_2$ leaking into the space vehicle or surface habitat. Current $\text{O}_2$ limits range from ~20/21% at sea level with maximum levels of 30% in a 10.2 psi environment. (This upper limit mitigates flammability concerns and is dictated by ambient pressure.) The system should incorporate real-time remote monitoring and control capabilities.

**Medical Grade Water Generation**

Methods and technologies for in-flight creation of medical grade water from any available water source are required. Because some pharmacological preparations appear to degrade in the space environment, it is highly desirable, from both a consumables perspective as well as from the standpoint of mass, to fly desiccated pharmacological substrates whenever possible and to reconstitute them only when needed. For this reason, medical grade water is required along with a low-g (e.g., 0 g, 1/3 g, and 1/6 g) system to deliver generated water to the substrate and mix as necessary. The general requirements of low mass, user-friendly interface, reliability, and automation are critical to this system. There should be a mechanism included to verify that the water produced meets standard requirements for the medical grade designator.

**Diagnostic Imaging Capability**

During long duration flights, it will be important to have medical imaging capability available to assist in diagnosis, treatment, and monitoring during and after medical events. This capability is likely to be an ultrasonic, low power, portable device that provides for diagnostic assistance via data processing algorithms. These algorithms would be expected to provide guidance for the crewmember administering the exam as well as identifying probable diagnoses options and possible treatments for each. The system should be flexible enough to provide fracture analysis, bone density levels, and body cavity status.

**In-Flight Suction**

Long duration missions must have the capability to provide medical suction for patients in the event of injury or serious illness. This system must be capable of providing suction for a variety of body orientations in multiple reduced gravity environments. It should be a stand-alone system that does not require oversight by another crewmember. In the event of malfunction, it should provide an audio alert, a display of the malfunction type, plus a safing algorithm. The contents of the suction system must be easily disposed of safely and without release of contents into the environment.

**Biomedical Signal Processing**

Assessment of an ill or injured crewmember may sometimes be accomplished in large part by the status of the biomedical signal, or EKG. This will have to be a “smart” system, which analyzes sensor placement, sensor health, signal monitoring, signal normalcy, and signal analysis. It is required that the biomedical signal be capable of monitoring cardiac health and physiological state. The processor must be fail-safe and must annunciate an audible alarm when a malfunction occurs. A display should provide a readout of the anomaly type and the system must safe itself when malfunctions occur. (NOTE: There may be a subset of malfunctions (e.g., loose lead) that will not require a shut-off or self-safing function.) The system must be volumetrically small with minimal mass.
Intelligent Software Modules

Software modules with the capability to review medical data in a SQL compliant database, assign or suggest appropriate SNOMED CT codes, and store the suggested codes in electronic format with discrete elements is highly desirable to avoid having to train hierarchical nomenclature to crewmembers. The hierarchical relationships between SNOMED codes should be maintained and stored in the output.

Life Support and Habitation Topic X12

Achieving sustained human presence in space and on lunar and Martian sites requires innovative life support and habitation technologies. Proposals are sought that improve life support and habitation systems in the areas of: Advanced Life Support including closed loop, and to a lesser extent, open loop technologies for air revitalization (including lunar dust abatement technologies), water reclamation, solid waste management (including small disposal units for human waste), food management systems (including galley), and biomass production; Extra Vehicular (EVA) technologies including suit assembly, life support systems, power communications and information handling; Contingency Response technologies including fire prevention, detection and suppression, in situ fabrication and repair, and in situ resource utilization; Advanced Environmental Monitoring and Control including air, water and surface monitoring, external environment monitoring, and life support integrated control.

Sub Topics:

X12.01 Advanced Life Support: Air and Thermal

Lead Center: JSC

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

Advanced life support systems will be essential to enable human planetary missions as outlined in the Vision for Space Exploration. Innovative, efficient, and practical concepts are needed for regenerative air revitalization, ventilation, temperature, and humidity control. Requirements include safe operability in micro- and partial-gravity, ambient and reduced-pressure environments, high reliability, regeneration and minimal use of expendables, ease of maintenance, and low-system volume, mass, and power. Proposals should explicitly describe how their work is expected to improve power, volume, mass, logistics, crew time, safety and reliability, with comparisons to existing state-of-the-art technologies. Information and documentation on advanced life support systems can be found at http://advlifesupport.jsc.nasa.gov [2].

Air Revitalization

The management of cabin atmosphere in spacecraft and habitats includes concentration, separation, and control techniques for oxygen, carbon dioxide, water vapor, particulates and trace chemical components. This includes processing and recovering resources derived from waste streams and from in situ planetary resources. Technologies focused at closing the air loop will have higher priority. Areas of emphasis include:
• Atmosphere revitalization process integration to achieve energy and logistics mass reductions;

• Separation of carbon dioxide from a mixture primarily of nitrogen, oxygen, and water vapor to maintain carbon dioxide concentrations below 0.3% by volume;

• Recovery of oxygen from carbon dioxide including approaches to deal with by-products of the process;

• Regenerable processes for removing trace chemical components from cabin air and/or gas product streams from other systems (e.g., water reclamation, waste management, etc.);

• Regenerable, re-usable, particulate filters for air;

• Novel approaches to suspended particulate matter removal from cabin and habitat atmospheres, including approaches to isolating cabin and habitat living areas from external dust sources such as Martian or lunar soil; and

• Methods of storage and delivery of atmospheric gases to reduce mass and volume and improve safety.

Advanced Thermal Control Systems

Thermal control is an essential part of any space vehicle, as it provides the necessary thermal environment for the crew and equipment to operate efficiently during the mission. A primary goal is to provide advanced technologies for temperature and humidity control; however, advanced active thermal control also includes technologies in the areas of heat acquisition, transport, and rejection. Areas of emphasis include:

• Liquid-to-liquid heat exchangers that provide two physical barriers preventing inter-path leakage;

• Advanced technologies to control cabin temperature and humidity in microgravity. Condensate that is collected must be able to be recovered and transported to the water recovery system;

• Alternate methods of atmospheric humidity control that do not use liquid-to-air heat exchanger (dependent on the spacecraft active thermal control system) or mechanical refrigeration technology;

• Technologies to inhibit microbial growth on wetted surfaces. Applications include condensate collection surfaces for humidity control and heat exchangers resident in water loops;

• Lightweight, versatile, and efficient heat acquisition devices including flexible cold plates, to provide cooling to electronics, motors, and other types of heat producing equipment that is internal to the cabin;

• Lightweight, controllable, evaporative heat rejection devices that can operate in environments ranging from space, Mars' atmosphere, and Earth's atmosphere;

• Alternative heat transfer fluids that are non-toxic, non-flammable, and have a low freezing temperature;

• Energy storage devices that maintain the integrity of food or science samples. For maintenance of temperatures of -20°C, -40°C, -80°C or -180°C;

• Highly accurate, remotely monitored, in situ, non-intrusive thermal instrumentation; and
• Low-energy, low-noise, high-capacity fans or similar devices for moving air.

**Component Technologies**

Energy efficient, low mass, low noise, low vibration, or vibration isolating, fail-safe, and reliable components for handling gases, fluids, particulates, and solids applicable to spacecraft environmental control and air revitalization, including actuators, fans, pumps, compressors, coolers, tubing, ducts, fittings, heat exchangers, couplings, quick disconnects, and valves that operate under varied levels of gravity, pressure, and vacuum. Mass flow monitoring and control devices that have similar attributes and that are easily calibrated and serviced.

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**X12.02 EVA Technologies**

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

Advanced Extravehicular Activity (EVA) systems are necessary for the successful support of future human exploration space missions. Advanced EVA systems include the space suit pressure garment, the portable life support system, tools and equipment, and mobility aids such as rovers. Exploration EVA missions require innovative approaches for maximizing human productivity and for providing the capability to perform useful work tasks. Top-level requirements include reduction of system weight and volume, increased hardware reliability, maintainability, durability, and operating lifetime, increased human comfort, and less-restrictive work performance capability in the space environment, in hazardous ground-level contaminated atmospheres, or in extreme ambient thermal environments. Areas in which innovations are solicited include the following:

**Environmental Protection**

• Radiation protection technologies that protect the suited crewmember from radiation;

• Puncture protection technologies that provide self-sealing capabilities when a puncture occurs and minimizes punctures and cuts from sharp objects;

• Dust and abrasion protection materials or technologies to exclude or remove dust and withstand abrasion; and prevent dust adhesion; and

• Flexible space suit thermal insulation suitable for use in vacuum and low ambient pressure.

**EVA Mobility**

• Space suit low profile bearings that maximize rotation necessary for partial gravity mobility requirements and are lightweight.

**Life Support System**
• Long-life and high-capacity chemical oxygen storage systems for an emergency supply of oxygen for breathing;

• Low-venting or non-venting regenerable individual life support subsystem(s) concepts for crewmember cooling, heat rejection, and removal of expired water vapor and CO₂;

• Fuel cell technology that can provide power to a space suit and other EVA support systems;

• Lightweight convection and freezable radiators for thermal control;

• Innovative garments that provide direct thermal control to crewmember;

• High reliability pumps and fans that provide flow for a space suit but can be stacked to give greater flow for a vehicle;

• CO₂ and humidity control devices that, while minimizing expendables function in a CO₂ environment; and

• Variable conductivity flexible suit garment that can function as a radiator for high metabolic loads and as an insulator during period of low physical activity and low metabolic rates.

Sensors, Communications, Cameras, and Informatics Systems

• Space suit mounted displays for use both inside and outside the space suit-outside mounted displays will be compatible with the space environment;

• CO₂, bio-med (heart rate and blood oxygen level), radiation monitoring, and core temperature sensors with reduced size, lightweight, increased reliability, decreased wiring, and packaging flexibility;

• Visible spectrum camera that provides environment awareness for crewmembers and the public and are integratable into a spacesuit that is lightweight and low power;

• Lightweight sensor systems that detects N₂, CO₂, NH₄, O₂, ammonia, hydrazine partial pressures, including self-powered sensors;

• Lightweight, low power, radio and laser communications with the capability to integrate audio, video, and data on the same data stream to provide reliable communications between the crew and a lander or habitat; and

• Low power, lightweight, radiation hardened, or radiation tolerant informatics computer systems with standard graphics outputs and standard audio inputs and outputs, capable of running commercial operating systems and applications.

Integration

• Robot control by EVA crewmember via voice control or other methods;

• Minimum gas loss airlocks providing quick exit and entry and can accommodate an incapacitated crewmember; and

• Work tools that assist the EVA crewmember during operations in zero gravity and at worksites; specifically, devices that provide temporary attachments, which rigidly restrain equipment to other equipment and the
EVA crewmember, and that contain provisions for tethering and storage of loose articles such as tool sockets.

EVA Navigation and Location

- Systems and technologies for providing an EVA crewmember real-time navigation and position information while traversing on foot or a rover; and
- Systems and technologies for managing and locating tools during planetary surface science and maintenance EVA sorties.

X12.03 Contingency Response Technologies

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

Decades of experience in manned space flight have demonstrated that during any mission, unexpected events will occur. If the crew is adequately equipped to address such contingencies during exploration missions, the chances of successfully completing that mission can be greatly increased. The objective of this subtopic is to develop technologies in the areas of fire prevention, detection, and suppression (FPDS) and in situ fabrication and repair (ISFAR) that will support the crew in the event of a fire or if a critical component breaks during a mission, respectively. These technologies may be in the form of devices, models, and/or instruments for use in microgravity and/or for commercial applications on Earth. The top-level requirements for a viable technology include the reduction of system hardware weight and volume and increased hardware reliability, durability, and operating lifetime. Research conducted during the Phase 1 contract should focus on demonstrating the technical feasibility of the FPDS or ISFAR protocol/system and show a path toward a Phase 2-specific deliverable. The contractor will, when appropriate, deliver a demonstration unit of the instrumentation for NASA testing before the completion of the Phase 2 contract.

Fire Prevention, Detection, and Suppression

The objective of the Fire Prevention, Detection, and Suppression (FPDS) subtopic is to develop technologies that, when incorporated into the design philosophy and functional design of exploration vehicles and habitats, will quantitatively reduce the likelihood of a fire and reduce the impact to the mission should a fire occur. The element is composed of four major theme areas including: fire prevention and material flammability, fire signatures and detection, fire suppression and response, and analysis of fire scenarios. Innovations are sought in the following theme areas:

- Quantifying the effects of microgravity, 1/6-g (lunar) and 1/3-g (Martian) on the ignitability of materials and the subsequent flame spread, particularly related to determining relevant low-gravity behavior from normal gravity tests;
- Improving the performance of spacecraft fire safety systems through the development of advanced fire detection and suppression systems and strategies as well as predicting the effects of smoke and precursor
generation and transport; and

- Developing techniques for creating and analyzing the effectiveness of fire resistant materials and coatings, including fire prevention techniques, for spacecraft structures, radiation shielding materials, paneling, fabrics (cotton, paper, synthetics), foams, etc.

**In Situ Fabrication and Repair**

*In Situ* Fabrication and Repair develops technologies for life support system maintenance and integrated habitat radiation shielding fabrication with a focus on contingency response and maximization of *in situ* resource utilization to reduce launch mass and volume. The manufacture or repair of components during a mission is essential to human exploration and development of space. Fabrication and repair beyond low Earth orbit is required to reduce resource requirements, spare parts inventory, and to enhance mission security. Proposals are sought in the technical themes listed below:

- Application of Free Form Fabrication (FFF) methods to low gravity (3/8 and 1/6 g level) manufacturing of near net shape products and spare parts from *in situ* derived resources or provisional feedstock;
- Processes for extracting *in situ* resources into raw materials and feedstock for use with rapid prototyping technology;
- Extension of fused deposition methods to the use of binderless metal wire feed stock;
- Adaptation of ultrasonic consolidation methods to use narrow ribbon metal feedstock to reduce subsequent machining operations and waste;
- Novel and innovative *in situ* repair methods such as but not limited to: welding, composite repair, and self healing materials;
- Development of highly automated habitat construction methods that incorporates *in situ* materials on surface or primary structure may use *in situ* construction;
- Development of dust mitigation techniques applicable to planetary habitat construction;
- Integration of radiation shielding materials into habitat construction methods; and
- Innovative approaches for recycling of materials for secondary uses.

**X12.04 Advanced Environment Monitoring and Control**

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

This subtopic addresses monitoring and control technologies, which support the operation of an Advanced Life Support (ALS) system for future long duration space missions. There are two application areas: Acoustics Monitoring and Environmental Controls.
Acoustics Monitoring Section

The objective is a proof-of-concept acoustic sensor system consisting of fixed and crew-worn transducers. At least ten fixed transducers shall be distributed in a habitable volume of at least 2x2x6m. The goal for the fixed microphones is to provide sound pressure level measurements with Type I measurement accuracy over the Octave Band frequency range from 63 Hz through 20 kHz. The system shall be capable of measuring 1/3 Octave Band, Octave Band, and Narrow Band sound pressure levels averaged over a specified interval with user defined data acquisition parameters. The fixed microphones shall also operate as an acoustic dosimeter with Type III accuracy and shall measure and log the maximum, A-weighted, Overall Sound Pressure Level every 30 seconds for at least 24 hours. The system shall also detect Hazard Levels of 85+ dBA and generate an alarm. The crew-worn transducer, clipped to a shirt collar, shall operate as a Type III acoustic dosimeter and shall measure and log the maximum, A-weighted, Overall Sound Pressure Level every 30 seconds for at least 24 hours. The size and mass of the device shall be comparable to COTS dosimeters. All system measurements shall be carried out remotely and the data managed by software. The system shall be demonstrated in a mock-up, and calibrations and comparisons made with appropriate instruments and methods.

Environmental Controls

Advanced Environmental Controls - the development of advanced control system technologies is necessary for the integrated operation of environmental systems for future long-duration human space missions. The interdependence of advanced environmental processing systems requires a non-avionics requirements process that allows design for controllability. This year particular emphasis is placed on the following:

- Control strategies for closed-loop systems - closed loop and biological systems have different constraints and control paradigms than conventional processes. There is a need for new control algorithms, analyses, design methodologies, strategies, and techniques to provide this capability;

- Ontologies for integrated operations - human exploration missions involve hundreds of systems developed by dozens of organizations. To develop software that can integrate across these systems and integrate with operations requires the use of common terminology across multiple disciplines. A common ontology must be developed to enable the integration of control of advanced life support systems; and

- Development and integration of autonomous system and inter-system control with crew and ground operations - there is a need for tools, architectures, and technologies that can support the integration of operations between crew, ground operators, ground applications, and on-board applications.

X12.05 Advanced Life Support: Food Provisioning and Biomass

Lead Center: JSC

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

Exploration missions beyond low Earth orbit greatly limit allowable consumables and require development of innovative low maintenance, reconfigurable, reusable, or self-sufficient food production. Advancements are necessary to develop a combination of extended duration shelf life stored foods augmented with fresh foods grown within the spacecraft. Crop systems, in addition to producing fresh vegetables, storage roots, grains and legumes may contribute to air revitalization and utilize wastes from water recovery and waste management systems.
Crop Systems

The production of biomass (in the form of edible food crops) in closed or nearly closed environments is essential for the future of long-term planetary exploration and human settlement in lunar and Mars base applications. These technologies will lead not only to food production but also to the reclamation of water, purification of air, and recovery of inedible plant resources in the comprehensive exploration of interplanetary regions. Areas in which innovations are solicited include:

- Crop lighting, such as LED, solar collectors and innovative technologies. Lighting transmission and distribution systems, luminaries, fiber optics, water jackets, and other heat removal technologies are also areas of interest;
- Water and nutrient management systems such as hydroponics and/or solid substrates for food production and separation of nutrients from waste streams are solicited. In this area, regenerable media for seed germination plant support are also of interest as is separation and recovery of usable minerals from wastewater and solid waste products for use as a source of mineral nutrients. Consideration should be given for systems operation in microgravity and hypogravity (1/6 g on Moon, 3/8 g on Mars) environments; and
- Other areas of interest: crop mechanization and automation, facility or system sanitation, crop health measurement, flight equipment support, structures and environmental monitoring and control technologies that are specific to crop systems (e.g., ethylene detection and removal, sensors for root zone oxygen and water content, etc.).

Food Provisioning

- Safe, nutritious, acceptable, and varied shelf-stable foods with a shelf life of 3 to 5 years will be required to support the crew during future exploration missions to the Moon or Mars. Shelf-life extension may be attained through food preservation methods and/or packaging. Packaging materials must provide sufficient oxygen and water barrier properties to maintain shelf life. Food packaging technologies are needed that minimize a potentially significant trash management problem by using packaging with less mass and volume and/or by using packaging that is biodegradable, recyclable, or reusable;
- Processing crops or bulk ingredients into edible food ingredients or table-ready products will be necessary to provide a self-sustaining food system for an exploration mission. Equipment that is highly reliable, safe, automated, and minimizes crew time, power, water, mass, and volume will be required. Equipment for processing raw materials must be suitable for use in hypogravity (e.g., 1/6g on Moon, 3/8g on Mars) and in hermetically sealed habitats;
- Food preparation systems will be required to heat and rehydrate the shelf stable food items and to prepare meals from the processed and re-supplied items. Technologies to support on-orbit crew meal storage, preparation, dining activities, and trash dispensing are being sought; and
- Food quality and safety are essential components in the maintenance of crew health and well being. Efforts should be focused on control of food spoilage and food quality throughout the entire shelf life of the food. Effects of radiation on crop functionality and the stored food system quality are also needed.
X12.06 Habitation Systems

Lead Center: JSC

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

Habitation Systems

Habitation systems for future crewed micro-gravity transits, reduced gravity planetary lunar or Martian surfaces, and long duration, deep-space environments are requested. Products can include basic research, system analysis, mockup evaluation, functionality demonstrations/tests, and actual prototype hardware. Exploration missions away from low Earth orbit greatly limit allowable consumables and require development of innovative low maintenance, re-configurable, and reusable systems. Minimal volume configurations (or dual use) during non-use mission phases are highly desirable.

Habitation systems should consider the following broad themes: re-configurable crew volumes for multi-gravity environments (micro and reduced gravity), multi-use work stations, multi-gravity translation strategies, crew radiation exposure mitigation, physically and psychologically ergonomic personal volumes, automated deployment, quiescent operations between missions, multi-purpose stowage systems for food/trash, advanced hygiene systems, and automated housekeeping/self-repairing habitat surfaces, durability, commonality of hardware/systems, and low total life-cycle costs. Specific areas in which advanced habitability system innovations are solicited include:

**Wardroom Systems**: Erectable or inflatable systems that support crew dining, conference, external viewing (windows), illumination, and relaxation activities. Includes off-nominal uses (emergency medical or repair) while maintaining hygienic conditions.

**Galley Systems**: Systems requiring minimal crew preparation (heating, cooling, and rehydration) for food heating and accurate water dispensing. Specific areas include systems that allow individual crew meal flexibility and high-energy efficiency.

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

**Crew Accommodation Systems**: Reconfigurable, deployable, or inflatable integrated crew accommodations that provide visual and acoustical isolated crew volumes for sleeping, audiovisual communication/entertainment, personal stowage, quiet ventilation/thermal control, and radiation exposure reduction/safe-haven.

**Clothing Systems**: Low mass reusable or long usage clothing options that meet flammability, out gassing, and crew comfort requirements. Used clothing cleaning/drying systems with low-water usage and non-toxic detergents/enzymes compatible with biological water reclamation systems or non-water cleaning methods.
**Stowage Systems:** Interior/exterior stowage systems for partial gravity environments that maximize usable volume and include contents identification and inventory control systems. Long-term external stowage for biological or other wastes on a planetary surface that safe and consistent with planetary protection policies.

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**X12.07 Advanced Life Support: Water and Waste Processing**

**Lead Center:** JSC

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

Regenerative closed-loop life support systems will be essential to enable human planetary exploration as outlined in the Vision for Space Exploration. These future systems must provide additional mass balance closure to further reduce logistics requirements and to promote self-sufficiency. Recovery of useful resources from liquid and solid wastes will be essential. Requirements include safe operability in micro- and partial-gravity, ambient and reduced-pressure environments, high reliability, regeneration and minimal use of expendables, ease of maintenance, and low-system volume, mass and power. Proposals should explicitly describe how the work is expected to improve power, volume, mass, logistics, crew time, safety and/or reliability, giving comparisons to existing state-of-the art technologies. Additional documentation and information can be found at [http://advlifesupport.jsc.nasa.gov](http://advlifesupport.jsc.nasa.gov) [2], including the expected composition of solid wastes and wastewater, which can be found within the "Baseline Values and Assumptions Document".

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**Water Reclamation**

Efficient, direct treatment of wastewater and product water consisting of urine, brines, wash water, humidity condensate, and or product water derived from *in situ* planetary resources, to produce potable and hygiene water supplies. Technologies that contribute to closing the water loop will be given higher priority. Areas of emphasis include:

- Novel methods of process design and integration to minimize trace contaminant carryover from the cabin atmosphere leading to reduced logistics needs;
- Physicochemical methods for primary wastewater treatment to reduce total organic carbon from 1000 mg/L to less than 50 mg/L and/or total dissolved solids from 1000 mg/L to less than 100 mg/L;
- Post-treatment methods to reduce total organic carbon from 100 mg/L to less than 0.25 mg/L in the presence of 50 mg/L bicarbonate ions, 25 mg/L ammonium ions and 25 ppm other inorganic ions;
- Methods for the phase separation of solids, gases, and liquids in a microgravity environment that are insensitive to fouling mechanisms;
- Methods for the recovery of water from brine solutions;
- Methods to eliminate or manage solids precipitation in wastewater lines;
Disinfection technologies for potable water storage and point-of-use. Residual disinfectants for potable water that is compatible with processing systems including biological treatment; and Techniques to minimize or eliminate biofilm and microbial contamination from potable water and water treatment systems, including components such as pipes, tanks, flow meters, check valves, regulators, etc.

Solid Waste Management

Wastes (trash, food packaging, feces, biomass, paper, tape, filters, water brines, clothing, hygiene wipes, etc.) must be managed to protect crew health, safety, and quality of life, to avoid harmful contamination of planetary surfaces (Moon, Earth, and Mars), and to recover useful resources. Treatment methods can include both oxidative and non-oxidative approaches. Areas of emphasis include:

- Volume reduction of wet and dry solid wastes;
- Small and compact fecal collection and/or treatment systems;
- Water recovery from wet wastes (including human fecal wastes, food packaging, brines, etc.);
- Stabilization, sterilization, and/or microbial control technologies to minimize or eliminate biological hazards (to the crew, to Mars, to Earth) associated with waste;
- Mineralization of wastes (especially fecal) to ash and simple gaseous compounds (e.g. CO₂, CH₄);
- Containment of solid wastes onboard the spacecraft that incorporates odor abatement technology;
- Containment devices or systems, with low volume and mass, that can maintain isolation of disposed waste on planetary surfaces (such as Mars); and
- Microgravity-compatible technologies for the containment and jettison of solid wastes in space.

Component Technologies

Energy-efficient, low-mass, low-noise, low-vibration or vibration isolating, fail-safe, and reliable components for handling fluids, slurries, biomass, particulates, and solids applicable to spacecraft wastewater treatment and solid waste management, including particle size reduction technologies (0.2 cm to 100 microns), actuators, pumps, conveyors, tubing, ducts, bins, fittings, tanks, couplings, quick disconnects, and valves that operate under varied levels of gravity, pressure, and vacuum.
Human Systems Integration Topic X13

Long-term presence in space in confined, isolated, and foreign environments may lead to impairments of human performance and behavioral health problems. Proposals are sought in the areas of space human factors engineering such as physical, cognitive, and team performance; behavioral health and performance including psychosocial, neurobehavioral adaptation as well as cognitive task performance, and sleep and circadian rhythms. The topics include, but are not limited to: design and verification tools that provide predictions of human-system performance; tools that facilitate designing human-system interfaces or environments; tools useful in verifying human-system requirements; psychological factors relevant to crew selection and performance; pre-launch and in-flight crew training systems; self-sufficient operations in case of emergency and without external resources; technology that can assist the mission control operations: design of workflow in vehicle maintenance, preparation checkout, and launch control.

Sub Topics:

**X13.01 Space Human Factors Engineering**

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

The long-term goal for this subtopic is to enable planning, designing, training, and carrying out human space missions of up to 5 years with crew independence, without re-supply and without real-time communications to Earth. Specifically, this subtopic's focus is the development of innovations in crew equipment; and the development of technologies for assessment, modeling, and enhancement of human performance; and the development of design tools for engineers to incorporate human factors engineering requirements into hardware and software. Proposals are solicited that seek to develop technologies that address these specific needs:

- Monitoring and maintaining human performance non-intrusively. Specifically, minimally invasive and unobtrusive devices and techniques to monitor the behavior and performance (physical, cognitive, perceptual, etc.) of individuals and teams during long-duration space flights or analog missions. Embedded measures to detect significant changes in crew readiness to perform physical or cognitive tasks;

- Predicting human performance: methods and models for predicting effects on physical performance of encumbrances of clothing, space suits, etc. Models for predicting effects of physical environment (e.g., lighting, noise, temperature, contaminants) on human performance. Models to simulate and optimize interactions between humans and equipment/vehicle. Capability to implement time-delay algorithm and functionality into simulation for higher fidelity and effectiveness. Models for predicting effects of cognitive changes on performance;

- Tools to aid in design and evaluation of human-system interfaces for speed, accuracy, and acceptability in a cost-effective and reliable manner: automated analysis of computer-user interfaces for complex display systems to conduct objective review of displays and controls, and to determine compliance with guidelines and standards. Quantitative measures of the effectiveness of user interfaces to be used for task-sensitive evaluations;

- Tools that facilitate the user interface design for human computer interfaces, and for facilitators such as procedures, labels, and instructions. Tools should assist the designer in incorporating contextual information such as the user’s task, the user’s knowledge, and the system limitations; and

- Tools to build just-in-time system and operational information software to aid human users conducting routine and emergency operations and activities. Such tools might include effective and efficient job aids (e.g., “intelligent” manuals, checklists, and warnings) and support for designing flexible interfaces between users and large information systems. Methods for development of “facilitators” (procedures, labels, etc.) adapted for the development of space vehicle and payload applications.
X13.02 Behavioral Health and Performance

Lead Center: ARC

Behavioral Health and Performance provides the necessary technology, techniques, capabilities, and knowledge that will support mission success, during human exploration flight and return to Earth. This will be accomplished by optimizing the behavioral health and performance of each astronaut and crewmember, and by mitigating psychosocial, neurobehavioral, sensorimotor, cognitive, and sleep chronobiology risks. Behavioral health and performance research contributes to medical standards, guidelines, and requirements and produces design tools and diagnostic measures for the Chief Health and Medical Officer, flight surgeons, and astronauts. The technical areas supported by this program include performance readiness, effective and efficient teamwork for pre-, in-, and post-flight expedition missions, and psychological selection validated criteria, tools, and procedures. Prolonged missions and the associated adaptation and de-conditioning due to microgravity, as well as significant time delays between Earth and the space environment increase the likelihood of serious crew conflict as well as behavioral health and performance decrements. Proposals are solicited that seek to develop core knowledge, predictive models, and enabling technologies that address these specific needs:

- Non-intrusively monitoring and maintaining human performance. Specifically, minimally invasive and unobtrusive devices and techniques to monitor the behavior and performance (physical, cognitive, perceptual, sensorimotor, etc.) of individuals and teams during long-duration space flights or analog missions. Embedded measures to detect significant changes in crew readiness to perform physical or cognitive tasks; and

- Monitoring and maintaining non-intrusively behavioral health. For example, self assessment tools for determining levels of stress, fatigue, conflict, and anxiety of an individual crewmember and training techniques for coping and on-board support tools for behavioral health.

X13.03 Systems Engineering and Requirements

Lead Center: JSC

Participating Center(s): ARC, KSC

The goal of effective Human Systems Integration challenges many areas of technology, including distributed data management and control, sensor interpretation, planning and scheduling, modeling and simulation, and validation and verification of autonomous systems. These various technology areas must eventually be integrated into a system-of-systems. Particular emphasis is placed on the following:

System Engineering Tools

Technologies, tools, and methodologies are needed that assure development activity is congruent with Exploration Mission capability requirements. Decision support tools are needed to help in the visualization of portfolio balance and clear representation of complex systems as well as a capture method for the interactions/interdependencies/interfaces between system elements.
System Simulation Tools

The ability to analyze, synthesize, and develop integrated function-based and simulation-based system architectures in support of Human Systems. Key to this requirement is either the further extension/enhancement of current available SE tools or acquisition/development of tools that will allow for system level concept development and concept simulation.

System Integration Tools

The ability to enable human system integration for exploration missions is strongly affected by the structure and architecture of the systems used to sustain and protect the crew. There is a need for the development and evaluation of control architectures and strategies for determining relative benefit, risk, and costs of the utilization of candidate system architectures. Tools for capturing state knowledge of the entire portfolio by project, including dependencies, maturity, and relationships to requirements are also needed.

Capability-based requirements methods require tools and methodologies that enable capture of current practice for information integration between ground-based systems, on-board systems, and crew systems; goal analysis; surveys of existing and proposed technologies; mapping of technology to tasks; prototyping; integrated testing and evaluation criteria; and development of experienced personnel.

Integration Test Bed Tools and Applications

Integrated ground tests for human exploration missions will provide a test bed for development of hardware, requirements, hardware acquisition strategies, novel system concepts, and management. Tools are needed that provide techniques for real-time analysis; techniques for planning, scheduling, and conducting complex integrated mission simulations; tools to develop system-level mathematical models of missions; and systems engineering and analysis tools for mission architecture studies.

Human-System Integration for Manufacturing and Launch Site Operations

Human-System Integration of Manufacturing and Launch Site Operations addresses the following functional areas: Manufacturing, Spacecraft Processing, Launch Control, Landing and Recovery, Repair and Refurbishment, and Enabling Operations. Specific areas of interest include intelligent work instruction systems; maintainer/launch controller situational awareness; human/robotic maintainer on-board capability; reduced size ground crew training modules; and predictive labor requirement models.

Research should be conducted to demonstrate technical feasibility during the Phase 1 contract and show a path toward a Phase 2 hardware and software demonstration. The contractor will, when possible, deliver a demonstration unit of the monitoring instrumentation for NASA testing before the completion of the Phase 2 contract.
Space-Based Industry Enabling Technologies Topic X14

The goal of this topic is to enable the optimization of investments made in technologies for the development of systems to support and maintain space-based industries and for benefiting NASA's exploration missions infrastructures. As stated in the Report of the President's Commission on Implementation of United States Space Exploration Policy, "This new space industry will reduce the cycle time for critical technology innovation. It will immeasurably augment NASA's ability to explore the universe." It is anticipated that, in order to go to the Moon and beyond, a sizable in-space commercial infrastructure will be required. NASA will need this commercially driven infrastructure to build upon in order to further exploration that is affordable and sustainable. This topic seeks breakthrough technologies, concepts, and methods that reduce the cost and risks of the expansion of space-based industries. Innovative approaches are needed that identify what the space-based industries might be doing and their needed infrastructures as well as the technologies required to achieve the infrastructures.

Sub Topics:

**X14.01 Space-Based Industries**

**Lead Center: MSFC**

Innovative techno-economic research proposals are sought for space-based industries ideas that identify their purpose, basic required infrastructures, and how they might complement NASA's exploration missions. The Phase 1 work must sufficiently develop one or more industry ideas to show they are sufficiently feasible, both technically and economically, for Phase 2 demonstrations of their viability. The demonstrations may use physical and mathematical modeling and other research techniques. Each industry idea may have infrastructures that include a wide variety of needed innovations that will be common to NASA's exploration goals as well as to space industries that have a wide variety of purposes like tourism, servicing and maintenance of satellites, food production, energy production, fuels and propellants production, entertainment, in-space fabrication, workshops, hotels and habitats, life support systems, vehicles, freight and warehousing, roads, and spaceports. The research should include economic business models, cost feasibility examination, and analyses that can show how innovations that are common to the multiple goals can save money for NASA as well as space industries. The technical innovations may include, but are not limited to: materials, fabrication processes, power and power distribution, communications, waste management, robotic support, and more. It is expected that the technical innovative ideas will go further than the specific exploration topics and subtopics requests made elsewhere in this 2005 solicitation due to the broader scope of applications.

**X14.02 Multi-Use Microgravity and Software**

**Lead Center: JSC**

The purpose of this subtopic is to develop technologies, methodologies, and tools that can support the integrated development of the software system-of-systems necessary for exploration missions. Human space flight challenges many areas of software technology, including distributed data management and control, sensor interpretation, planning and scheduling, modeling and simulation, and validation and verification of autonomous systems. This subtopic focuses on the development portion of the mission life cycle and the dependence of the eventual mission solutions on the processes and methods used to define and build vehicles and support operations. The need for such technologies, methodologies, and tools is evidenced by the low success rate of commercial and government
systems, where failure occurs at delivery rather than during operation. Management of the development of such large systems is essential to integration.

Software Architecture and Systems Integration

The challenges of human system integration for exploration missions is strongly affected by the structure and architecture of the software systems required to provide control and status pathways to ground support systems and personnel; to support mission planning and operation; to provide crew interfaces for status, control, and operation of the vehicle systems, science, and operations, including communications, planning, task management, interpersonal activity, system configuration management, inventory, food, workflow, resource management, experiments, and vehicle operation and maintenance. Onboard software must integrate, and be interoperable with the ground support systems for planning, logistics, operations, science, medical, and engineering, as well as with subsequent exploration spirals. This requires the development of structures and methods for determining relative benefits, risks, and costs of the utilization of various engineering approaches. Project management tools are needed that can conduct and manage Exploration Mission capability and technology gap analysis; provide technology-to-capability mapping; map technology gaps to research initiatives; and provide decision support.

Systems Engineering Support to Human Systems

There is a need for new tools to support the development of non-avionic control systems throughout the program life cycle. This includes tools for managing prototyping, requirements, design, design knowledge capture, testing, and growth and maintenance across multiple development teams. Particular emphasis is placed on design methods that address the interdependencies between systems. Adapting the Joint Capabilities Integration and Development System (JCIDS) approach to systems engineering requires development of tools and methodologies that enable: surveys of current information integration practices between ground-based systems, on-board systems and crew systems; goal analysis (software task analysis); surveys of existing and proposed technologies; mapping of technology to tasks; prototyping to drive out design constraints and detailed requirements; development of testing and evaluation criteria for advanced or untried architectures and technologies and maturation of those technologies into an integrated system of systems; tracking lessons learned, methods, and processes; and development of an experienced personnel base.

Research should be conducted to demonstrate technical feasibility during the Phase 1 contract and show a path toward a Phase 2 demonstration. The contractor will, when possible, deliver a demonstration unit of the hardware and software for NASA testing before the completion of the Phase 2 contract.
The goal for this subtopic is the development of advanced space technology to further high-performance computers and computing architectures and reliable electronic systems that can operate effectively for long periods of time in harsh environments. These systems require management of low power and radiation, and must be reliable, robust and reconfigurable.

The objective for this development goal is to elicit novel architectural concepts and component technologies that have realistic potential and achievable applications and are responsive to the priority areas of this subtopic. Technologies will be selected based on the potential that their final end products are sustainable (affordable, reliable/safe and effective), and will advance solutions to the challenges of reusability, modularity and autonomy. Priority areas are:

**Data processing**

- General purpose processors (piece part, rather than an entire board) possessing fault tolerance at cell and or die levels, floating point and error correction.
- Technologies that reduce the physical size and power requirements of computing systems: making the data system more adaptable, modular, and cost effective.
- New standard models for analysis of interplanetary radiation and radiation belts, and technologies that enable radiation measurements such as total dose and single event effects in computing systems: enhances capability to design radiation tolerant data systems, monitor systems in flight, and predict errors and contingencies.

**Reconfigurable Electronics and Implementations**

- Reconfigurable designs and architectures that support fault tolerance and are functionally and physically modular.
- Solutions, designed around generic blocks, for recovery from multipoint failures (as opposed to single fault) component failure, where a system can monitor and identify the failing components, and self-repair or bypass small portions of the electronics. These prioritized generic blocks would enable graceful degradation of higher functions while maintaining the system core functionality.

**Data System Support Electronics**

- Radiation-hard microcontrollers, phase lock loops (PLL), and high-speed oscillators (greater than 150 MHz, equal duty cycle).
- FPGA: Environmentally tested, reliable, tolerant IO, radiation hardened cell structures, Anti-Fuse or reconfigurable.
- Robust and reliable non-volatile storage devices such as EEPROMs and FLASH memory.

**Command and Data Transfer**
Inter-system data transfer communications between spacecraft subsystems based on standard interfaces that address high multi-drop throughput (10 to 100 mbps), self diagnosis, inherent redundancy and low power, and support subsystem data transfer to realize higher autonomy.

Intra-system data transfer communications within the spacecraft subsystems, between cards within a box, to replace the conventional passive backplanes, e.g., switched fabric backplanes with fault detection and serial interfaces.

Sub Topics:

Extreme Environment Electronics/SEE Topic X1.02
Moon equatorial regions experience wide temperature swings from -180°C to +130°C during the lunar day/night cycle, and the sustained temperature at the shadowed regions of lunar poles can be as low as -230°C. Mars diurnal temperature changes from about -120°C to +20°C. All exploration endeavors, including robotic, habitat, and ISRU systems that are expected to reliably operate on the Moon or Mars surface for years will need electronics that are able to survive and operate in a wide temperature range and thermal-cycling environment. The lunar and Martian temperatures are well outside the specification range of military and commercial electronics. While many types of devices, especially Si CMOS transistors, can operate down to low temperatures. There are significant circuit design challenges that need to be addressed, especially in the case of mixed signal and analog circuits.

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

Proposals are sought in following specific areas:

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

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

- Wide temperature (-180°C to +130°C) and ultra-low temperature (-230°C) RF electronics for short range and long-range communication systems.

- Computer Aided Design (CAD) tools for predicting the electrical performance, reliability, and life cycle for low-temperature electronic systems and components.
Research should be conducted to demonstrate technical feasibility during Phase 1 and show a path toward a Phase 2 hardware/software demonstration, and when possible, deliver a demonstration unit for testing at the completion of the Phase 2 contract.

Sub Topics:
Sensing and Imaging Topic X1.03
Sensing and imaging systems can provide a number of capabilities required for anticipated NASA missions including exploration of Mars and the Moon. Capabilities of interest include the following:

- Orbiting sensors to map:
  - Extent and concentration of useful, surface, or subsurface resources to identify promising outpost or science sites and traversable terrains;
  - Surface topography and roughness to identify promising safe landing sites for human, robotic science, and pre-provisioning missions, and to guide pinpoint landing algorithms.

- Robot-mounted sensors for: estimating robot pose and motion; recovering 3D scene structure; identifying hazards or objects of interest; identifying articulation of observed objects, and performing visual serving. Flight ready (radiation and temperature hardened), high cycle rate, and low power systems are generally preferred. Applications include:
  - Autonomous rendezvous and docking;
  - Pinpoint landing;
  - Surface navigation;
  - Surface and on-orbit assembly/construction;
  - Resource mining/processing;
  - Multi-vehicle cooperation.

Specific technologies of interest in addressing these challenges include:

- Rapid frame rate arrays for 1, 1.5 and 2 µm vision (2D and 3D);
- Multi-wavelength laser arrays;
- Flight-ready, high-speed, medium-resolution (640x480) stereo-vision sensors;
Flight-ready, low-power lighting systems (headlights) to allow imaging during nighttime robotic operations;

- Tightly coupled inertial and vision sensors for pose estimation;

- Ground truthing systems for evaluating performance of ranging systems.

A number of related technologies are of interest but are covered under other subtopics, including:

- High power or high rep-rate lasers (S6.02, S1.04);
- Ultra-high sensitivity detectors and arrays (S4.01);
- Active and passive microwave sensors (S6.04, S6.05).

Sub Topics:
Surface Networks & Access Links Topic X1.04
To develop safe and sustainable exploration capabilities at minimum cost, while maximizing return, an incremental spiral development process will guide a build out of an integrated communication, navigation, networking, computing, informatics, and power architecture that supports all surface and proximity nodes, including humans in spacesuits, robots, rovers, human habitats, satellite relays, and pressurized vehicles.

The architecture will enable operational activities in which both fixed and mobile nodes with vastly differing communications requirements are seamlessly interoperable. Nodes are simultaneously connected to each other, to Earth, and to the CEV via in-space relay orbiters, and via wired and wireless networks that provide the bidirectional voice, video, and data needed. The need to be self-sufficient during exploration requires local control and an unprecedented level of autonomous operation to seamlessly connect the nodes and reduce operations cost. The Moon and Mars environments require SEU and extreme temperature-tolerant equipment tightly constrained by power, mass, and volume. Human presence requires at least one usable bidirectional link to the communications network at all times and high definition video to engage the public interest.

This subtopic focuses on the modular, reconfigurable RF communications and networking technologies needed to support a human presence on remote lunar and planetary surfaces with surface-to-surface and surface-to-orbit (access) communications.

Surface Networks
The complexity of astronaut excursions, habitats, surface manned and unmanned rovers, and landers make surface operations and man-occupation complex and daunting tasks. Exploration of planetary surfaces will require short-range, bidirectional, multi-point links to provide on-demand, autonomous interconnection among surface-based assets. Some of the nodes will be fixed (base stations) and some will be moving (rovers and humans). This will encompass a number of communications and networking technologies for communications in the 2.4 Ghz range, including: integrated low mass, low power (100's of milliwatts) transceivers for very short-range interfaces with sensors and other small devices; power-efficient, miniature, modular transceivers for short-range communications among large (e.g., lander) and medium-sized (e.g., rover) surface assets; reconfigurable directionally selectable, multi-frequency arrays for wide coverage, high-gain links among surface assets; miniaturized modular antenna technology for surface-to-surface communications among mobile and fixed nodes;
wireless products integrated with low-power space-rated ASICs and FPGAs; short (~ 1km) range access point base stations, or wireless router bridges for extending surface network coverage; fixed, long (~ 50km) range, wireless network terminals for extending high data rate communications over large distances; self-healing ad-hoc network MAC and protocols for intelligent, autonomous link management; and networking technologies to enable autonomous, seamless interconnectivity among all nodes.

**Access Links**

To interface with orbiting relays, terminals capable of providing seamless connectivity between surface networks and orbiting relays will be positioned on lunar and planetary surfaces and in orbit. Such an access link communications system will include: high rate, efficient, solid state amplifiers capable of very high data rates over 1,000-10,000 km distances with ranging signals embedded; very low-power data rates, and cost inter-spacecraft S-band transceivers/transponders for inexpensive spacecraft; optical transceivers capable of very high data rates over 1,000-10,000 km distances; SEU and solar flare tolerant transponders capable of: programmable wide-carrier frequency ranges from S-band to Ka-band, taking GPS measurements, and handling IP at the digital level; micro software radio technology for autonomous and intelligent space applications; low mass, volume, power, and cost-stable oscillators to provide accurate time and frequencies for autonomous operations; autonomously reconfigurable receivers capable of automatic link configuration and management; microwave ranging hardware built into communication systems for rendezvous and collision avoidance; and ad hoc long range spacecraft-to-spacecraft network protocols to setup links on demand, such that each node can route data through to another node.

**Sub Topics:**

**Advanced Materials Topic X2.01**

Technology areas included in this subtopic are high performance, super lightweight structural materials, space-durable materials, multifunctional materials, and flexible material systems. Materials of interest include ceramics, metals, polymers, and their composites as well as coatings for erosion resistance and environmental protection. Proposals with innovative and revolutionary ideas in the area of advanced materials are sought for explorations applications such as:

- Flexible fabrics and thermal insulation for spacesuits and habitats;
- High strength-to-weight and high temperature composite materials for lightweight vehicle structures and power and propulsion systems;
- Self-healing materials to repair damage to spacesuits, habitats, and wire insulation electronics, sensing, and actuators for monitoring system health and adapting to changing mission conditions;
- Flexible fabrics relevant to mission needs such as inflatable systems for ballutes, habitats, airbags, parachutes, and suits;
• Innovative approaches to materials systems yielding durable, lightweight, flexible films and fabrics.

Sub Topics:
Structures and Habitats Topic X2.02
This subtopic solicits innovative structural concepts, materials, and assembly techniques that support the development of modular space systems. Also needed is a criteria to judge the different concepts in terms of impact on the overall performance and weight. Structural concepts can include inflatable, erectable, deployable, or easily connected modules to create large space structures utilizing membranes, composites, or other material concepts. Modular units can provide reconfigurable structures, such as multiple-energy configurations using cables and linkages, compliant structures or mechanisms that adapt to varying surfaces, or multi-purpose integrated structures, such as load-bearing modular power distribution, thermal management, or radiation protection systems. Additionally, this subtopic includes research related to novel rotating devices, actuators, tribology, and seals. It further includes intelligent structural, electrical, and fluid interfaces to enable the assembly (or ‘self-assembly’) of modular systems.

Of particular interest are inflatable structures and habitats to minimize launch volume and costs. Large inflatable structures can be folded into compact packages for launch, pressurized for deployment once in space, and rigidized after deployment so that internal pressure is not required to maintain structural stiffness and shape.

New concepts, materials, and methods for in-space structures and habitats to enable humans to safely and effectively live and work in space are needed. Specifically, structures or habitats with integral radiation shielding, impact shielding, thermal management, and integral diagnostics/health monitoring capabilities are of interest as well as high strength-to-weight materials (e.g., foamed materials), structural elements, and beams that can be deployed or fabricated in situ. Development of smart and multifunctional modular structures, including the use of embedded sensors and actuators, is encouraged.

Also solicited are assembly technologies such as innovative connectors for joining and/or bonding techniques, module positioning and alignment concepts, component deployment or erection concepts, and component/module inspection and verification techniques. Structures and materials that support reconfigurable modular architectures are also solicited.

Modeling and structural testing techniques and analyses that support the design of modular structural concepts or their assembly are of interest. Two areas are of particular interest: one is controls-structures interaction (CSI) techniques and the second one is hybrid-test and physics based-modeling approaches. Application of advanced controls-structures interaction (CSI) techniques for measuring and controlling structural dynamics and geometry are important. Solutions for incorporation of CSI techniques for controlling such inflatable structures are also highly desirable. On hybrid modeling, ways to integrate test and physics-based models for cases where the physics-based models are not sufficient is also desirable.

Sub Topics:
Nanostructured Materials Topic X2.03
The applications of advances in Nanotechnology are anticipated to have a profound impact on NASA's future missions by offering significant advantages in terms of cost affordability and reliability from multifunctional materials. Nanotechnology enables systems performance beyond those expected from conventional materials. While many fundamental findings are reported in the literature, there is a strong need to focus efforts on the demonstration of real benefits provided by nanostructured material systems.

It is especially interesting to meet exploration challenges with the development of high strength-to-weight and multi-functionality possible from the unique combinations of desirable properties of the nano-structured materials. The promise of high strength-to-weight, multi-functional, nano-structured materials has led to intense interest in developing them for near-term applications for human spaceflight and exploration.

Nano-structured materials of interest include, but are not limited to, the utilization of single wall, carbon, nanotube-based composites, ceramic nanofibers, and bio/nano-inspired materials and composites.

Due to the size scale and fundamental physical properties of the structures involved, a successful proposal for applications development should demonstrate a mature understanding of nano-material synthesis and material quality, as well as incorporate the development and use of new characterization methodologies to fully assess the impact of the nano-structured materials upon a given matrix or system.

The specific focus of this subtopic will include, but not be limited to:

- New materials for structures and components offering significant mass reduction and increased strength with improved thermal conductivity, low permeability, low density, and improved damage tolerance through self-repairing mechanisms;
- Application of nano-structured materials to self-healing and self-repair materials and concepts;
- Nano-structured materials offering enhanced radiation protection;
- Development of nano-material systems that are resistant to large thermal fluctuations, radiation, electrostatic charging, abrasion, and micrometeoroid debris damage;
- Nano-materials for energy generation, storage, and distribution.

Sub Topics:

Power Generation & Transmission Topic X3.01
All innovative technologies for power generation and conversion are highly encouraged under this subtopic. Proposals addressing technologies, including solar photovoltaic conversion, thermo-photovoltaic conversion, thermoelectric conversion, and thermodynamic conversion (heat engines), etc., are encouraged. In addition,
research and technology development in topics related to advanced power cabling and power management are also needed.

Significant improvements in photovoltaic systems are required to enable future exploration missions. Dramatic increases in array mass specific power (>1000 W/kg), reductions in stowed volume, increases in operational voltages to 1000V, increases in radiation hardness enabling reliable operation in high-radiation environments, increases in survivability over wide temperature extremes, as exists on a lunar surface, and developments of automated deployment systems for surface power applications. Developments are sought for photovoltaic cells on flexible, ultra-lightweight substrates, array technologies that maintains the high mass specific power of these cells, nanostructures incorporated to enhance the performances of thin-film, organic/inorganic, or single-crystal photovoltaic cells and thermo-photovoltaic cells. Demonstrations of high efficiency, lightweight, concentrator cell and supporting array techniques, multi-quantum well and multi-quantum dot devices, and advanced multi-band gap devices are also of interest. Advanced photovoltaic areas of emphasis include high-efficiency quantum well technology. Nano-engineered materials are an area of emphasis for all of these applications.

High power solar dynamic power conversion systems, including Brayton and Stirling, support the development of solar-electric propulsion and power systems requiring low overall system specific mass (kg/kW). The objectives for solar dynamic systems, with power output capacities ranging from 100W to >100kW, require demonstrating thermal efficiencies greater than 30% over a range of cycle temperature ratios and heat rejection temperatures. A system specific mass of

Technological advances are needed for large deployable solar concentrators and secondary concentrators, high temperature heat receivers with thermal energy storage capability, and advanced lightweight heat rejection sub-systems. For Brayton power, advances are needed in ceramic high temperature turbine technology, high efficiency compressors matched to turbine performance, high efficiency alternators, lightweight carbon composite heat exchangers and recuperators.

For Stirling, advances required are: high frequency, low inductance linear alternators, low mass displacer, hot-end materials and structures, efficient cold-end thermal integration with lightweight radiators, high efficiency low mass controllers, and regenerators.

For power management and distribution systems, areas of emphasis include: high reliability, light weight, radiation-hardened power electronic components (semiconductor switches, diodes, capacitors, and transformers); high voltage switching contactors (>100Vdc) tolerant to corona discharge; and high efficiency (>95%) modular DC converters for boost and buck conversion. Concepts for monitoring power system status, fault tolerance, redundancy, and energy management. Advanced power cabling including high voltage, superconductors, carbon nanotube, and cable mbedded with structural elements. Also of importance are, intelligent and modular distribution switchgear and power management that can autonomously reconfigure in response to faults and changing loads.

Research for Wireless Power Transmission (WPT) technology development, to reduce the cost of electrical power and to provide a stepping stone to NASA for delivery of power between objects in space, between space, and surface sites, between ground and space, and between ground and air-platform vehicles. WPT can involve lasers or microwaves along with the associated power interfaces. Microwave and laser transmission techniques have been studied with several promising approaches to safe and efficient WPT identified. These investigations have included microwave phased array transmitters, as well as visible light laser transmission, and associated optics. There is a need to produce "proof-of-concept" validation of critical WPT technologies for both the near-term as well as far-term applications. These investments will be harvested in near-term, beam-safe demonstrations of commercial WPT applications. Proposals are sought that include such activities as the technology elements,
Sub Topics:

Energy Storage Topic X3.02
All exploration missions require advanced primary and rechargeable energy storage devices that are high-density, have long-life capability, and have the ability to function at extreme temperatures. The energy storage requirements vary significantly from a few watt-hours (astronaut equipment) to hundreds of kilowatt-hours (human outposts), depending on the mission. Similarly, power requirements also vary from a few watts (astronaut equipment) to several kilowatts, depending on the mission (human rovers, human outposts, and crew exploration vehicles).

Advanced energy storage devices, such as primary batteries, rechargeable batteries, fuel cells, and flywheels are required to enable future robotic and human exploration missions. Advanced primary batteries are required for applications such as astronaut equipment, communication devices, in situ resource utilization systems, sensor networks, etc. Advanced rechargeable batteries are required for solar powered landers and rovers, solar powered human outposts, astronaut equipment, and spacecraft. Primary fuel cells are required for crew exploration vehicles and rovers. Regenerative fuel cells provide an enabling, mass-efficient solution for surface electrical energy storage for future long-duration human exploration of the lunar and Mars surfaces. Flywheels provide an effective solution to meeting peak power requirements when used in hybrid systems with battery or fuel cell systems providing the base power, and offer the capability of integrated power and attitude control.

Energy Storage devices are needed for EVA and EVA accessory applications as well as vehicle and base back-up or peaking power applications. Areas of emphasis include advanced battery materials and cell designs with the potential to achieve the performance and safety advancements required for manned applications. Hybrid systems consisting of fuel cells, batteries, flywheels, and/or ultra capacitors are of interest. Also sought are high energy density fuel cell reactant storage innovations compatible with the performance and safety goals specified herein. Micro and nano-engineered materials are an area of emphasis for all of these applications. Proposals addressing micro-batteries, and integrated power generation and storage are sought.

Primary and rechargeable lithium-based batteries with advanced anode and cathode materials and advanced liquid and polymer electrolytes and solid-state systems are of particular interest. Technology advancements that contribute to the following performance goals are sought: specific energy >180 Wh/kg, calendar life (>15 years), and a wide operating temperature range (-60°C to 60°C). Primary batteries with the following performance targets are of interest: low temperature operation capable of delivering >30% of their ambient temperature capacity at temperatures as low as -100°C, specific energy: >400 Wh/kg, long calendar life >15 years, and high rate capability >C/10.

Fuel cell (FC) and regenerative fuel cell (RFC) systems with power capabilities in the range of 100-1000 watts and 2-10kW are of interest. Technological advances are sought that FC/RFC based systems with the following characteristics: specific energies: FC >1500 W/kg, RFC >600 Wh/kg. Efficiencies: FC>70% at 1500 W/kg, RFC >60% at 600 Wh/kg, and lifetimes: FC >10,000 hours, RFC >1500 cycles. Concepts that incorporate passive operation and advanced reactant storage options (example: \(\text{H}_2, \text{O}_2\)) are sought.
Advanced fuel cell development should include proton exchange membrane fuel cells (PEMFC - high and low temperature), regenerative fuel cells (RFC), and solid oxide fuel cells (SOFC). PEMFC areas of emphasis include long-life stacks and systems with emphasis on gravity-independent water management within the stack or elsewhere in the system, passive water separators, and passive reactant recirculation devices. RFC areas of emphasis include long-life, high-efficiency PEMFCs and electrolyzers. SOFC areas of emphasis include the capability to utilize CO/CO₂ and methane fuels for power generation.

Flywheel technology areas of interest are: system configuration concepts for high specific energy (>100Wh/kg for systems >500Whr and >50Wh/kg for systems 600 Wh/kg, and/or concepts that integrate energy storage, momentum storage, and spacecraft structure are sought.

Sub Topics:
Cryo & Thermal Management Topic X3.03
This subtopic includes technologies for waste heat management, movement, and rejection; technologies including lightweight and/or high-temperature radiators, heat pipes, heat sinks, etc. Also includes cryo-coolers and related low-temperature systems. These technologies will impact space solar power systems, spacesuits and habitation systems, robotics, and surface systems.

Spaceport operations, both on Earth as well as extraterrestrial, are heavily dependent upon a wide range of cryogenic systems, including liquid oxygen, liquid nitrogen, liquid helium, and supercritical breathing air. Each above application has unique performance requirements that need to be met. Sizes of these systems range from the small (3400 m³ for LOXand LH² ground propellant storage). Advanced cryogenic technologies are being solicited for all these applications. Proposed technologies should offer enhanced safety, reliability, or economic efficiency over current state-of-the-art, or should feature enabling technologies to allow NASA to meet future space exploration goals. Technology focus areas are divided as follows: passive systems, storage and distribution components, refrigeration systems, advanced instrumentation, and advanced operational concepts.

Cryogenic propellants such as hydrogen, methane, and oxygen are required for many current and future space missions. Operating efficiency and reliability of these cryogenic systems must be improved considering the launch environment, operations in a space environment, and system life, cost, and safety. Innovative concepts are requested for cryogenic insulation systems, fluid system components, and instrumentation. Although this subtopic solicits unique and innovative concepts in the cryogenic components and instrumentation areas, there is an emphasis at this time for:

- Advanced thermal switches to isolate heat transfer from a de-powered cryocooler;
- Advanced low-gravity submersible pumps designed specifically for moving cryogen heat that enters the tank wall to the heat exchanger coupled to the cryocooler;
- Advanced tank support systems capable of supporting tanks during the launch environment, but decoupling on on-orbit to minimize thermal loads;
- Advanced cryocoolers which are reliable, lightweight, and capable of removing significant heat at liquid hydrogen temperatures;
- Low heat leak cryogenic quick disconnects capable of sealing against the vacuum of space;
- Long-life, low power valves capable of sealing at cryogenic temperatures and being cycled many times without consuming pressurant gas;
- Liquid acquisition devices capable of preventing gas ingestion into engine feed lines in low gravity;
- Methods for cryogenic fluid acquisition and transfer in zero gravity;
- Methods of determining liquid remaining in propellant tanks in low gravity;
- High accuracy differential pressure transducers, which can be read submerged in liquid cryogen;
- On-orbit leak detectors;
- Lightweight, low-power temperature sensors which can be placed internally to the storage tank with a minimum number of feed-throughs;
- New technology valves for cryogenic applications, including LOX, LH\textsubscript{2} and Lhe, that minimize thermal losses and pressure drops. Components include shutoff and flow-control valves. Valves should be adaptable to electromechanical actuation and range in size from \(\frac{1}{2}\) to 6 inches;
- Integrated heat exchangers in large-scale storage systems designed to provide for zero boiloff and densification of liquid hydrogen and liquid oxygen;
- Advanced low-temperature materials for cryogenic containment;
- Insulation materials capable of retaining structural integrity while accommodating large operating temperatures ranging from cryogenic to elevated temperature conditions.

Thermal management systems are needed for the rejection of heat to hot environments for daytime operations on the lunar surface, large space radiators to dissipate heat from power and propulsion systems, thermal control for mobile systems, cryogenic propellant storage and handling for in-space refueling, and long-term cryogen storage for propellant depots.

Thermal management concepts include advanced heat sinks, heat pipes, and interface materials with high thermal conductivity that are electrically isolative. Innovative methods of increasing the specific thermal capacitance of the power systems are also sought:

- Qualified heat pumps to reject heat to hot environments;
- Multi-zone thermal control systems for spacesuits and mobile systems;
- Lightweight deployable low temperature radiators for use on the lunar surface;
- Concepts for the thermal management of advanced power system component designs for operation in deep space, lunar, and Martian environments.
Sub Topics:
  Technology Systems Analysis Topic X4.01
The goal of this subtopic is to develop new tools to ensure that advanced technology investments are guided by appropriate analyses. These analyses are needed in areas involving all of the various element programs within ESR&T. The analyses will support the definition of technology road maps for ESR&T.

The scope of Technology Systems Analysis Tools includes the development of advanced tools to support technology systems analyses, such as: portfolio analysis; campaign analysis; system technology architecture impact analysis; advanced concept analysis; sensitivity analysis; verification and validation analysis; development cost analysis; and the population of advanced technology databases and information systems. The ASCT analyses planned will be performed using low-fidelity/high-level techniques. They will focus on entry level technologies and notional architectures. Higher fidelity assessments will be performed using ESMD (Exploration Systems Mission Directorate) Simulation Based Acquisition (SBA) resources.

This Technology Systems Analysis Tools subtopic is currently focusing on developing advanced tools which enable the following:

- Conducting exploratory research and development of emerging technologies and advanced concepts with high potential payoff;
- Performing architecture, campaign, and technology analyses to identify and inform portfolio development for relevant exploration applications;
- Technology analysis to identify and prioritize mission enabling technologies;
- Architecture, mission, advanced concept, and technology risk analysis;
- Technology databases, roadmaps, and portfolio development;
- Exploration and implementation of different advanced concepts development methodologies and techniques to enable more effective and efficient study development;
- Development of advanced concepts analyses and sensitivity analyses that can incorporate the full range of technical fields related to space exploration;
- Analysis of advanced concepts, advanced technologies, and portfolio analysis;
- Campaign analysis including the synthesis and analysis of many missions, architectures and competing capabilities and technologies against FOMs;
- Technology analysis that identifies SOA and levels of performance metrics associated with cost- and risk-dependent chronologies (technology datasheets);
- Advanced concept and system technology verification and validation;
- Effective techniques for presenting tradeoffs and recommendations to decision-makers.
Sub Topics:
Design and Analysis Tools Topic X4.02
The goal of this subtopic is to maximize the credibility of the integrated systems analysis efforts being performed within ASCT by providing validated systems design, system analysis, and systems engineering tools. This will include the development of tools to produce: a modeling and simulation environment, design and analysis databases, system engineering models, engineering discipline analysis, parametric-based risk analysis, and probabilistic risk analysis (PRA), etc. This effort will closely coordinate with and support the development of the Simulation Based Acquisition (SBA) system in support of Exploration System Mission Directorate (ESMD) program acquisition and analysis.

The scope of System Design and Analysis Tools includes tool development activities in the following areas: advanced systems simulation modeling environment; design and analysis databases and system models; performance and structural sizing; SBA advanced systems engineering tools for mid-technology level simulation and visualization of life cycle cost, risk, reliability, supply chain logistics, maintainability, availability, and other system engineering Figures of Merit.

This subtopic is currently focusing on the following technology areas:

- Systems engineering tools and discipline analysis tools in support of Simulation Based Acquisition. See ESMD-RQ-0025, ESMD-RQ-0026 and SBA Strategy in the Crew Exploration Vehicle Procurement Bidder's library (http://exploration.nasa.gov/acquisition/cev_procurement.html) for additional information.
- Advanced engineering tools that integrate performance, risk, and cost modeling.
- Development of system engineering tools that implement new analytical methodologies and techniques in support of both ESR&T and SBA activities.
- Advanced systems simulation modeling environment that includes database technologies and data collection tools.
- Seamless integration of design tools, modeling tools, simulation tools, and other systems engineering tools via standards-based software interoperability.
- Novel approaches to assessing the performance, cost, or risk of proposed mission architectures.
- Techniques for characterizing and optimizing investments in Modeling and Simulation.
- Methods to extend and reuse models and simulations over the program lifecycle.
- Model-based techniques for optimizing designs in distributed, multi-organization, multi-contract design teams.
The objective of this subtopic is to bring to fruition software engineering technologies that enable engineers to cost-effectively develop and maintain NASA mission-critical software systems. Particular emphasis will be on software engineering technologies for sustaining engineering: achieving affordable reliability over successive spirals of mission software development, maintenance, and upgrades for Crew Exploration Vehicle and Project Constellation. A key requirement is that projects address the usability of software engineering technologies by NASA (including NASA contractors) engineers, and not only specialists.

Many of the capabilities needed for successful human exploration of space will rely on software. In addition to traditional capabilities, such as GNC (guidance, navigation, and control) or C&DH (command and data handling), new capabilities are under development: integrated vehicle health management, autonomous vehicle-centered operations, automated mission operations, and mixed human-robotic teams to accomplish mission objectives. These capabilities will be needed in exploration spirals 2 and 3, including the extended lunar missions. Ensuring that these capabilities are reliable and can be developed and maintained affordably, will be challenging but critical to both the lunar missions and the subsequent Martian missions. Proposals should clearly indicate how the technology is expected to address the challenge of reliability and affordability. Mission phases that can be addressed include not only the software life-cycle (requirement engineering through verification and validation) but also upstream activities (e.g., simulation-based acquisition for software capabilities; mission planning that incorporates trade-space development of software-based capabilities) and post-deployment (e.g., new approaches for computing fault tolerance; rapid reconfiguration, and certification of mission-critical software systems).

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

- Software-based radiation fault tolerance for computation;
- Methods and tools for development and validation of autonomic software systems (systems that are self protecting and self healing);
- Automated software generation methods from engineering models that are highly reliable;
- Scalable verification technology for complex mission software, e.g., model-checking technology that addresses the 'state explosion' problem and static-analysis technology that addresses mission-critical properties at the system level;
- Automated testing that ensures coverage targeted both at the system level and software level, such as model-based testing where test-case generation and test monitoring are done automatically from system-level models;
- Technology for calibrating software-based simulators and test-beds against high-fidelity hardware-in-the-loop test-beds in order to achieve dependable test coverage; and
- Technology for verifying and validating autonomy capabilities including intelligent execution systems, model-based diagnosis, and adaptive control.
A requirement for a sustainable and affordable human exploration presence in space is the need for modular, reusable elements and subsystems. Major subsystems (e.g., integrated vehicle health management) will present challenges in terms of software-based reconfigurability needed over a long sequence of missions. Projects can address technology development and maturation that provide for the following and related capabilities:

- Software reuse for mission-critical, real-time applications;
- Architectures that facilitate reconfiguration with upgraded components;
- Affordable verification, validation, and certification of upgraded components and sub-systems within a system (or system-of-systems) context;
- Intelligent management of software assets;
- Middleware that enables software platforms to migrate to new hardware platforms (e.g., middleware that enables command and control software to be transparently ported to distributed grid and cluster computer platforms).

Sub Topics:

Human Autonomy Interaction Topic X5.02

Autonomous and automated operations will be required for systems fulfilling the Vision for Space Exploration. This subtopic addresses the need for modeling and analysis tools and technologies for design, test, and evaluation of human-autonomy interaction systems. The tools will support analyses of scenarios, tasks, information, and communication. They can validate and build confidence in human-autonomy interfaces and interaction support by identifying and mitigating risks (e.g., workload, situational awareness, and error). The technologies will interoperate with models and tools for design, evaluation, and certification of hardware and software systems, and will support understanding by engineers and planners who are not experts in human-system design or human factors. They will be cost-effective to use and be easily updated and reconfigured to reflect changes in designs and plans.

The human-autonomy modeling and analysis technology will be applied to astronaut crew-autonomy and ground-crew-autonomy interactions in space missions. Autonomous systems can include exploration vehicles and subsystems, science stations, robots, robotic manipulators, rovers, and communications satellites. Autonomous operations can include rendezvous, proximity operations, mating of on-orbit elements, in-space assembly, maintenance, and robotic operations, including inspection, material transport, and sampling. These operations can be nominal, off-nominal, or contingency operations. Autonomy will be essential to ensure safe robot operation in the proximity of critical systems and humans. Autonomous functions can include science traverse and path planning, crew and resource scheduling, procedure execution, and control of subsystems such as a power, thermal, propulsion, and communications.

Innovative human-autonomy modeling and analysis technologies are needed to address unique challenges of space missions. These include multi-modal interfaces, asynchronous communication with long delays and long blackouts, unanticipated problems, and rare crew interactions by exception. Human-autonomy interactions can include supervisory control, communication, and coordination in shared planning and operations. They can include interactions to adapt, modify, and maintain systems to respond to emerging requirements and challenges. The interactions can also include dynamic control and adjustment of level of autonomy or supervision, type of coordination, and type of communication.
This subtopic seeks projects that will demonstrate innovative technologies for use by engineering and operations teams for analyzing human-autonomy interactions and risks and for evaluating proposed mitigations of these risks, within the constraints of an affordable and timely mission design and planning process.

Sub Topics:
Intelligent Operations Systems Topic X6.01
The goal of this subtopic is to develop intelligent systems and technologies that could dramatically improve the affordability and productivity of long-duration human space operations, while preserving the high degree of safety and flexibility offered by state-of-the-art approaches. The current operations models used for the Space Shuttle and International Space Station, which require large ground teams continuously managing the daily operation of the spacecraft and the activities of the crew, are a major cost driver for these programs. As the human exploration campaign ventures farther into deep space, the communications time delays and longer-duration missions will require greater crew autonomy from Earth-based support. To achieve NASA's exploration goals, technologies are needed that can enable a new paradigm for human space operations.

Intelligent Planning and Execution Systems for Crew Autonomy
Greater autonomy from Earth-based support implies that crewmembers will need to manage their exploration missions holistically. This will be possible only if automation helps the crew to integrate the complex interactions among many spacecraft subsystems efficiently and to manage and prioritize human and automated activities. Intelligent systems will need to be seamlessly integrated with operational procedures so that all the information required to make key decisions is continuously updated and presented to the crew in a rapidly comprehensible fashion. Crew interfaces (e.g., displays, voice recognition, etc.) will need to be intuitive and reliable. Validated, automated systems are needed that help a spacecraft/habitat crew coordinate and prioritize plans and execute nominal/off-nominal procedures in accordance with codified mission rules and objectives. These systems should improve upon capabilities already demonstrated in human space exploration missions (e.g., Space Shuttle and International Space Station).

To evaluate proposed intelligent systems technologies, it is important to identify measurable performance objectives. Such performance measures include: (1) the speed and ease by which astronauts can plan and schedule future activities and understand the consequences of exercising various planning options; (2) the reliability, speed, and ease by which astronauts can maintain comprehensive situational awareness of a complex spacecraft/habitat without cognitive overload; (3) the reliability, speed, and ease by which astronauts can derive (on demand, or in response to detection, of an off-nominal condition) sufficiently detailed knowledge of the spacecraft/habitat, to issue commands that isolate anomalies, perform recovery procedures, and make other safety/mission-critical decisions.

Modular designs that employ open architectures and interface standards are very important to assure cost-effectiveness and flexibility of intelligent operations systems. These architectures should promote extensibility/evolvability and accommodate future system upgrades. Such designs could include standalone tools
that capture and manage corporate knowledge about manned spacecraft operations.

Also of interest, though of lesser priority, are innovative technologies that can significantly enhance ground operational efficiency and performance.

**Intelligent Modular Training Systems**

Intelligent training systems are needed that enable flight crews to operate complex spacecraft safely and effectively, retain proficiency during long-duration missions, adapt easily to an evolving and expanding set of flight systems during the course of the exploration campaign, and achieve flight certification faster and more cost-efficiently than is possible with existing systems. Plug-and-play crew training systems that employ open architectures and interface standards are very important. These architectures should promote extensibility/evolvability and accommodate future system upgrades. The intelligent training systems should enable connectivity with models from various sources, with simulated or flight data (real-time and archived), with students and teachers at multiple locations, and with various platforms including ground-based/desktop environments and in-space, zero-g/partial-g portable or control station systems. When integrated with an operational environment, these systems must demonstrate effectiveness while ensuring that the performance of the vehicle or facility is unaffected.

Focus should be on the following applications:

- Intelligent onboard technologies for human space exploration; and
- Intelligent human space exploration mission control technologies.

Note: Related technologies of interest but covered under other SBIR subtopics include:

- X5.01 Software Engineering;
- X5.02 Human Autonomy Interaction;
- X6.03 Launch Site Technologies (Launch site command and control system technologies); and
- X8.01 Vehicle Health Management Systems.

**Sub Topics:**

**Space Assembly Maintenance & Servicing Topic X6.02**

The goal of this subtopic is to develop technologies that enable reliable and affordable in-space assembly, maintenance, and servicing for human and robotic exploration missions in Earth orbit and beyond. Systems that enhance crew safety and mission reliability by automating these functions (whether robotically, tele-robotically, or with integrated human/robotic teams) are needed. Technologies that enable robust and reliable Earth-orbit
assembly of spacecraft components (both modular and non-uniform), and thus alleviate the difficulties of launching larger, pre-integrated payloads, are of particular interest. Long-duration maintenance and servicing systems that are modular and generically applicable to a variety of orbital or transfer exploration spacecraft are also of interest.

Focus should be on the following applications:

- Earth-orbit assembly of large spacecraft systems (e.g. heat shields, propellant stages);
- Autonomous inspection of spacecraft systems using either small free-flying inspection spacecraft or attached, highly-mobile inspection robots; and
- Autonomous removal and replacement of failed spacecraft systems.

Specific technologies of interest in addressing these challenges include:

- Self-contained collision prevention/avoidance systems for robots (free-flying or attached) in close proximity to spacecraft, instruments, astronauts, etc.;
- Dexterous robotic end-effectors/manipulators for robotic assembly and maintenance, including systems that accommodate instability between robotics and target surfaces;
- Robotic non-destructive structural inspection technologies;
- Advanced robotic control systems (e.g., systems that provide active damping of robotic arms to reduce uncommanded motion, high degree-of-freedom (DOF) systems, systems that function in multiple mission environments, and systems that incorporate intuitive man-machine interfaces and/or virtual reality simulation);
- Robotic tele-operation control systems that accommodate latency and enable “real time” robotic operations;
- Vision systems for both autonomous and tele-robotic operations, including systems that demonstrate: autonomous and rapid object recognition, affordable zoom/focus lens control, robust spatial perception of working environments, ability to operate under various lighting conditions, economical video compression and 3-D mapping techniques, and low power autonomous visual inspection systems;
- Robotically operable structural/precision interface attachment systems;
- Modeling of contact dynamics in zero gravity for capture and manipulation;
- Test beds to validate robotic systems, including 6-DOF simulated weightless testing; and
- Orbital mechanics optimization of libration point rendezvous for assembly and servicing.

Note: Related technologies of interest but covered under other SBIR subtopics include:
Robot-mounted sensors for on-orbit assembly/construction (X1.03 Sensing and Imaging), and
Plug-and-play avionics and attachment technologies for autonomous rendezvous and docking (X8.02 Intelligent Modular Systems).

Sub Topics:
Launch Site Technologies Topic X6.03
The purpose of this subtopic is to develop technologies and concepts that will improve launch processing safety through the use of automated systems with limited human contact; make launch operations more cost- and time-efficient through standardization, commonality, and interoperability of launch systems and spaceport infrastructure; and improve the flexibility and adaptability of spaceport infrastructure in order to accommodate multiple vehicle types and diverse missions. Improvements in launch site operations can enable airport-like efficiencies at reduced cost and shortened processing turnaround time, thereby contributing significantly to the goal of a sustained and affordable space exploration program. Additionally, advanced launch operations technologies and concepts that may significantly improve launch vehicle specific energy or otherwise improve launch performance, affordability, and sustainability for space exploration missions are of interest. Topic areas that will be emphasized for improvements in launch site operations include:

- Propellant handling systems: autonomous propellant loading; automated umbilicals; improved control of cryogenic mass loss; hazardous leak and flame detection; and improved cryogenic cooling, insulation, and sealing technologies;
- Common integrated command and control system technologies for launch site operations: ground integrated health management systems, work control, configuration management, and other support systems;
- Test equipment: universal avionics test equipment and automated and wireless built-in test equipment that reports launch vehicle and/or payload status;
- Launch acoustic modeling and mitigation systems; and
- Payload and launch vehicle systems handling equipment.

Modular designs that employ open architectures and interface standards are very important to assure cost-effectiveness and flexibility of launch site technologies. These architectures should promote extensibility/evolvability and accommodate future system upgrades. Topic areas related to advanced launch operations technologies and concepts include:

- Horizontal launch assist ground systems, including systems that preclude the need for vehicle take-off gear. Specific technology areas of interest include: vehicle acceleration mechanisms, vehicle structural support or levitation systems, control and stabilization systems, separation mechanisms, runway or track stability and maintenance systems, and energy storage and delivery systems; and
Other novel launch operations technologies and concepts.

Focus should be on the following applications:

- Earth-based launch site systems for human and robotic space exploration missions.

Note: Related technologies of interest but covered under other SBIR subtopics include:

- X6.01 Intelligent Operations Systems.

Sub Topics:
Chemical Propulsion Systems and Modeling Topic X7.01
The goal of this subtopic is to develop innovative chemical propulsion systems and system concepts as well as modeling tools and capabilities that support chemical propulsion system design and analysis. Applications of interest include earth-to-orbit and in-space transportation, with a particular focus on versatile, multi-use in-space cryogenic engines with exceptionally high reliability, space-based reusability (i.e. capability for many restarts with little to no maintenance), and deep-throttling capability. These are needed for all phases of exploration missions, including trans-lunar injection, decent to the lunar surface, ascent to lunar orbit, and return to Earth. Also of interest are safe and affordable earth-to-orbit systems that enable high overall vehicle payload mass-to-liftoff mass ratios, with improvements in thrust-to-engine weight ratio, trajectory-averaged specific impulse, and overall reliability.

Specific areas of interest for technology advancement and innovations include:

- Propulsion system design concepts that address LOX/LH₂, as well as LOX/CH₄ and other LOX/Hydrocarbon engine and main propulsion systems integration issues;
- Integrated chemical propulsion system concepts that integrate primary propulsion and reaction control system elements;
- Design and analysis tools that significantly enhance the overall systems engineering evaluation of advanced chemical propulsion system concepts. These include tools for sensitivity analysis, quantification of system benefits to changes, propulsion system operability, "bottoms up" weight estimating, cost estimating, and reliability prediction for propulsion systems;
- Manufacturing techniques that allow for significant reduction in the cost and schedule required to fabricate
engine and main propulsion system components. These techniques can use current or emerging processes and manufacturing technologies to develop engine and main propulsion system components that will reduce complexity, increase reliability, and that are easier to assemble, install, and test when integrated onto the vehicle;

- Concepts for solid or hybrid rockets that increase mass fraction, decrease the need for thermal insulation, and reduce or eliminate the need for staging; and

- High-performance advanced propellants (as indicated by high specific impulse and high specific impulse density) and non-toxic propellants that can significantly improve safety and cost of propulsion systems operations.

Note: Related technologies of interest but covered under other SBIR subtopics include:

- X7.02 Chemical Propulsion Components
- X8.01 Vehicle Health Management Systems

Sub Topics:

**Chemical Propulsion Components Topic X7.02**

The goal of this subtopic is to develop innovative chemical propulsion component technologies that improve the safety, operability, reliability, and performance of propulsion systems required for human and robotic exploration missions. Components should be applicable to earth-to-orbit or long-duration in-space transportation systems (both primary propulsion and reaction control systems) for a variety of exploration mission phases, including trans-lunar injection, decent to the lunar surface, ascent to lunar orbit, and return to Earth.

System masses will be critical in these far-reaching missions, dictating the use of lightweight components and the use of propellants harvested or manufactured on the surface of the Moon, Mars, or other destinations—an approach known as *in situ* resource utilization (ISRU). Candidate ISRU propellants include hydrogen, oxygen, carbon monoxide, carbon dioxide, methane, various other hydrocarbons, and compounds derived from these materials.

In some scenarios, one propellant may be manufactured *in situ* while its oxidizer or fuel is brought from Earth. Because the use of ISRU propellants represents a departure from the state-of-the-art and from the existing base of engines and technologies, a new suite of propulsion system and component technologies will be required.

These new in-space propulsion systems are expected to encounter conventional challenges such as regulator leakage, valve leakage, valve heating (on pulsing engines), solubility effects (such as combustion instabilities caused by gas bubble evolution in liquid propellants), and propellant acquisition (i.e., extracting gas-free propellant from the tank and delivering it to the engine). In-space chemical propulsion systems that incorporate long-term use of cryogenic propellants such as hydrogen, methane and oxygen present new challenges, including efficient, reliable, and durable propellant cryocooling, storage, acquisition (from tanks), transfer (through feed lines), gauging and flow measurement; however, these particular challenges are addressed by a separate sub-topic, X3.03 Cryo and Thermal Management.
Chemical propulsion component technologies that demonstrate improved capabilities using a variety of propellant combinations are of interest, including:

- Advanced turbopumps with wider throttle range and improved cavitation control, plus specific turbomachinery components such as bearings, turbines, and impellers that demonstrate greater reliability and lifetime;
- Injectors with low thermal mass and long-duration reliability (e.g. for high duty-cycle attitude control thrusters);
- Long-life combustion chambers (e.g., based on use of advanced materials);
- Innovative thruster valve designs that tolerate high thermal loading due to heat soak-back during pulse mode operation;
- Innovative concepts for fast acting valves to enable use of larger thrusters for small impulses (i.e. spacecraft fine pointing);
- Highly-reliable long-duration seals;
- Light-weight, high-reliability ignition systems;
- Light-weight, highly reliable gas compressors for pumping gaseous propellant into pressure vessels either in-flight or on a terrestrial surface;
- Novel pressurization approaches that minimize dissolution of pressurant gas in storable propellants (e.g., nitrogen tetroxide, hydrazine, and hydrazine derivatives);
- Novel concepts that increase performance or decrease mass of pressurization systems;
- Development of advanced materials that exhibit high compatibility with gaseous oxygen;
- Propulsion components based on microelectromechanical systems (MEMS) technology;
- Advanced nozzle concepts for in-space propulsion systems;
- Reaction control system thrusters that burn in situ and non-toxic propellants;
- Innovative thruster designs that minimize or prevent high heat soak-back during pulse mode operation;
- Highly reliable, lightweight compressors for use in gaseous propellant storage and distribution systems;
- Advanced lightweight multi-use positive expulsion devices for storable propulsion systems; and
- Other innovative chemical propulsion system components that improve system safety, affordability, or effectiveness.

Note: Related technologies of interest but covered under other SBIR subtopics include:
Sub Topics:

High-Power Electric Propulsion Topic X7.03
The goal of this subtopic is to develop innovations in high-power (100 kW to MW-class) electric propulsion systems. High-power (high-thrust) electric propulsion may enable dramatic mass and cost savings for lunar and Mars cargo missions, including Earth escape and near-Earth space maneuvers. At very high power levels, electric propulsion may enable piloted exploration missions as well. Improved performance of propulsion systems that are integrated with associated power and thermal management systems and that exhibit minimal adverse spacecraft-thruster interaction effects are of interest. Innovations are sought that increase system efficiency, increase system and/or component life, increase system and/or component durability, reduce system and/or component mass, reduce system complexity, reduce development issues, or provide other definable benefits. Desired specific impulses range from a value of 2000 s for Earth-orbit transfers to over 6000 s for planetary missions. System efficiencies in excess of 50% and system lifetimes of at least 5 years are desired. Specific technologies of interest in addressing these challenges include:

- Long-life, high-current cathodes (100,000 hours);
- Electric propulsion designs employing fuels that are more readily available (whether from Earth or in situ space resources) and easy to store/handle;
- Electrode thermal management technologies;
- Innovative plasma neutralization concepts;
- Metal propellant management systems and components;
- Cathodes for metal propellants;
- Low-mass, high-efficiency power electronics for RF and DC discharges;
- Lightweight, low-cost, high-efficiency power processing units;
- Low-voltage, high-temperature wire for electromagnets;
- High-temperature permanent magnets and/or electromagnets;
- Application of advanced materials for electrodes and wiring;
- Highly accurate propellant control devices/schemes;
- Miniature propellant flow meters;
- Lightweight, long-life storage systems for krypton and/or hydrogen;
Fast-acting, very long-life valves and switches for pulsed inductive thrusters;

Superconducting magnets;

Lightweight thrust vector control for high-power thrusters; and

High fidelity methods of determining the thrust of ion, Hall, and advanced plasma engines without using conventional thrust-stands.

Note: Related technologies of interest but covered under other SBIR subtopics include:

Low- to medium-power solar electric propulsion for planetary science missions (S8.04 Spacecraft Propulsion).

Sub Topics:
Aeroassist Systems Topic X7.04
The goal of this subtopic is to develop innovative human-rated aeroassist systems for missions including lunar return to Earth and precursor missions for human Mars exploration. Systems are needed to support the following flight regimes: aerocapture, entry interface to subsonic speeds, and Mach 5 to subsonic speeds. Systems must be capable of controlled flight and be compatible with pinpoint, soft landing systems, which achieve landing accuracies of 10s of meters at touchdown or powered descent initiation. These systems must be compatible with launch vehicles and transit vehicles and capable of safely discarding unneeded and constraining hardware on landing and providing surface access. Technology needs include aeroassist system design, Thermal Protection System (TPS) designs, modeling capabilities, sensor systems, and navigation technologies that support reliable aerocapture or aerobraking of multi-metric-ton-class piloted or cargo spacecraft. In particular, this subtopic seeks innovations in the following areas:

Innovative aeroassist system designs. This includes low-mass, rigid aeroassist systems based on robust, high-temperature structures and adhesives, modular or deployable/inflatable aeroshells with large surface area, and inflatable ballutes;

TPS designs for human-rated aeroassist vehicles returning to Earth from the Moon and Mars, and for Mars aerocapture and Entry, Descent and Landing (EDL). Innovative TPS concepts are solicited to reduce current TPS mass fractions by 25% to 50% and to reduce TPS costs;

Ablative and reusable TPS materials and concepts that significantly enhance performance and reduce mass. This includes development and characterization of single- and multi-use TPS materials, TPS for rigid aeroshells, and flexible TPS materials for deployable aeroshells. Thermo-chemical and mechanical properties data for probabilistic design, spallation characteristics, and accurate simulation tools to predict material behaviors and material compatibility are required. Innovative TPS concepts are solicited to reduce current TPS mass fractions by 25% to 50% and to reduce TPS costs;

Aerothermodynamic modeling tools with greater accuracy and less uncertainty: (1) Innovative and accurate computer modeling of fluid structure interactions, including flow stability and surface deflections under dynamic conditions for decelerator deployment and inflation; (2) Modeling and simulation of
convection/radiation/ablation coupled three-dimensional flow fields, for both optically thick and thin shock layers and highly ionized flows; (3) Accurate prediction of wake heating including radiative heating components; (4) Accurate prediction of single and multiple rocket plume effects (e.g., reaction control system thrusters) on the vehicle aerodynamics and heating;

- Innovative sensor systems which are capable of providing real-time or near real-time updates to atmospheric pressure, temperature, density, and winds to support the guidance systems used on aeroassist vehicles;

- Innovative sensor systems for inflatable aeroassist vehicles capable of providing real time aerosurface temperature, strain, deflection, flight loads and other significant parameters; and

- Lightweight flexible materials that will reduce the mass and increase the strength and thermal characteristics for applications to deployable aeroshells and supersonic deployed decelerators.

Focus should be on aeroassist systems applied to the following mission classes:

- **Earth return of piloted spacecraft from the Moon.** Return-to-Earth scenarios for human lunar missions include: (1) short-range direct entry and landing; (2) extended-range entry using a skip out of the atmosphere with subsequent EDL to the Earth's surface; and (3) aerocapture into a low-energy Earth orbit followed by EDL. Inertial arrival speeds of approximately 11 km/s (up to 12 km/s for some abort scenarios) with entry masses of at least 5 metric tons are expected for normal lunar return. Acceptable sustained loads for these piloted missions are limited to about 5 gs perpendicular to the human spine in the "eye balls in" direction; and

- **Mars precursor missions for human exploration.** These include robotic missions designed to deliver pre-deployed cargo or to conduct technology demonstrations in anticipation of follow-on human Mars missions. Candidate human mission scenarios for Mars include human and cargo aerocapture into a Mars orbit followed by EDL to the Mars surface and return to Earth. Mars aerocapture missions are expected to have arrival speeds of 6 to 8 km/s and aerocapture mass on the order of many 10s of metric tons. Return-to-Earth scenarios for human Mars missions are similar to those for lunar missions, except for higher arrival speeds (11.5 - 12.5 km/s, up to 14 km/s for some off-nominal scenarios).

Note: Related technologies of interest but covered under other SBIR subtopics include:

- Inflatable and other innovative structures (X2.02 Structures and Habitats); and

- Aeroassist systems for deep space robotic science missions (S5.01 Low Thrust and Propellantless Propulsion Technologies).
In order to meet the automation and autonomy requirements of the Vision for Space Exploration, innovative health management technologies are required throughout the system lifecycle including design, development, test, validation, integration, operation, maintenance, and disposition. Traditional means of supporting vehicle health such as invasive inspections are extremely limited in their utility for exploration missions. Other solutions such as ground-based monitoring of telemetry data become less useful as communication delays or bottlenecks increase. Under these circumstances, autonomous and automated solutions to systems health management provide the best means of increasing crew safety and mission success probability for future space exploration missions.

Another significant concern is in mission operations. Operations models that require large numbers of ground controllers and other mission support staff will be cost prohibitive in the future. Future systems must provide appropriate levels of safety and mission success factors while reducing support staff on the ground. In addition, future space missions will have to maintain a healthy balance and seamless transition between crewed and robotic operations.

Proposals should be responsive to the overall goals and objectives of the Exploration System-of-Systems as defined in Project Constellation requirements. Proposals may address specific vehicle health management capabilities required for exploration system elements (crewed spacecraft, launch systems, habitats, rovers, etc.). In addition, projects may focus on one or more relevant subsystems such as propulsion, structures, thermal protection systems, power, avionics, life support, and communications. Proposals that involve the use of existing NASA health management test beds (power, propulsion, systems integration, life support, diagnostics, networking, etc.) for technology validation are encouraged.

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

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

- Health monitoring and management technologies to enable situational awareness of system health, safety, and margins. Solutions may include novel approaches to fault detection and isolation, diagnostics, and mitigation of system degradations and failures. Solutions may also include innovative health management system architectures that are robust to single point failures and are scalable, modular, and expandable without costly redesigns;

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

- System-of-systems health management concepts to provide robust cooperation of multiple Exploration elements, e.g., spacecraft constellations or rendezvous and docking operations;

- Prognostic techniques able to anticipate system degradation and enable further improvements in mission success probability, operational effectiveness, human-machine teaming, and automated recovery of function;

- Real-time data analysis methods for structural sensing, including detection, localization, damage assessment, and automated assessment of thermal protection system integrity;
- Crew-automation interfaces that are capable of reporting quantitative/qualitative sensor readings, assessing system status, explaining current conditions, predicting likely system behaviors, and proposing corrective actions in a manner that does not exceed the capacity of human understanding, especially in high-risk situations requiring rapid human response. Innovative ways for the health management system to convey a wealth of information quickly and effectively are desired; and

- End-to-end health management system architectures that are integrated with and validated on spacecraft subsystems on ground-based (or virtual) test beds.

Sub Topics:
Intelligent Modular Systems Topic X8.02
This subtopic will involve development and demonstration of a range of technologies for reconfigurable, intelligent, modular space subsystems, systems, and systems of systems. Technologies should focus on establishing the validity of new approaches to Earth-Moon human and robotic operations, with a view toward longer-term applications for the inner Solar System (e.g., Mars) exploration missions. Many of these future missions, systems, and capabilities imply the need for the development of large and complex systems and infrastructures in space. But, the size-constraints, mass-capability, and cost of launching large monolithic payloads into space limit the development and realization of these capabilities. If a different design approach using intelligent modular systems rather than monolithic payloads is used, these large space systems become more tractable. Also, intelligent modular systems include low system impact of a single launch vehicle loss, since modular systems are launched on multiple vehicles at multiple times. Replacement of modules over the system lifetime is, in many cases, a more reasonable approach to maintaining a system; and, graceful degradation of the system capability can be more readily managed with modular units. Hardware costs of multiple identical units can be reduced through economies of scale, and modular approaches can accommodate cost-phased programs that develop and fly a "pilot" system, which can initially prove a capability, and then be added to later as demand for capability increases. Technologies of interest include:

Modular Structures (MSFC)
Structural technologies of interest include inflatable, erectable, deployable, or easily connected modules to create large space structures. Assembly technology of interest may include approaches for integrating deployable modular units with larger structures such as habitation modules or propellant tanks, and approaches for assembly of erectable modules that form backbones or support trusses. Attachment technologies such as autonomous rendezvous and docking, innovative connectors and joining, bonding techniques, and module positioning and alignment systems are also of interest.

Adaptable and Reconfigurable Modular Systems (GSFC)
Integrated, reconfigurable modular systems incorporating multiple elements such as solar collection arrays, radiators, power, data, utility lines, science instruments, plug and play avionics, and integrated inspection and verification techniques are solicited, including modular structures using embedded sensors and actuators.

Human-Robotic Modular Systems (JSC)
Multi-functional robotic hardware and software systems are of interest to aide in surface and in-space operations. Robotic surface operations including exploration, assembly, fabrication, construction and transportation operations are of interest as well as similar systems for in-space operations. In addition, techniques are solicited for effective, efficient, and intuitive operation and control of robotic hardware through design and development of advanced
human-computer interfaces.

Sub Topics:
In-Situ Resource Utilization & Space Manufacturing Topic X9.01

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

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

In Situ Resource Extraction and Separation

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

- Technologies, processes, and systems for robotic precursor and early human missions to the Moon in the areas of resource characterization, excavation and extraction of lunar resources (especially in the polar regions), and performing initial resource separation and collection of water, regolith volatiles, or feedstock for Surface Manufacturing, Surface Construction, or in situ Resource Processing;

- Technologies, processes, and systems for robotic precursor missions to Mars in the areas of resource characterization, excavation and extraction of Mars resources, and performing initial resource separation and collection of atmospheric gases, regolith water/volatiles, or feedstock for in situ Resource Processing; and

- Evaluation of granular physics in low gravity and development of models and its effect on material excavation and handling; and developing dust-insensitive excavation hardware, actuators, and bearings particularly for lunar resource extraction.

**In Situ Resource Processing and Refining**

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

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

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

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

**Surface Manufacturing w/ In Situ Materials**

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

- Additive Manufacturing Techniques;
- Subtractive Manufacturing Techniques;
- Formative Manufacturing Techniques; and
- Part Assembly/Integration.

**Manufacturing Support Processes**

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

**Surface Construction w/ In Situ Materials**

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

- Construction techniques for robotic precursor and early human missions that support site planning and preparation and the use, manipulation, and placement of raw materials and expected feedstock materials from *in situ* Resource Processing and Refining for lander plume debris, meteorites, and solar/galactic radiation shielding;
• Construction techniques for robotic precursor and early human missions that support bunker and habitat structure construction using and manipulating raw and expected feedstock;

• Construction techniques that can be demonstrated on robotic precursor missions that demonstrate dust mitigation concepts for surface mobility around landing pads, habitats, dust-sensitive instruments, and airlocks; and

• Lunar in situ fabrication techniques that can be demonstrated on robotic precursor missions that enable growth in solar power generation, storage, management, and distribution capabilities using raw materials, expected feedstock. Demonstrations can initially assume use of Earth supplied consumables in small amounts.

**Point of Departure Mission Information for Proposals**

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

Excavation, separation, and processing needs for lunar missions depend on the resource of interest, location, and concentration of the resource and the processing technology considered. Mars sample return missions that incorporate in situ propellant production require atmospheric carbon dioxide collection and possibly atmospheric or regolith water extraction to support the production of 300 kg to 2000 kg of propellant depending on the size of the sample and whether the mission is a Mars orbit rendezvous or direct Earth return mission. Breathing rates for astronauts are approximately 0.07 kg of oxygen (O$_2$/person/hour in habitats and 0.1 kg O$_2$/person/hour for Extra-Vehicular Activities (EVAs). Early human lunar mission surface durations may vary from 3 to 45 days and can include from 2 to 6 crewmembers. Lunar human landers require approximately 5000 to 8000 kg of propellant for ascent and approximately 15,000 to 25,000 kg for landing and ascent combined. Mars mission surface durations are 30 to 90 days for opposition class missions and 450 to 600 days for conjunction class missions. Mars human ascent vehicles typically require 20,000 to 30,000 kg of propellant. Fuel cell reagent consumption rates depend on the power required for the application, the reagents, and the fuel cell technology used. EVA suits and small rovers can require 500W to 1 KW of power/hour, unpressurized rovers can require 3 to 6 KW of power/hour and pressurized rovers can require 10 KW/hour and above.

**Sub Topics:**

Surface Mobility/Mechanisms Topic X9.02

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

**Precursor Mobility Systems**

Precursor mobility systems address development of hardware and software mobility technologies for precursor lunar missions that also support missions to Mars. Topics include enabling technologies for modular robotic systems, alternative mobility systems, and the development of software to autonomously control and integrate mobility technologies. Mechanisms include traditional wheel motor and harmonic drives, distributed mechanical drives, traction drives, tracked drives, and walking mechanisms.
Proposals may also focus on surface systems for autonomous robotic outposts. Emphasis is placed on the ability to test, verify, and validate such system prototypes in representative laboratory and field environments. The applicable technologies and design concepts span the full range of surface mobility including high dexterity robotic scouts, long-range navigation on the lunar surface, and robotic systems for structural construction, inspection and repair.

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

Crew Mobility Systems

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

Sub Topics:

Long-Life Validation and Flight Qualification of Nuclear Space Systems Hardware Prior to Flight Use Topic X10.01

Nuclear space systems are expected to be an integral part of the national Vision for Space Exploration. Nuclear electric power would allow human and robotic exploration to reach beyond the constraints of solar power systems and is expected to be crucial for long-duration habitation and exploration of the Moon and Mars. Nuclear propulsion systems offer the potential for significantly higher specific impulse and/or significantly higher delta-V than chemical engines, reducing the amount of propellant and associated costs needed to perform a given mission. Nuclear thermal propulsion (NTP) systems up to several hundred megawatts and nuclear electric propulsion (NEP) systems from 30 kW to hundreds of kilowatts and more, are being considered for the economical delivery of lunar and Mars cargo, rapid crew transit to Mars, and, in the case of nuclear electric propulsion, robotic exploration of the solar system and beyond. However, the long-duration performance and life testing of these high power nuclear space systems can be very expensive and poses several unique and significant challenges. The intent of this solicitation is to elicit new or significantly improved approaches that accelerate or simplify the long-life validation and flight qualification of high power nuclear space systems hardware.

While the testing of nuclear reactors is clearly beyond the scope of this solicitation, proposals are invited for innovative methods that simplify, accelerate, reduce the cost, or otherwise improve upon current techniques to ground test and validate the life and performance of non-reactor high power space nuclear power and propulsion components, subsystems, and systems. Also invited are proposals that address new and innovative approaches to seamlessly integrate high power space nuclear power and propulsion hardware elements into complete systems of systems, with corresponding methods for flight qualification prior to flight use.
Sample high power space nuclear power and propulsion areas that could benefit from accelerated or simplified performance and life validation include, but are not limited to: electric power conversion systems for in-space or planetary surface power; electric power management and distribution systems; accelerated testing of pulsed or steady-state high power electric thrusters or thruster arrays under appropriate vacuum and thermal conditions; performance and life testing of component materials and structures under simulated NTP hot hydrogen flows; the simulated operation, shut-down, and restart of NTP system components over simulated mission profiles in relevant vacuum, thermal, and radiation test environments; other space nuclear power and propulsion hardware elements that must operate in extreme environments over extended mission durations; and simplified or accelerated techniques for hardware integration and flight qualification of a complete system of systems prior to flight use. Proposed methods should substantially and demonstrably reduce the time and expense to validate the life and performance of space nuclear power and propulsion technologies compared to state of the art techniques.

Sub Topics:

Critical Technologies for In-Space Application of Nuclear Thermal Propulsion Topic X10.02

NASA is interested in the development of critical technologies for first in-space applications of solid core nuclear thermal propulsion (NTP) systems for use in a variety of future exploration missions. For short, round trip, human missions to Mars, NTP systems may be enabling. It can potentially also help reduce launch mass or increase payload delivery for cargo and crewed missions to the Moon and other destinations. The first anticipated in-space application of solid core NTP systems could occur in the time frame of 2025 to 2030 and could be based on a high-thrust/high-Isp (~850 - 950s) NTP system that uses a fission reactor with U-235 fuel as its source of thermal energy. During the short primary propulsion maneuvers of a typical conceptual mission, large quantities of thermal power (100s of MWt) would be produced within the NTP system and removed using LH\textsubscript{2} propellant that is pumped through the engine's reactor core. The superheated hydrogen gas is then exhausted out the engine's nozzle to generate thrust. Recent NASA studies have shown that small engines (~15-25 klbf), used individually or in clusters, could support a broad range of mission types. Representative ranges of engine performance include: 1) hydrogen exhaust temperatures ~2500-2900 K; 2) propellant flow rates ~7-13 kg/s; 3) chamber pressures ~500 -1500 psi ; and 4) nozzle expansion area ratio ~200:1-500:1.

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

- High temperature, radiation tolerant instrumentation and avionics for engine health monitoring. Non-invasive designs for measuring neutron flux (outside of reactor), chamber temperature, operating pressure, and H\textsubscript{2} propellant flow rates over wide range of temperatures are desired;
- Long-life, lightweight, reliable hydrogen turbopump designs and technologies;
- Lightweight, long-life, high heat flux thrust chambers, regenerative-cooled nozzles and radiation-cooled skirt extensions that are compatible with hot hydrogen;
- Radiation tolerant materials compatible with above engine subsystem applications and operating environments;
- High temperature, low-to-moderate burn-up carbon- and ceramic-metallic (cermet)-based nuclear fuels for use in NTR and BNTR engines;
• Improved chemical vapor deposition (CVD)/coating techniques for heritage “Rover/NERVA” type carbon-based fuels that reduce and/or prevent cracking, fuel element erosion via H₂ attack, and release of fission product gases into the engine’s H₂ exhaust stream;

• Mass-optimum neutron and gamma radiation shielding materials and designs that minimize exposure/damage to key engine components and subsystems (e.g., LH₂ turbopumps) and provide radiation protection for the crew; and

• Dual-use shielding materials and designs that also provide habitat protection against galactic cosmic rays and solar flares are also encouraged.

Note that any associated NTP simplified test approaches, power systems, and thermal management/heat rejection systems technologies should be submitted to subtopic areas X10.01, X10.03, and X10.04, respectively.

SubTopics:

Critical Technologies for Space-Based Nuclear Fission Power Systems Topic X10.03
NASA is interested in the development of highly advanced systems, subsystems, and components for use with high-power, fission power systems for a variety of future robotic and manned exploration missions to the Moon, Mars, and beyond. Anticipated electric power levels range from 30 to 100s of kilowatts for the nearer-term and possibly up to multi-megawatts for the far-term. Fission-based systems are anticipated to enable long duration stays of approximately 45 to 90 days over the lunar night and may have in situ resource utilization applications. Power levels needs are anticipated to be between 30-50 kWe for these early exploration missions.

Potential Mars-surface human outpost applications for high-power space nuclear power systems could include habitats, resource processing, propellant production/liquefaction/maintenance, and excavating and mining equipment. These potential Mars surface human mission activities could require power in the 100 kWe range. Also, space nuclear power systems could be needed for robotic outposts as a precursor to human Mars surface exploration with 50-500 day stays. Power levels of about 30-50 kWe may be needed to support these initial robotic outposts and other science applications such as: deep drilling, resource production demonstrations, rovers, weather stations, etc.

Potential electric propulsion applications include high power space nuclear power systems for primary electric propulsion, vehicle housekeeping, cryogenic propellant maintenance, orbiting power assets and science payloads. Power levels in the 100-200 kWe range are envisioned for robotic vehicles. Far-term vehicles for human missions may also be needed and could require about 1-2 MWe for high-mass cargo vehicles to the Moon or Mars and the low 10s of MWe for piloted electric propulsion vehicles. Nuclear thermal propulsion systems could also be designed to produce electric power and power levels of about 50 kWe could be needed to meet crew habitat, propellant boil-off, and other spacecraft power requirements.

Proposals are sought in the following specific technologies areas:

• Advanced, high-efficiency, high-temperature high-power conversion >20%, 30-200 kWe for the nearer-term, and up to MWe-unit size for the far-term (with technical issues of scaling to high power unit);

• Electrical power management, control and distribution in the 1000-5000 V range;
• Deployment systems/mechanisms and innovative methodologies for surface mobility systems for remote emplacement of power systems and for use of indigenous shielding materials;

• Material compatibility with local environments;

• Systems/technologies to mitigate lunar and planetary surface environments including dust accumulation, lunar surface temperature extremes, wind, planetary atmospheres (CO₂, corrosive soils, etc.);

• Power system design considerations for long life (>10 years), autonomous control and operation, including sensor technologies; and

• Radiation tolerant systems and materials (including lunar, Mars and in-space environments) for robust, long-life operation.

In addition to reducing overall system mass, volume and cost, increased safety, and reliability are of extreme importance. It is envisioned that these high power space nuclear power system technologies could be used on robotic and human exploration missions and it is to NASA's advantage to develop those technologies that evolve from robotic to human exploration mission requirements with a minimum of redesign. Technologies that enable challenging missions such as, nuclear electric propulsion, planetary surface power, and in-space electric power generation are of particular interest. Technologies that easily and efficiently scale in power output and can be used in a host of applications (high commonality) are desired.

Proposals for thermal management systems and innovative materials computational engineering should be proposed to X10.04 and X10.05, respectively.

Sub Topics:

Heat Rejection Technologies for Nuclear Systems Topic X10.04

NASA is interested in the development of advanced heat rejection subsystems for use with high-power, fission-based power and propulsion systems for a variety of future robotic and manned exploration missions to the Moon, Mars, and beyond. Anticipated electric power levels for these high-power, space nuclear systems could range from 30 to 100s of kilowatts for the nearer-term and possibly up to multi-megawatts (2-20 MWe) for the far-term. Potential applications include in-space transfer vehicles and planetary orbiters, and surface bases with global site capability on the lunar and Mars surface. The heat rejection sub-systems for any of the possible high power space nuclear power plant choices would need to be matched with the thermodynamic cycles of the power plants in a manner that will maximize space nuclear power system performance while keeping heat rejection subsystem and overall power system specific mass (kg/kW) to a minimum. The levels of heat rejection could be from about 100 kilowatts to many megawatts, and the task could be even more challenging by the long life requirements imposed by deep space missions, the extreme radiation environments possibly encountered, and the unique challenges imposed by surface missions including the effect of an atmosphere, elevated sink temperature, and particle contamination. The radiator operating temperature range can vary greatly depending on the mission, but temperatures as low as 400K and in excess of 1000K are possible.

Typical heat rejection systems usually include a) a heat transport loop carrying heat to radiator surfaces for rejection to space, and b) a space radiator, which accomplishes the final heat rejection to space by thermal radiation. If the cycle working fluid is different from the radiator heat transport fluid, a "heat sink" heat exchanger and a fluid-circulating pump also need to be included in the design.
Proposals are sought in the following critical technologies areas:

- Low areal density heat rejection radiators (2);
- Innovative heat transfer approaches between heat transport loop and radiating surfaces;
- Development of light weight, radiation tolerant, thermally stable, high-performance components and pump loop systems including heat pipes and pumps in the low to intermediate temperature ranges (300K to 500K), intermediate temperature ranges (450K to 650K), and intermediate to high temperature ranges (700K to 1000K and higher);
- Pumped loops that take advantage of the abundance of waste heat and transport some of it to the spacecraft and payload components for thermal management. Waste heat source to spacecraft radiator distances will likely be too large for passive technologies, and pumped loops may offer a possible solution. Since rejection of megawatts of waste heat could require large radiating surfaces, loop heat pipes may provide a lightweight solution to distributing this heat over long distances. Specific areas of interest for this area include:
  - Long term material/working fluid compatibility, lightweight material integration, and working fluid performance for the various temperature ranges; and
  - High temperature, long-life pump technology, single- and two-phase systems, and thermal bus concepts involving multi-evaporators and condensers.
- High temperature, lightweight heat rejection system materials. Such materials may include those to enable lightweight radiators and heat pipes. Work in this area should address harsh radiation environments, launch/landing loads, and long life issues;
- Durable low-absorptivity/high-emissivity and variable emissivity coatings for radiating surfaces;
- Novel and efficient deployment systems/mechanisms for radiators in zero gravity and/or non-zero gravity fields to minimize mass, complexity, and stowed area/volume;
- Systems and technologies to mitigate adverse effects of planetary surface operating environments, such as cosmic and fission process induced radiation, dust accumulation, wind loading, planetary atmospheric effects due to CO\(_2\), and variable sink temperatures;
- Design considerations for heat rejection subsystems should include long service life (>10 years) and autonomous operation;
- Development of advanced, high temperature heat pump technologies based upon conventional vapor compression cycles, absorption/adsorption cycles, and advanced thermoelectric and/or thermo-acoustic technologies;
- Advanced eutectic working fluids capable of extended duration use that would mitigate design issues related to the freezing and subsequent reuse of thermal management coolants; and
- Alternate cooling technologies for the rejection of waste heat from large capacity planetary or surface nuclear power systems. Such systems may include, but are not limited to, deployable cooling towers and/or optimized radiators.

In addition to reducing overall system mass, volume, radiator area, and cost, increased safety and reliability are of
prime importance. Technologies are desired that readily scale in heat rejection capability for various power plant outputs, and thus can be used in a range of applications.

Sub Topics:
Computational Material Science Tools for Space Nuclear Systems Design Topic X10.05

NASA is interested in the development of highly advanced systems, subsystems, and components for use with high-power, fission power and propulsion systems for a variety of future robotic and manned exploration missions, including in-space, lunar-surface, and Mars-surface applications. Advanced high-power space nuclear power and propulsion systems for robotic and human exploration missions involve a range of specialized materials for the reactor, heat transfer system, energy conversion system, propulsion system, and other nuclear vehicle systems. These materials may include carbon-carbon, super alloys, refractory alloys, structural ceramics, ceramic matrix composites, and other high-temperature space nuclear systems materials. Long-term stability greater than 10 years is critical for long-life space nuclear power system applications. Materials would be subjected to fission process radiation while exposed to in-space (plasma, out-gassing, etc.) and/or planetary operating environments.

This subtopic is focused on the development of computational materials science tools to develop and select these specialized space nuclear systems materials. Many considerations go into selection of materials for demanding applications. These include strength, creep resistance, phase stability, oxidation/corrosion resistance, nuclear capture cross-section, and radiation tolerance. In recent years computational materials science has assisted with not only the selection of existing materials with a given set of properties but also with the development of new materials with those properties. These tools include first principles calculations of phase equilibria, computational thermodynamics (the CALPHAD technique), and creep modeling.

Proposals are sought for the specific technologies areas:

- A computational 'toolbox' for material selection with particular emphasis on space nuclear power and propulsion systems requirements;
- Computational tools to address particular issues in mechanical property degradation in space nuclear power and propulsion systems over long times. This includes, but is not limited to, long-term creep modeling;
- Computational tools to predict long-term oxidation/corrosion and flow-induced erosion issues in the high temperature portions of these systems, including the heat transfer system. This includes thermodynamic modeling of heat transfer media attack of alloys;
- Computational tools to predict long term stability of various joining techniques used in these space nuclear systems. This includes diffusion modeling in alloys; and
- Computational tools to predict interaction of the radiation environment. This includes effective capture cross-section for complex materials systems and production of secondary energy and potential impact on components.

It is anticipated that Phase 1 will focus primarily on the new computational tools for material selection and development with some limited experimental verification. Later phases should involve more extensive verification,
to the point where these tools could be readily utilized for the design of space nuclear systems.

Sub Topics:
Radiation Health Topic X11.01
The goal of the NASA Space Radiation Research Program is to assure that we can safely live and work in the space radiation environment, anywhere, any time. Space radiation is distinct from terrestrial forms of radiation, being comprised of high-energy protons and heavy ions and their secondaries produced in shielding and tissue. The Radiation Program Element uses the NASA Research Announcement as a primary means of soliciting research to reduce the uncertainties in risk projections; however, there are specific areas where the SBIR technologies can potentially contribute to NASA's overall goal:

Ground-Based Heavy Ion Accelerator Research Support Equipment

NASA utilizes facilities at Brookhaven National Laboratory (BNL) to conduct fundamental radiobiology and shielding experiments. However, the facilities at BNL were not developed with NASA's high number of investigators in mind, thus there are areas where technology developments can improve efficiency and throughput. Technologies of specific interest include, but are not limited to, the following:

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

High Throughput Genomic Analysis Techniques

Following low-dose irradiation of cells by protons and heavy ions, damage is localized to only a very few cells. The ability to separate cells with or without genetic changes in an automated manner is of interest. Current technologies are inefficient in identifying small-scale genetic changes (less than several thousand base-pairs (Mbp)) under these conditions. Technologies of interest are:
Complementary technologies to the fluorescence *in situ* hybridization (FISH) method used to score large scale (>1 Mbp) genetic changes to chromosomes following low dose irradiation in order to rapidly score small-scale genetic changes.

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

**Radiation Shielding and Fabrication**

The NASA Space Radiation Research Program uses the NASA Research Announcement (NRA) as the primary means of soliciting research to conceive and radiation-test new radiation shielding materials concepts. The materials concepts include new and innovative lightweight radiation shielding materials to shield humans in crew exploration vehicles, large space structures such as space stations, orbiters, landers, rovers, habitats, and spacesuits. The materials emphasis is on non-parasitic radiation shielding materials, or multifunctional materials, where one of the functions is the radiation shielding, but also serves as structural and other functional components of flight and/or habitat systems. The specific areas in which SBIR-developed technologies can contribute to NASA’s overall mission requirements for advanced radiation shielding materials technologies are:

- Characterization of the physical, chemical and relevant functional properties and the validation and qualification of such multi-functional radiation shielding materials;
- New and innovative manufacturing techniques for producing quality-controlled advanced radiation shielding products and structural components, including innovative scale-up methods for producing quality-controlled viable quantities of advanced radiation shielding materials;
- New and innovative processing methods for producing quality-controlled advanced radiation shielding materials of all forms - resins, fibers, fabrics, composites and fiber-reinforced composite materials;
- New and innovative fabrication techniques for fabricating advanced radiation shielding materials into useful products and structural components; and
- New and innovative commercialization strategies to introduce advanced radiation shielding materials technologies into the marketplace to enable availability of the technologies for use by NASA and the space exploration community.

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

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

- Advanced spaceflight detector systems to provide reliable environment data for a specific spectrum of energies, including: real time dosimetry providing dose and particle types and energies and cumulative dosimeters for characterizing space environments for use onboard spacecraft and planetary surfaces as
well as alarm systems for Solar Particle Events; and

- Microdosimetry for operational and research applications, including implantable dosimeters for biological studies, that translate particle counts into biologically relevant dose or damage.

Sub Topics:

Human Health Countermeasures Topic X11.02

In order for humans to live and function safely and efficiently in space or in the hypogravity of the Moon (1/6g) or Mars (3/8g), a good understanding of the effects of micro- and hypogravity and other factors associated with the space environment on human physiology and human responses to the space and extra planetary environments is required. A variety of countermeasures must be developed to oppose the deleterious changes that occur in space and upon subsequent exposure to other gravitational fields. The ability to monitor the effectiveness of countermeasures and alterations in human physiology during space exploration missions, particularly when several countermeasures are used concurrently, is equally important. This subtopic seeks innovative technologies in several very specific key areas. Since launch costs relate directly to mass and volume, instruments and sensors must be small and lightweight with an emphasis on multi-functional capabilities. Low power consumption is a major factor, as are design enhancements to improve the operation, design reliability, and maintainability of these instruments in the environment of space and on planetary surfaces. As the efficient use of time is extremely important, innovative instrumentation setup, ease of usage, improved astronaut (patient) comfort, noninvasive sensors, and easy-to-read information displays are also very important considerations. Extended shelf life and ambient storage conditions of consumables are also key necessities. Ability to operate in 0g, 1/6g, and 3/8g becomes more important as we march towards human Moon and Mars missions.

Exercise and Related Hardware

Development of an immersive visual display system is required to be interfaced with treadmill exercise devices. This system may not be head-mounted but could be free standing and provide at least a 180° field of view. This visual display would allow visual flow patterns to be displayed to a non-encumbered subject during in-flight or on-surface treadmill exercise. In addition, miniaturized exercise hardware (treadmill or resistance exercise); physiological monitoring devices; and metabolic gas (carbon dioxide and oxygen) analysis systems for use with exercise and miniaturized interactive feedback and entertainment systems.

A tool or toolkit should simulate and visualize the exercise device design and performance. A comprehensive, scaled 3D/virtual human model interface would be valuable to show biomechanical and kinetic effects of the exercise device. Relative physiological data from anthropometry to stress/fatigue to trauma/insult onset should be targeted. If in-flight/on-orbit micro gravitational and planetary surface gravitational forces can be simulated, this could help produce germane simulations with which to implement new designs and products. A time-delay algorithm would be advantageous in helping provide for latency-moderated haptics (force-feedback) and long-distance teleoperative control. This will allow remote teleoperation with force-feedback despite the high latencies involved.

Noninvasive Pharmacotherapy and Monitoring

Development of innovative technologies resulting in noninvasive methods for diagnosis, treatment, and therapeutic drug monitoring is needed to facilitate effective pharmacotherapy of humans in space. Many questions remain about the effectiveness of pharmaceuticals in micro- and hypo-gravity environments, which may interfere with their activity by sensitizing or desensitizing the crewmember or interfering in other ways with the desired physiological effect. Micro-encapsulation of drugs, radio contrast agents, crystals, and development of novel drug delivery systems wherein immiscible liquid interactions, electrostatic coating methods, and drug release kinetics from
microcapsules or liposomes can be altered under microgravity. Devices for continual monitoring of physiology during pharmacotherapy would also be advantageous to ensure that on-orbit expression of therapies relates to on-Earth histories.

**Device for Providing Increased Neuromuscular Activation during Spaceflight**

Astronauts returning from spaceflight exhibit post-flight postural and gait instabilities that are a result of neural adaptation to microgravity. A small, lightweight countermeasure device is required to stimulate somatosensory receptors on the plantar surface of the feet during in-flight exercise with the goal of increasing neuromuscular activation and enhancing sensorimotor integration. This system would integrate with in-flight exercise hardware and coupled with visual stimulation systems would allow a more complete sense of immersion to enhance in-flight postural and locomotor training.

**Device for Measuring Body Fluid Shift**

A body impedance device to measure fluid shifts in four segments of the body associated with a short-radius centrifuge. The device should measure the following parameters, namely, resistance, change in resistance and rate of change of resistance and reactance. The device should withstand g forces (5g) produced by centrifugation and meet safety standards such as subject isolation.

**MEMS-Based Human Blood Cell Analyzer**

Development of a small, automated and micro- and hypo-gravity capable instrument that will analyze micro liter quantity of human whole blood and provide a complete blood cell count (RBC, WBC, platelet, hemoglobin concentration, hematocrit, WBC differential, and calculated RBC indices) that correlates with traditional ground-based impedance or light-scattering technologies is needed. Likely devices based on MEMS will employ a biocompatible combination of micro fluidics, micromechanics, micro-optics, microelectronics, and data telemetry capabilities in an integrated handheld package with a user-friendly operator interface.

**Cell/Tissue Analog Studies**

Cell/Tissue analog studies in ground-based, microgravity-analog bioreactors allow us to understand the ill-effects of microgravity and radiation on human tissues-especially, bone, muscle, and cardiac and immune response. Technologies that allow automated biosampling, lyophilization of mammalian cells, miniaturized protein microarray analyzer, tools derived from Bionanotechnology relevant to the understanding are of interest.

**Sub Topics:**

**Autonomous Medical Care Topic X11.03**

Exploration missions require a healthy, well-performing crew supported by a robust infrastructure for the monitoring, diagnosis, and treatment of medical conditions. Since return time to Earth and communications delays during such missions will greatly reduce the effectiveness of Earth-involvement, the crew must be capable of performing the majority of medical activities independently. Therefore, this system of autonomous medical care must provide the capability for patient care as well as measure and assess fitness levels for duty during a mission with little or no real-time support from Earth. The objective of this subtopic is to sponsor applied research leading to the development of such an infrastructure with the associated medical devices and procedures that will mitigate crew health, safety, and performance risks during future flight missions to the Moon and Mars. Medical diagnostic,
treatment, and monitoring devices are critical for providing health care and medical intervention during missions, particularly extended-duration spaceflight to the Moon and Mars. Of particular interest are devices with minimized mass, volume, consumables, and power consumption that are capable of multiple functions in both micro-g and sub-g environments. Design enhancements that improve the operation, reliability, flexibility, and maintainability of medical devices in the space environment are also sought. Additional considerations include innovative approaches to human-device interactivity and interface, automation of device functions, improved ease of use, and astronaut comfort.

Device for Body Chemistry Assessment

Development of an integrated, adaptable laboratory analysis system/sensor system for in-flight assessment of body fluids (including blood) and solids is desired. This system would be used to obtain quantitative measurement of dissolved gases, calcium ions, and other electrolytes, proteins, lipids, hormones, carbohydrates, vitamins, minerals and clinical drug levels with minimal or no consumables usage or specimen preparation skill. Likely candidates will be based on MEMS technology and will employ a biocompatible combination of micro fluidics, micromechanics, micro-optics, microelectronics, and data telemetry capabilities in an integrated handheld package with a user-friendly operator interface.

Voice- and Gesture-Actuated Interactive Procedures

Astronauts working in space or on the lunar or Martian surface will require a hands-free, interactive, step-by-step environment for performing flight medical procedures. This system should have the capability to utilize links, prepare textual or graphical indication of progress through a procedure, return to previous steps, page forward/page backward, and automatically annotate verbal input relative to subject response during procedure or treatment. An inventory capability must exist for obtaining and stowing required items (including medications) as well as a mechanism to assess the resulting consumables status after a procedure has been completed. Ground-monitoring capability is also required, at least in the early stages.

Closed Loop Medical Respirator

A closed loop flight and human certified medical respirator with real-time remote monitoring and remote control capability is required. This respirator must incorporate a function to limit the amount of O₂ leaking into the space vehicle or surface habitat. Current O₂ limits range from ~20/21% at sea level with maximum levels of 30% in a 10.2 psi environment. (This upper limit mitigates flammability concerns and is dictated by ambient pressure.) The system should incorporate real-time remote monitoring and control capabilities.

Medical Grade Water Generation

Methods and technologies for in-flight creation of medical grade water from any available water source are required. Because some pharmacological preparations appear to degrade in the space environment, it is highly desirable, from both a consumables perspective as well as from the standpoint of mass, to fly desiccated pharmacological substrates whenever possible and to reconstitute them only when needed. For this reason, medical grade water is required along with a low-g (e.g., 0 g, 1/3 g, and 1/6 g) system to deliver generated water to the substrate and mix as necessary. The general requirements of low mass, user-friendly interface, reliability, and automation are critical to this system. There should be a mechanism included to verify that the water produced meets standard requirements for the medical grade designator.

Diagnostic Imaging Capability
During long duration flights, it will be important to have medical imaging capability available to assist in diagnosis, treatment, and monitoring during and after medical events. This capability is likely to be an ultrasonic, low power, portable device that provides for diagnostic assistance via data processing algorithms. These algorithms would be expected to provide guidance for the crewmember administering the exam as well as identifying probable diagnoses options and possible treatments for each. The system should be flexible enough to provide fracture analysis, bone density levels, and body cavity status.

In-Flight Suction

Long duration missions must have the capability to provide medical suction for patients in the event of injury or serious illness. This system must be capable of providing suction for a variety of body orientations in multiple reduced gravity environments. It should be a stand-alone system that does not require oversight by another crewmember. In the event of malfunction, it should provide an audio alert, a display of the malfunction type, plus a safing algorithm. The contents of the suction system must be easily disposed of safely and without release of contents into the environment.

Biomedical Signal Processing

Assessment of an ill or injured crewmember may sometimes be accomplished in large part by the status of the biomedical signal, or EKG. This will have to be a "smart" system, which analyzes sensor placement, sensor health, signal monitoring, signal normalcy, and signal analysis. It is required that the biomedical signal be capable of monitoring cardiac health and physiological state. The processor must be fail-safe and must annunciate an audible alarm when a malfunction occurs. A display should provide a readout of the anomaly type and the system must safe itself when malfunctions occur. (NOTE: There may be a subset of malfunctions (e.g., loose lead) that will not require a shut-off or self-safing function.) The system must be volumetrically small with minimal mass.

Intelligent Software Modules

Software modules with the capability to review medical data in a SQL compliant database, assign or suggest appropriate SNOMED CT codes, and store the suggested codes in electronic format with discrete elements is highly desirable to avoid having to train hierarchical nomenclature to crewmembers. The hierarchical relationships between SNOMED codes should be maintained and stored in the output.

Sub Topics:
Advanced Life Support: Air and Thermal Topic X12.01
Advanced life support systems will be essential to enable human planetary missions as outlined in the Vision for Space Exploration. Innovative, efficient, and practical concepts are needed for regenerative air revitalization, ventilation, temperature, and humidity control. Requirements include safe operability in micro- and partial-gravity, ambient and reduced-pressure environments, high reliability, regeneration and minimal use of expendables, ease of maintenance, and low-system volume, mass, and power. Proposals should explicitly describe how their work is
expected to improve power, volume, mass, logistics, crew time, safety and reliability, with comparisons to existing state-of-the-art technologies. Information and documentation on advanced life support systems can be found at http://advlifesupport.jsc.nasa.gov [2].

Air Revitalization

The management of cabin atmosphere in spacecraft and habitats includes concentration, separation, and control techniques for oxygen, carbon dioxide, water vapor, particulates and trace chemical components. This includes processing and recovering resources derived from waste streams and from in situ planetary resources. Technologies focused at closing the air loop will have higher priority. Areas of emphasis include:

- Atmosphere revitalization process integration to achieve energy and logistics mass reductions;
- Separation of carbon dioxide from a mixture primarily of nitrogen, oxygen, and water vapor to maintain carbon dioxide concentrations below 0.3% by volume;
- Recovery of oxygen from carbon dioxide including approaches to deal with by-products of the process;
- Regenerable processes for removing trace chemical components from cabin air and/or gas product streams from other systems (e.g., water reclamation, waste management, etc.);
- Regenerable, re-usable, particulate filters for air;
- Novel approaches to suspended particulate matter removal from cabin and habitat atmospheres, including approaches to isolating cabin and habitat living areas from external dust sources such as Martian or lunar soil; and
- Methods of storage and delivery of atmospheric gases to reduce mass and volume and improve safety.

Advanced Thermal Control Systems

Thermal control is an essential part of any space vehicle, as it provides the necessary thermal environment for the crew and equipment to operate efficiently during the mission. A primary goal is to provide advanced technologies for temperature and humidity control; however, advanced active thermal control also includes technologies in the areas of heat acquisition, transport, and rejection. Areas of emphasis include:

- Liquid-to-liquid heat exchangers that provide two physical barriers preventing inter-path leakage;
- Advanced technologies to control cabin temperature and humidity in microgravity. Condensate that is collected must be able to be recovered and transported to the water recovery system;
- Alternate methods of atmospheric humidity control that do not use liquid-to-air heat exchanger (dependent on the spacecraft active thermal control system) or mechanical refrigeration technology;
- Technologies to inhibit microbial growth on wetted surfaces. Applications include condensate collection surfaces for humidity control and heat exchangers resident in water loops;
- Lightweight, versatile, and efficient heat acquisition devices including flexible cold plates, to provide cooling
to electronics, motors, and other types of heat producing equipment that is internal to the cabin;

- Lightweight, controllable, evaporative heat rejection devices that can operate in environments ranging from space, Mars’ atmosphere, and Earth's atmosphere;

- Alternative heat transfer fluids that are non-toxic, non-flammable, and have a low freezing temperature;

- Energy storage devices that maintain the integrity of food or science samples. For maintenance of temperatures of -20°C, -40°C, -80°C or -180°C;

- Highly accurate, remotely monitored, in situ, non-intrusive thermal instrumentation; and

- Low-energy, low-noise, high-capacity fans or similar devices for moving air.

Component Technologies

Energy efficient, low mass, low noise, low vibration, or vibration isolating, fail-safe, and reliable components for handling gases, fluids, particulates, and solids applicable to spacecraft environmental control and air revitalization, including actuators, fans, pumps, compressors, coolers, tubing, ducts, fittings, heat exchangers, couplings, quick disconnects, and valves that operate under varied levels of gravity, pressure, and vacuum. Mass flow monitoring and control devices that have similar attributes and that are easily calibrated and serviced.

Sub Topics:

EVA Technologies Topic X12.02

Advanced Extravehicular Activity (EVA) systems are necessary for the successful support of future human exploration space missions. Advanced EVA systems include the space suit pressure garment, the portable life support system, tools and equipment, and mobility aids such as rovers. Exploration EVA missions require innovative approaches for maximizing human productivity and for providing the capability to perform useful work tasks. Top-level requirements include reduction of system weight and volume, increased hardware reliability, maintainability, durability, and operating lifetime, increased human comfort, and less-restrictive work performance capability in the space environment, in hazardous ground-level contaminated atmospheres, or in extreme ambient thermal environments. Areas in which innovations are solicited include the following:

Environmental Protection

- Radiation protection technologies that protect the suited crewmember from radiation;

- Puncture protection technologies that provide self-sealing capabilities when a puncture occurs and minimizes punctures and cuts from sharp objects;

- Dust and abrasion protection materials or technologies to exclude or remove dust and withstand abrasion; and prevent dust adhesion; and

- Flexible space suit thermal insulation suitable for use in vacuum and low ambient pressure.

EVA Mobility
• Space suit low profile bearings that maximize rotation necessary for partial gravity mobility requirements and are lightweight.

**Life Support System**

• Long-life and high-capacity chemical oxygen storage systems for an emergency supply of oxygen for breathing;

• Low-venting or non-venting regenerable individual life support subsystem(s) concepts for crewmember cooling, heat rejection, and removal of expired water vapor and CO$_2$;

• Fuel cell technology that can provide power to a space suit and other EVA support systems;

• Lightweight convection and freezable radiators for thermal control;

• Innovative garments that provide direct thermal control to crewmember;

• High reliability pumps and fans that provide flow for a space suit but can be stacked to give greater flow for a vehicle;

• CO$_2$ and humidity control devices that, while minimizing expendables function in a CO$_2$ environment; and

• Variable conductivity flexible suit garment that can function as a radiator for high metabolic loads and as an insulator during period of low physical activity and low metabolic rates.

**Sensors, Communications, Cameras, and Informatics Systems**

• Space suit mounted displays for use both inside and outside the space suit-outside mounted displays will be compatible with the space environment;

• CO$_2$, bio-med (heart rate and blood oxygen level), radiation monitoring, and core temperature sensors with reduced size, lightweight, increased reliability, decreased wiring, and packaging flexibility;

• Visible spectrum camera that provides environment awareness for crewmembers and the public and are integratable into a spacesuit that is lightweight and low power;

• Lightweight sensor systems that detects N$_2$, CO$_2$, NH$_4$, O$_2$, ammonia, hydrazine partial pressures, including self-powered sensors;

• Lightweight, low power, radio and laser communications with the capability to integrate audio, video, and data on the same data stream to provide reliable communications between the crew and a lander or habitat; and

• Low power, lightweight, radiation hardened, or radiation tolerant informatics computer systems with standard graphics outputs and standard audio inputs and outputs, capable of running commercial operating systems and applications.

**Integration**

• Robot control by EVA crewmember via voice control or other methods;
• Minimum gas loss airlocks providing quick exit and entry and can accommodate an incapacitated crewmember; and

• Work tools that assist the EVA crewmember during operations in zero gravity and at worksites; specifically, devices that provide temporary attachments, which rigidly restrain equipment to other equipment and the EVA crewmember, and that contain provisions for tethering and storage of loose articles such as tool sockets.

EVA Navigation and Location

• Systems and technologies for providing an EVA crewmember real-time navigation and position information while traversing on foot or a rover; and

• Systems and technologies for managing and locating tools during planetary surface science and maintenance EVA sorties.

Sub Topics:
Contingency Response Technologies Topic X12.03

Decades of experience in manned space flight have demonstrated that during any mission, unexpected events will occur. If the crew is adequately equipped to address such contingencies during exploration missions, the chances of successfully completing that mission can be greatly increased. The objective of this subtopic is to develop technologies in the areas of fire prevention, detection, and suppression (FPDS) and in situ fabrication and repair (ISFAR) that will support the crew in the event of a fire or if a critical component breaks during a mission, respectively. These technologies may be in the form of devices, models, and/or instruments for use in microgravity and/or for commercial applications on Earth. The top-level requirements for a viable technology include the reduction of system hardware weight and volume and increased hardware reliability, durability, and operating lifetime. Research conducted during the Phase 1 contract should focus on demonstrating the technical feasibility of the FPDS or ISFAR protocol/system and show a path toward a Phase 2-specific deliverable. The contractor will, when appropriate, deliver a demonstration unit of the instrumentation for NASA testing before the completion of the Phase 2 contract.

Fire Prevention, Detection, and Suppression

The objective of the Fire Prevention, Detection, and Suppression (FPDS) subtopic is to develop technologies that, when incorporated into the design philosophy and functional design of exploration vehicles and habitats, will quantitatively reduce the likelihood of a fire and reduce the impact to the mission should a fire occur. The element is composed of four major theme areas including: fire prevention and material flammability, fire signatures and detection, fire suppression and response, and analysis of fire scenarios. Innovations are sought in the following theme areas:

• Quantifying the effects of microgravity, 1/6-g (lunar) and 1/3-g (Martian) on the ignitability of materials and the subsequent flame spread, particularly related to determining relevant low-gravity behavior from normal gravity tests;

• Improving the performance of spacecraft fire safety systems through the development of advanced fire
detection and suppression systems and strategies as well as predicting the effects of smoke and precursor generation and transport; and

- Developing techniques for creating and analyzing the effectiveness of fire resistant materials and coatings, including fire prevention techniques, for spacecraft structures, radiation shielding materials, paneling, fabrics (cotton, paper, synthetics), foams, etc.

**In Situ Fabrication and Repair**

*In Situ* Fabrication and Repair develops technologies for life support system maintenance and integrated habitat radiation shielding fabrication with a focus on contingency response and maximization of *in situ* resource utilization to reduce launch mass and volume. The manufacture or repair of components during a mission is essential to human exploration and development of space. Fabrication and repair beyond low Earth orbit is required to reduce resource requirements, spare parts inventory, and to enhance mission security. Proposals are sought in the technical themes listed below:

- Application of Free Form Fabrication (FFF) methods to low gravity (3/8 and 1/6 g level) manufacturing of near net shape products and spare parts from *in situ* derived resources or provisional feedstock;
- Processes for extracting *in situ* resources into raw materials and feedstock for use with rapid prototyping technology;
- Extension of fused deposition methods to the use of binderless metal wire feed stock;
- Adaptation of ultrasonic consolidation methods to use narrow ribbon metal feedstock to reduce subsequent machining operations and waste;
- Novel and innovative *in situ* repair methods such as but not limited to: welding, composite repair, and self healing materials;
- Development of highly automated habitat construction methods that incorporates *in situ* materials on surface or primary structure may use *in situ* construction;
- Development of dust mitigation techniques applicable to planetary habitat construction;
- Integration of radiation shielding materials into habitat construction methods; and
- Innovative approaches for recycling of materials for secondary uses.

**Sub Topics:**

*Advanced Environment Monitoring and Control Topic X12.04*

This subtopic addresses monitoring and control technologies, which support the operation of an Advanced Life Support (ALS) system for future long duration space missions. There are two application areas: Acoustics Monitoring and Environmental Controls.

**Acoustics Monitoring Section**

The objective is a proof-of-concept acoustic sensor system consisting of fixed and crew-worn transducers. At least
ten fixed transducers shall be distributed in a habitable volume of at least 2x2x6m. The goal for the fixed microphones is to provide sound pressure level measurements with Type I measurement accuracy over the Octave Band frequency range from 63 Hz through 20 kHz. The system shall be capable of measuring 1/3 Octave Band, Octave Band, and Narrow Band sound pressure levels averaged over a specified interval with user defined data acquisition parameters. The fixed microphones shall also operate as an acoustic dosimeter with Type III accuracy and shall measure and log the maximum, A-weighted, Overall Sound Pressure Level every 30 seconds for at least 24 hours. The system shall also detect Hazard Levels of 85+ dBA and generate an alarm. The crew-worn transducer, clipped to a shirt collar, shall operate as a Type III acoustic dosimeter and shall measure and log the maximum, A-weighted, Overall Sound Pressure Level every 30 seconds for at least 24 hours. The size and mass of the device shall be comparable to COTS dosimeters. All system measurements shall be carried out remotely and the data managed by software. The system shall be demonstrated in a mock-up, and calibrations and comparisons made with appropriate instruments and methods.

Environmental Controls

Advanced Environmental Controls - the development of advanced control system technologies is necessary for the integrated operation of environmental systems for future long-duration human space missions. The interdependence of advanced environmental processing systems requires a non-avionics requirements process that allows design for controllability. This year particular emphasis is placed on the following:

- Control strategies for closed-loop systems - closed loop and biological systems have different constraints and control paradigms than conventional processes. There is a need for new control algorithms, analyses, design methodologies, strategies, and techniques to provide this capability;

- Ontologies for integrated operations - human exploration missions involve hundreds of systems developed by dozens of organizations. To develop software that can integrate across these systems and integrate with operations requires the use of common terminology across multiple disciplines. A common ontology must be developed to enable the integration of control of advanced life support systems; and

- Development and integration of autonomous system and inter-system control with crew and ground operations - there is a need for tools, architectures, and technologies that can support the integration of operations between crew, ground operators, ground applications, and on-board applications.

Sub Topics:
Advanced Life Support: Food Provisioning and Biomass Topic X12.05
Exploration missions beyond low Earth orbit greatly limit allowable consumables and require development of innovative low maintenance, reconfigurable, reusable, or self-sufficient food production. Advancements are necessary to develop a combination of extended duration shelf life stored foods augmented with fresh foods grown within the spacecraft. Crop systems, in addition to producing fresh vegetables, storage roots, grains and legumes may contribute to air revitalization and utilize wastes from water recovery and waste management systems.

Crop Systems

The production of biomass (in the form of edible food crops) in closed or nearly closed environments is essential for the future of long-term planetary exploration and human settlement in lunar and Mars base applications. These technologies will lead not only to food production but also to the reclamation of water, purification of air, and recovery of inedible plant resources in the comprehensive exploration of interplanetary regions. Areas in which
innovations are solicited include:

- Crop lighting, such as LED, solar collectors and innovative technologies. Lighting transmission and distribution systems, luminaries, fiber optics, water jackets, and other heat removal technologies are also areas of interest;

- Water and nutrient management systems such as hydroponics and/or solid substrates for food production and separation of nutrients from waste streams are solicited. In this area, regenerable media for seed germination plant support are also of interest as is separation and recovery of usable minerals from wastewater and solid waste products for use as a source of mineral nutrients. Consideration should be given for systems operation in microgravity and hypogravity (1/6 g on Moon, 3/8 g on Mars) environments; and

- Other areas of interest: crop mechanization and automation, facility or system sanitation, crop health measurement, flight equipment support, structures and environmental monitoring and control technologies that are specific to crop systems (e.g., ethylene detection and removal, sensors for root zone oxygen and water content, etc.).

**Food Provisioning**

- Safe, nutritious, acceptable, and varied shelf-stable foods with a shelf life of 3 to 5 years will be required to support the crew during future exploration missions to the Moon or Mars. Shelf-life extension may be attained through food preservation methods and/or packaging. Packaging materials must provide sufficient oxygen and water barrier properties to maintain shelf life. Food packaging technologies are needed that minimize a potentially significant trash management problem by using packaging with less mass and volume and/or by using packaging that is biodegradable, recyclable, or reusable;

- Processing crops or bulk ingredients into edible food ingredients or table-ready products will be necessary to provide a self-sustaining food system for an exploration mission. Equipment that is highly reliable, safe, automated, and minimizes crew time, power, water, mass, and volume will be required. Equipment for processing raw materials must be suitable for use in hypogravity (e.g., 1/6g on Moon, 3/8g on Mars) and in hermetically sealed habitats;

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

- Food quality and safety are essential components in the maintenance of crew health and well being. Efforts should be focused on control of food spoilage and food quality throughout the entire shelf life of the food. Effects of radiation on crop functionality and the stored food system quality are also needed.

**Sub Topics:**

Habitation Systems Topic X12.06

**Habitation Systems**

Habitation systems for future crewed micro-gravity transits, reduced gravity planetary lunar or Martian surfaces, and long duration, deep-space environments are requested. Products can include basic research, system analysis, mockup evaluation, functionality demonstrations/tests, and actual prototype hardware. Exploration missions away
from low Earth orbit greatly limit allowable consumables and require development of innovative low maintenance, re-configurable, and reusable systems. Minimal volume configurations (or dual use) during non-use mission phases are highly desirable.

Habitation systems should consider the following broad themes: re-configurable crew volumes for multi-gravity environments (micro and reduced gravity), multi-use work stations, multi-gravity translation strategies, crew radiation exposure mitigation, physically and psychologically ergonomic personal volumes, automated deployment, quiescent operations between missions, multi-purpose stowage systems for food/trash, advanced hygiene systems, and automated housekeeping/self-repairing habitat surfaces, durability, commonality of hardware/systems, and low total life-cycle costs. Specific areas in which advanced habitability system innovations are solicited include:

**Wardroom Systems:** Erectable or inflatable systems that support crew dinning, conference, external viewing (windows), illumination, and relaxation activities. Includes off-nominal uses (emergency medical or repair) while maintaining hygienic conditions.

**Galley Systems:** Systems requiring minimal crew preparation (heating, cooling, and rehydration) for food heating and accurate water dispensing. Specific areas include systems that allow individual crew meal flexibility and high-energy efficiency.

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

**Crew Accommodation Systems:** Reconfigurable, deployable, or inflatable integrated crew accommodations that provide visual and acoustical isolated crew volumes for sleeping, audiovisual communication/entertainment, personal stowage, quiet ventilation/thermal control, and radiation exposure reduction/safe-haven.

**Clothing Systems:** Low mass reusable or long usage clothing options that meet flammability, out gassing, and crew comfort requirements. Used clothing cleaning/drying systems with low-water usage and non-toxic detergents/enzymes compatible with biological water reclamation systems or non-water cleaning methods.

**Stowage Systems:** Interior/exterior stowage systems for partial gravity environments that maximize usable volume and include contents identification and inventory control systems. Long-term external stowage for biological or other wastes on a planetary surface that safe and consistent with planetary protection policies.

Sub Topics:
Advanced Life Support: Water and Waste Processing Topic X12.07
Regenerative closed-loop life support systems will be essential to enable human planetary exploration as outlined in the Vision for Space Exploration. These future systems must provide additional mass balance closure to further reduce logistics requirements and to promote self-sufficiency. Recovery of useful resources from liquid and solid wastes will be essential. Requirements include safe operability in micro- and partial-gravity, ambient and reduced-pressure environments, high reliability, regeneration and minimal use of expendables, ease of maintenance, and low-system volume, mass and power. Proposals should explicitly describe how the work is expected to improve power, volume, mass, logistics, crew time, safety and/or reliability, giving comparisons to existing state-of-the-art technologies. Additional documentation and information can be found at http://advlifesupport.jsc.nasa.gov [2], including the expected composition of solid wastes and wastewater, which can be found within the "Baseline Values and Assumptions Document".

Water Reclamation

Efficient, direct treatment of wastewater and product water consisting of urine, brines, wash water, humidity condensate, and or product water derived from in situ planetary resources, to produce potable and hygiene water supplies. Technologies that contribute to closing the water loop will be given higher priority. Areas of emphasis include:

- Novel methods of process design and integration to minimize trace contaminant carryover from the cabin atmosphere leading to reduced logistics needs;
- Physicochemical methods for primary wastewater treatment to reduce total organic carbon from 1000 mg/L to less than 50 mg/L and/or total dissolved solids from 1000 mg/L to less than 100 mg/L;
- Post-treatment methods to reduce total organic carbon from 100 mg/L to less than 0.25 mg/L in the presence of 50 mg/L bicarbonate ions, 25 mg/L ammonium ions and 25 ppm other inorganic ions;
- Methods for the phase separation of solids, gases, and liquids in a microgravity environment that are insensitive to fouling mechanisms;
- Methods for the recovery of water from brine solutions;
- Methods to eliminate or manage solids precipitation in wastewater lines;
- Disinfection technologies for potable water storage and point-of-use. Residual disinfectants for potable water that is compatible with processing systems including biological treatment; and
- Techniques to minimize or eliminate biofilm and microbial contamination from potable water and water treatment systems, including components such as pipes, tanks, flow meters, check valves, regulators, etc.

Solid Waste Management

Wastes (trash, food packaging, feces, biomass, paper, tape, filters, water brines, clothing, hygiene wipes, etc.) must be managed to protect crew health, safety, and quality of life, to avoid harmful contamination of planetary surfaces (Moon, Earth, and Mars), and to recover useful resources. Treatment methods can include both oxidative and non-oxidative approaches. Areas of emphasis include:

- Volume reduction of wet and dry solid wastes;
• Small and compact fecal collection and/or treatment systems;
• Water recovery from wet wastes (including human fecal wastes, food packaging, brines, etc.);
• Stabilization, sterilization, and/or microbial control technologies to minimize or eliminate biological hazards (to the crew, to Mars, to Earth) associated with waste;
• Mineralization of wastes (especially fecal) to ash and simple gaseous compounds (e.g. CO$_2$, CH$_4$);
• Containment of solid wastes onboard the spacecraft that incorporates odor abatement technology;
• Containment devices or systems, with low volume and mass, that can maintain isolation of disposed waste on planetary surfaces (such as Mars); and
• Microgravity-compatible technologies for the containment and jettison of solid wastes in space.

Component Technologies

Energy-efficient, low-mass, low-noise, low-vibration or vibration isolating, fail-safe, and reliable components for handling fluids, slurries, biomass, particulates, and solids applicable to spacecraft wastewater treatment and solid waste management, including particle size reduction technologies (0.2 cm to 100 microns), actuators, pumps, conveyors, tubing, ducts, bins, fittings, tanks, couplings, quick disconnects, and valves that operate under varied levels of gravity, pressure, and vacuum.

Sub Topics:
Space Human Factors Engineering Topic X13.01
The long-term goal for this subtopic is to enable planning, designing, training, and carrying out human space missions of up to 5 years with crew independence, without re-supply and without real-time communications to Earth. Specifically, this subtopic's focus is the development of innovations in crew equipment; and the development of technologies for assessment, modeling, and enhancement of human performance; and the development of design tools for engineers to incorporate human factors engineering requirements into hardware and software. Proposals are solicited that seek to develop technologies that address these specific needs:

• Monitoring and maintaining human performance non-intrusively. Specifically, minimally invasive and unobtrusive devices and techniques to monitor the behavior and performance (physical, cognitive, perceptual, etc.) of individuals and teams during long-duration space flights or analog missions. Embedded measures to detect significant changes in crew readiness to perform physical or cognitive tasks;
• Predicting human performance: methods and models for predicting effects on physical performance of encumbrances of clothing, space suits, etc. Models for predicting effects of physical environment (e.g.,
lighting, noise, temperature, contaminants) on human performance. Models to simulate and optimize interactions between humans and equipment/vehicle. Capability to implement time-delay algorithm and functionality into simulation for higher fidelity and effectiveness. Models for predicting effects of cognitive changes on performance;

- Tools to aid in design and evaluation of human-system interfaces for speed, accuracy, and acceptability in a cost-effective and reliable manner: automated analysis of computer-user interfaces for complex display systems to conduct objective review of displays and controls, and to determine compliance with guidelines and standards. Quantitative measures of the effectiveness of user interfaces to be used for task-sensitive evaluations;

- Tools that facilitate the user interface design for human computer interfaces, and for facilitators such as procedures, labels, and instructions. Tools should assist the designer in incorporating contextual information such as the user's task, the user's knowledge, and the system limitations; and

- Tools to build just-in-time system and operational information software to aid human users conducting routine and emergency operations and activities. Such tools might include effective and efficient job aids (e.g., “intelligent” manuals, checklists, and warnings) and support for designing flexible interfaces between users and large information systems. Methods for development of “facilitators” (procedures, labels, etc.) adapted for the development of space vehicle and payload applications.

Sub Topics:
Behavioral Health and Performance Topic X13.02
Behavioral Health and Performance provides the necessary technology, techniques, capabilities, and knowledge that will support mission success, during human exploration flight and return to Earth. This will be accomplished by optimizing the behavioral health and performance of each astronaut and crewmember, and by mitigating psychosocial, neurobehavioral, sensorimotor, cognitive, and sleep chronobiology risks. Behavioral health and performance research contributes to medical standards, guidelines, and requirements and produces design tools and diagnostic measures for the Chief Health and Medical Officer, flight surgeons, and astronauts. The technical areas supported by this program include performance readiness, effective and efficient teamwork for pre-, in-, and post-flight expedition missions, and psychological selection validated criteria, tools, and procedures. Prolonged missions and the associated adaptation and de-conditioning due to microgravity, as well as significant time delays between Earth and the space environment increase the likelihood of serious crew conflict as well as behavioral health and performance decrements. Proposals are solicited that seek to develop core knowledge, predictive models, and enabling technologies that address these specific needs:

- Non-intrusively monitoring and maintaining human performance. Specifically, minimally invasive and unobtrusive devices and techniques to monitor the behavior and performance (physical, cognitive, perceptual, sensorimotor, etc.) of individuals and teams during long-duration space flights or analog missions. Embedded measures to detect significant changes in crew readiness to perform physical or cognitive tasks; and

- Monitoring and maintaining non-intrusively behavioral health. For example, self assessment tools for determining levels of stress, fatigue, conflict, and anxiety of an individual crewmember and training techniques for coping and on-board support tools for behavioral health.

Sub Topics:
The goal of effective Human Systems Integration challenges many areas of technology, including distributed data management and control, sensor interpretation, planning and scheduling, modeling and simulation, and validation and verification of autonomous systems. These various technology areas must eventually be integrated into a system-of-systems. Particular emphasis is placed on the following:

**System Engineering Tools**

Technologies, tools, and methodologies are needed that assure development activity is congruent with Exploration Mission capability requirements. Decision support tools are needed to help in the visualization of portfolio balance and clear representation of complex systems as well as a capture method for the interactions/interdependencies/interfaces between system elements.

**System Simulation Tools**

The ability to analyze, synthesize, and develop integrated function-based and simulation-based system architectures in support of Human Systems. Key to this requirement is either the further extension/enhancement of current available SE tools or acquisition/development of tools that will allow for system level concept development and concept simulation.

**System Integration Tools**

The ability to enable human system integration for exploration missions is strongly affected by the structure and architecture of the systems used to sustain and protect the crew. There is a need for the development and evaluation of control architectures and strategies for determining relative benefit, risk, and costs of the utilization of candidate system architectures. Tools for capturing state knowledge of the entire portfolio by project, including dependencies, maturity, and relationships to requirements are also needed.

Capability-based requirements methods require tools and methodologies that enable capture of current practice for information integration between ground-based systems, on-board systems, and crew systems; goal analysis; surveys of existing and proposed technologies; mapping of technology to tasks; prototyping; integrated testing and evaluation criteria; and development of experienced personnel.

**Integration Test Bed Tools and Applications**

Integrated ground tests for human exploration missions will provide a test bed for development of hardware, requirements, hardware acquisition strategies, novel system concepts, and management. Tools are needed that provide techniques for real-time analysis; techniques for planning, scheduling, and conducting complex integrated mission simulations; tools to develop system-level mathematical models of missions; and systems engineering and analysis tools for mission architecture studies.

**Human-System Integration for Manufacturing and Launch Site Operations**

Human-System Integration of Manufacturing and Launch Site Operations addresses the following functional areas: Manufacturing, Spacecraft Processing, Launch Control, Landing and Recovery, Repair and Refurbishment, and Enabling Operations. Specific areas of interest include intelligent work instruction systems; maintainer/launch controller situational awareness; human/robotic maintainer on-board capability; reduced size ground crew training
modules; and predictive labor requirement models.

Research should be conducted to demonstrate technical feasibility during the Phase 1 contract and show a path toward a Phase 2 hardware and software demonstration. The contractor will, when possible, deliver a demonstration unit of the monitoring instrumentation for NASA testing before the completion of the Phase 2 contract.

Sub Topics:
Space-Based Industries Topic X14.01
Innovative techno-economic research proposals are sought for space-based industries ideas that identify their purpose, basic required infrastructures, and how they might complement NASA's exploration missions. The Phase 1 work must sufficiently develop one or more industry ideas to show they are sufficiently feasible, both technically and economically, for Phase 2 demonstrations of their viability. The demonstrations may use physical and mathematical modeling and other research techniques. Each industry idea may have infrastructures that include a wide variety of needed innovations that will be common to NASA's exploration goals as well as to space industries that have a wide variety of purposes like tourism, servicing and maintenance of satellites, food production, energy production, fuels and propellants production, entertainment, in-space fabrication, workshops, hotels and habitats, life support systems, vehicles, freight and warehousing, roads, and spaceports. The research should include economic business models, cost feasibility examination, and analyses that can show how innovations that are common to the multiple goals can save money for NASA as well as space industries. The technical innovations may include, but are not limited to: materials, fabrication processes, power and power distribution, communications, waste management, robotic support, and more. It is expected that the technical innovative ideas will go further than the specific exploration topics and subtopics requests made elsewhere in this 2005 solicitation due to the broader scope of applications.

Sub Topics:
Multi-Use Microgravity and Software Topic X14.02
The purpose of this subtopic is to develop technologies, methodologies, and tools that can support the integrated development of the software system-of-systems necessary for exploration missions. Human space flight challenges many areas of software technology, including distributed data management and control, sensor interpretation, planning and scheduling, modeling and simulation, and validation and verification of autonomous systems. This subtopic focuses on the development portion of the mission life cycle and the dependence of the eventual mission solutions on the processes and methods used to define and build vehicles and support operations. The need for such technologies, methodologies, and tools is evidenced by the low success rate of commercial and government systems, where failure occurs at delivery rather than during operation. Management of the development of such large systems is essential to integration.

Software Architecture and Systems Integration
The challenges of human system integration for exploration missions is strongly affected by the structure and architecture of the software systems required to provide control and status pathways to ground support systems and personnel; to support mission planning and operation; to provide crew interfaces for status, control, and operation of the vehicle systems, science, and operations, including communications, planning, task management, interpersonal activity, system configuration management, inventory, food, workflow, resource management, experiments, and vehicle operation and maintenance. Onboard software must integrate, and be interoperable with the ground support systems for planning, logistics, operations, science, medical, and engineering, as well as with subsequent exploration spirals. This requires the development of structures and methods for determining relative benefits, risks, and costs of the utilization of various engineering approaches. Project management tools are needed that can conduct and manage Exploration Mission capability and technology gap analysis; provide technology-to-capability mapping; map technology gaps to research initiatives; and provide decision support.

**Systems Engineering Support to Human Systems**

There is a need for new tools to support the development of non-avionic control systems throughout the program life cycle. This includes tools for managing prototyping, requirements, design, design knowledge capture, testing, and growth and maintenance across multiple development teams. Particular emphasis is placed on design methods that address the interdependencies between systems. Adapting the Joint Capabilities Integration and Development System (JCIDS) approach to systems engineering requires development of tools and methodologies that enable: surveys of current information integration practices between ground-based systems, on-board systems and crew systems; goal analysis (software task analysis); surveys of existing and proposed technologies; mapping of technology to tasks; prototyping to drive out design constraints and detailed requirements; development of testing and evaluation criteria for advanced or untried architectures and technologies and maturation of those technologies into an integrated system of systems; tracking lessons learned, methods, and processes; and development of an experienced personnel base.

Research should be conducted to demonstrate technical feasibility during the Phase 1 contract and show a path toward a Phase 2 demonstration. The contractor will, when possible, deliver a demonstration unit of the hardware and software for NASA testing before the completion of the Phase 2 contract.

Sub Topics: