



NASA SBIR 2016 Phase I Solicitation

Human Exploration and Operations

In-situ Resource Utilization (ISRU) Topic H1

In-situ Resource Utilization (ISRU) involves any hardware or operation that harnesses and utilizes 'in-situ' resources (natural and discarded) to create products and services for robotic and human exploration. ISRU products and services can be used to reduce Earth launch mass or lander mass by not bringing everything from Earth, reduce risks to the crew and/or mission by reducing logistics, increasing shielding, and providing increased self-sufficiency, or reduce costs by needing less launch vehicles to complete the mission and/or through the reuse of hardware and lander/space transportation vehicles. An important aspect of ISRU is to make mission critical consumables for propulsion, life support, and fuel cell power systems and feedstock for in-situ manufacturing and construction. Production of propellants allows for significant savings in launch or landed mass and transportation and lander reuse. Production of feedstock for manufacturing and construction processes from local and recycled materials with little or no Earth provided binders/reactants can provide significant improvements in failure recovery, shielding, self-sufficiency, and eventual infrastructure growth. Since ISRU can be performed wherever resources may exist, ISRU systems will need to operate in a variety of environments and gravities and need to consider a wide variety of potential resource physical and mineral characteristics. Also, because ISRU systems and operations have never been demonstrated before in missions, it is important that ISRU concepts and technologies be evaluated under relevant conditions (gravity, environment, and vacuum) as well as anchored through modeling to regolith/soil, atmosphere, and environmental conditions.

Sub Topics:

H1.01 In situ Resource Utilization - Production of Feedstock for Manufacturing and Construction

Lead Center: JSC

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

The overall goal of in-situ Resource Utilization (ISRU) is to transform available resources, both natural and man-made, on extraterrestrial surfaces into usable materials and products that assist in sustaining and growing human exploration capabilities. ISRU involves all the steps associated with identifying, collecting, and converting local resources into products that can reduce mission mass, cost, and/or risk. It is imperative that novel technologies be developed to effectively utilize these resources for mission critical consumables, as well as to produce feedstock for additive manufacturing of replacement parts, construction for habitat, and infrastructure expansion. In the case of Mars, carbon dioxide and other atmospheric constituents, along with regolith and water/ice can be harvested for basic elements that could be utilized to generate various simple and complex organic and inorganic compounds, composites and products. The subtopic seeks proposals for critical technologies associated with the design, fabrication, and testing of hardware associated with one or more of the areas of interest below:

- *Plastic production for in-space additive manufacturing* - Production of plastic that can be fed into in space manufacturing devices. Define and demonstrate all steps required for conversion of some or all of the following in-situ constituents (H_2 , CO, CO_2 , O_2 , N_2 , and CH_4) into a final plastic product. It is expected that intermediate products, such as longer chain hydrocarbons, alcohols, aromatics, etc. will be required to achieve final plastic production. Proposals will need to identify all the steps and intermediate products. Phase I proposals will need to demonstrate critical steps, especially the first step from the list of starting constituents. Each step in Phase I can be performed/demonstrated individually. Phase II proposals will need to demonstrate all steps in an integrated manner. Production rates for plastic production will initially be low at 1 to 5 kg/day. Ability to breakdown and recycle the plastic produced is desired but not required. If additional constituents are required to make in-situ plastic, proposer can include them but will need to identify whether the constituents can be obtained in-situ or needs to be brought from

Earth. Information on thermoplastic feedstock glass transition temperature and melting point properties for 3D printer plastic feedstocks that might be useful can be found at: (<http://3dprintingfromscratch.com/common/3d-printer-filament-types-overview/> [1]). Since the loads and environments of the parts made using the feedstock are not known at this time, it is recommended that the properties be commensurate with commercially available feedstocks. Some desired characteristics of the parts made from the feedstock are high temperature resistance, low moisture adsorption, and ability to bond using adhesives. Feedstock produced must be tested in a commercially available additive manufacturing device in Phase II.

- *Metal extraction from extraterrestrial material for additive manufacturing* - Metal extraction from extraterrestrial material including lunar regolith, Mars soil, and ordinary and carbonaceous chondrites asteroidal material. Regeneration of any reactants used in the metal extraction process is required. Metals found in extraterrestrial material such as iron, aluminum, silicon, magnesium, and nickel are desired for future in-situ additive manufacturing. It is not expected that the quality and purity of the extracted metals will be to the same standard obtained from terrestrial processes so proposer needs to consider the possible extraction method and subsequent purity of the feedstock. In Phase I, the proposer is required to demonstrate the feasibility of extracting the desired feedstock. Methods used for extraction can be physical/chemical or biological. In Phase II, these feed stocks should be ready for introduction into a fabrication process by being pre-processed to have appropriate physical properties and forms (e.g., granulated, spooled wire, plate, billet, ingots, etc.). Manufacturing processes should be identified and feasibility demonstrated using the regolith derived feed stocks in partial and/or micro gravity environments. Regolith acquisition and delivery of up to 100 kg/hour can be assumed as an input material stream. Using a waste stream from another ISRU process to produce feedstock for fabrication may be considered such as regolith that has already been processed to extract water or oxygen from minerals.
- *ISRU for additive construction techniques* - Bulk or modified regolith can also be used as a construction material (with or without a binder) to form a material that can be extruded to produce a floor, structural wall, or ceiling, or into bricks or slabs for landing pads, roads, and shielding. These construction material can be used for making structures, shelters, radiation shielding, and thermal shading and for micrometeorite protection. Binders and additives must be less than 10% by mass of the construction material feedstock. Use of binders that can also be produced in-situ are preferred. Use of water is not excluded, but steps to be taken mitigate losses and amounts used and lost must be clarified to compare to non-water based construction materials. In Phase II, demonstration of the feasibility of additive construction using construction material feedstock is required (demonstration in partial or micro gravity environments is desired). For extruded materials a linear printing rates 30 to 100 cm/minute is desired. Bricks and slabs should have ability to be joined or interlocked.

All proposals need to identify the state-of-the-art of applicable technologies and processes. Proposals must address the physical/mineral properties of the regolith/soil used. Proposers must specify whether the process is performed in batches or by continuous processing with appropriate sealing techniques to minimize reactant/product losses identified.

Space Transportation Topic H2

Achieving space flight remains a challenging enterprise. It is an undertaking of great complexity, requiring numerous technological advances conducted by a wide range of engineering disciplines with a high level of organizational skill. Human Exploration requires advances in space transportation systems, operations, and testing, for transport to the earth orbit, the moon, Mars, and beyond. NASA is interested in making space transportation systems more capable and less expensive. NASA is interested in technologies for advanced in-space propulsion systems to support exploration that reduce travel time, reduce acquisition costs, and reduce operational costs. The goal is a breakthrough in cost and reliability for a wide range of payload sizes and types supporting future orbital and exploration flight vehicles. Lower cost and reliable space access will provide significant benefits to civil space (human and robotic exploration beyond Earth as well as Earth science), to commercial industry, to educational institutions, to the International Space Station National Laboratory, and to national security. While other strategies can support frequent, low-cost and reliable space access, this topic focuses on the in-space propulsion technologies that dramatically alter acquisition, reusability, reliability, and operability of space transportation systems.

Sub Topics:

H2.01 LOX/Methane In-Space Propulsion

Lead Center: GRC

Participating Center(s): JSC, MSFC

NASA is developing high thrust in-space chemical propulsion capabilities to enable human and robotic missions into the proving ground (Mars and beyond). Successful proposals are sought for focused investments on key technologies and design concepts that may transform the path for future exploration of Mars, while providing component and system-level cost and mass savings. In-space propulsion is defined as the development and demonstration of technologies for ascent, orbit transfer, pulsing attitude/reaction control (RCS), and descent engines.

The goal of this subtopic is to examine novel technology options that include the use of additive manufacturing or other low cost processes which save mass and/or cost compared to current state-of-the-art (SOA) technologies and fabrication methods. Technologies of interest for operation with liquid oxygen and methane specifically are sought.

Proposers shall show how their technology works and provide the following:

- Assessment of SOA with the key performance parameters (KPP) of their choosing (such as performance, mass, response time, etc.), including specifics which may be referenced in backup material - provide SOA for each major technology element in the proposal.
- Address the outstanding technology performance being promised and the degree to which the concept is new, different, and important. Particularly how the technology and/or fabrication technique proposed saves cost and/or mass is desired.
- Provide quantitative assertions (e.g., x% improvement of y, z kg of mass savings, xx% in cost savings, etc.) to the advancement over the SOA.

Phase I Deliverables - Research to identify and evaluate candidate technology applications to demonstrate the technical feasibility and show a path towards a demonstration. Bench or lab-level demonstrations are desirable. The technology concept at the end of Phase I should be at a TRL of 4 to 5.

Phase II Deliverables - Emphasis should be placed on developing and demonstrating the technology under simulated mission conditions. The proposal shall outline a path showing how the technology could be developed into mission-worthy systems. The contract should deliver a demonstration unit for functional and environmental testing at the completion of the Phase II contract. The technology concept at the end of Phase II should be at a TRL of 5 to 6.

For reference, current anticipated performance goals for liquid oxygen/liquid methane systems are:

- Reaction control thruster development in the 100-800 lbf thrust class. The reaction control engines would operate cryogenic liquid-liquid for applications requiring integration with main engine propellants; or would operate gas-gas or gas-liquid for small total impulse type applications. RCEs operating on liquid cryogenic propellant(s) should be able to tolerate operation for limited duty cycles with gaseous or saturated propellants of varying quality. Integrated RCS (IRCS) capability desired (common propellant tanks for RCS and main engines).
- Descent pump-fed engine development with 50,000 lbf thrust and a minimum vacuum specific impulse of 360-sec. The propulsion system should be capable of stable throttling to 5:1 (20% power). Space survival time of greater than 3 years.
- Ascent pump-fed engine development with 25,000 lbf thrust and a minimum vacuum specific impulse of 360-sec. The propulsion system should be capable of stable throttling to 5:1 (20% power). Space survival time of greater than 4 years.
- Integrated Propulsion and Feed System technologies, such as for integrated reaction control systems (RCS). This would include thermal conditioning features, self-pressurization/re-pressurization control, and system isolation control.

For reference, some specific propulsion technologies of interest are included below. In all cases – interest in using additive manufacturing or novel fabrication methods to save cost and mass are desired to achieve the specific component objectives identified below:

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- Injector concepts with throttle range greater than 4:1 while maintaining stable combustion over the range of operation and inlet conditions and meeting performance goals at full throttle condition.
 - Regenerative cooled combustion chamber technologies which offer improved performance, especially at sub-critical or trans-critical conditions, and provide adequate chamber life. This includes methods for addressing differential boiling within regenerative channels and/or start up transients (gas/gas, to two-phase, to high-quality liquid/liquid) for both fuel and oxidizer circuits.
 - Turbopump technologies specific to liquid methane that are lightweight with a long shelf life that can meet deep-throttle requirements, including small durable high speed turbines, high speed lightweight electric direct current (DC) motor driven pumps, high fatigue life impellers, zero net positive suction head (NPSH) inducers, low leakage seals, and long life in-situ propellant fed bearings.
 - Engine valves with a focus on light-weight (at the system level, considering supporting pneumatics, batteries, etc.), fast-acting, low-leakage throttle valves, which meet the following performance considerations: Maintain consistent mixture ratio (MR) over the throttle range, 50% (minimum) force margin, cold and warm operations, easily chilled in, with leakage in the 10^{-4} to 10^{-6} standard cubic centimeters per second (SCCS) range (gaseous phase oxygen and methane).

H2.02 Nuclear Thermal Propulsion (NTP)

Lead Center: MSFC

Participating Center(s): GRC, SSC

Solid core NTP has been identified as an advanced propulsion concept which could provide the fastest trip times with fewer SLS launches than other propulsion concepts for human missions to Mars over a variety of mission years. The current NASA Strategic Space Technology Investment Plan states NTP is a high priority technology needed for future human exploration of Mars. NTP had major technical work done between 1955-1973 as part of the Rover and Nuclear Engine for Rocket Vehicle Application (NERVA) programs. A few other NTP programs followed including the Space Nuclear Thermal Propulsion (SNTP) program in the early 1990's. The NTP concept is similar to a liquid chemical propulsion system, except instead of combustion in the thrust chamber, a monopropellant is heated with a fission reactor (heat exchanger) in the thrust chamber. In addition, the engine components and surrounding structures are exposed to a radiation environment formed by the reactor during operation.

This solicitation will examine a range of modern technologies associated with NTP using solid core nuclear fission reactors and technologies needed to ground test the engine system and components. The engines are pump fed ~15,000-35,000 lbf with a specific impulse goal of 900 seconds (using hydrogen), and are used individually or in clusters for the spacecraft's primary propulsion system. The NTP can have multiple start-ups (>4) with cumulative run time >100 minutes in a single mission, which can last a few years. The Rover/NERVA program ground tested a variety of engine sizes, for a variety of burn durations and start-ups with the engine exhaust released to the open air. Current regulations require exhaust filtering of any radioactive noble gases and particulates. The NTP primary test requirements can have multiple start-ups (>8) with the longest single burn time ~50 minutes.

Specific technologies of interest to meet the proposed requirements include:

- Reactor fuel element designs with high temperature (> 2600K), high power density (>5 MW/L) to maximize hydrogen propellant heating. New additive manufacturing processes to quickly manufacture the fuel with uniform channel coatings and/or claddings to reduce fission product gas release and particulates into the engine's exhaust stream.
 - Composite or carbide designs with low burn-up coating technology.
 - Ceramic-metallic (cermet) based nuclear fuels need improved methods to apply W coatings on small UO_2 spheres and the best way to bond W- UO_2 wafers with integral claddings.
- Concepts to cool down the reactor decay heat after shutdown to minimize the amount of open cycle propellant used in each engine shutdown. Depending on the engine run time for a single burn, cool down time can take many hours.
- Low risk reactor design features which allow more flexible criticality control during burns beyond the reactor

circumferential rotating control drums, and/or provide nuclear safety for ground processing, launch, and possible launch aborts.

- Control of criticality with water submersion and compaction accidents.
- Concept for quick restart of reactor (2-6 hours) after 30-40 minute burns and accounting for Xe135 buildup.
- Ground test engine effluent processing technologies for efficient containment and/or filtering of radioactive particles and noble gases, and management of high temperature, high flow hydrogen exhausts (16-39 lbs/sec). In particular, to produce large quantities of hot hydrogen, and develop robust materials, advanced instruments and monitoring systems capable of operating in extreme temperature and radiation environments.
 - Advanced materials to resist high-temperature (<4400° F), hydrogen embrittlement and radiation environment.
 - Efficient non-nuclear generation of high temperature (<5000° F), high flow rate hydrogen (<39 lb/sec).
 - Effluent processing technologies for efficient filtering and management of high temperature, high flow hydrogen exhausts. Specific interests include:
 - Filtering of radioactive particles and debris from exhaust stream having an efficiency rating greater than 99.9%.
 - Removal of radioactive halogens, noble gases and vapor phase contaminants from a high flow exhaust stream with an efficiency rating greater than 99.5%
 - Applicable Integrated System Health Monitoring and autonomous test operations control systems that provide diagnostic capability to detect reactor fuel degradation in the engine exhaust.
 - Technologies providing an affordable low power (<20 MW) nuclear furnace to ground test a variety of fuel elements at conditions replicating a full scale NTP engine.

For all above technologies, research should be conducted to demonstrate technical feasibility during Phase I and show a path towards Phase II hardware/software demonstration with delivery of a demonstration unit or software package for NASA testing at the completion of the Phase II contract.

Phase I Deliverables - Feasibility study, including simulations and measurements, proving the proposed approach to develop a given product (TRL 2-3). Verification matrix of measurements to be performed at the end of Phase II, along with specific quantitative pass-fail ranges for each quantity listed.

Phase II Deliverables - Working engineering model of proposed product, along with full report of component and/or breadboard validation measurements, including populated verification matrix from Phase I (TRL 4-5). Opportunities and plans should also be identified and summarized for potential commercialization.

H2.03 High Power Electric Propulsion

Lead Center: GRC

Participating Center(s): JPL, MSFC

The goal of this subtopic is to develop innovative, high-power (>100-kW) electric propulsion systems. High-power solar or nuclear electric propulsion may enable dramatic mass and cost savings for lunar and Mars cargo missions, including Earth escape and near-Earth space maneuvers, at power levels that enable a wide range of exploration missions. Innovations and advancements leading to improvements in the end-to-end performance of high power electric propulsion systems are of interest. Methods are sought to increase overall system efficiency; improve system and/or component life or durability; reduce system and/or component mass, complexity, and development issues; or provide other definable benefits. In general, thruster systems providing total impulse values greater than 10^7 N-sec are desired. Specific impulse values of interest range from a minimum of 1500-sec for Earth-orbit transfers to over 6000-sec for planetary missions.

Advanced high-power concepts that provide quantifiable benefits over state-of-the-art electric propulsion systems are to be developed. Key figures of merit include: thrust density (to decrease thruster footprint), thruster efficiency (>60%), lifetime (>10³ hrs), reliability, and scalability. A practical and affordable method of performing relevant ground testing should be discussed, taking into account the pumping capabilities of state-of-the-art vacuum facilities. The proposed propulsion system should be mindful of the development of an efficient, low specific mass power processing unit, with an emphasis on reducing complexity and cost. Specific technologies of interest include

but are not limited to:

- Nesting/clustering moderately powered thrusters to reach a desired total throughput: This component development can include: an assessment of system performance and plasma plume interactions, a thermal characterization of the system, and an assessment of the system lifetime during multi-thruster operation. The impact of multi-thruster operation on the power processing unit and feed system performance should also be addressed.
- High-current electromagnetic accelerators that directly addresses thruster efficiency and lifetime. This component development can include an investigation of electrode geometries, thermal management designs, and material selection to mitigate electrode erosion, the major lifetime limiter. Innovative, high efficiency power processor architectures/convertors for high-amperage thrusters that can be evolved into space flight hardware and survive thermal and radiation environments are desired.
- Scalable, high-perveance gridded ion engines with thrust densities that significantly exceed the current state-of-the-art ($\sim 3 \text{ N/m}^2$ for the NEXT ion engine). This component development can include the development of novel designs of the discharge chamber and ion optics for maximizing anode current and beam extraction capability, respectively.
- Long-life hollow cathode technologies for use with high-power electrostatic engines. The cathodes should be tested in a relevant environment (e.g., comparable magnetic field environment) and provide sufficient current densities for high-power thruster operation.
- Components for inductively pulsed plasma thrusters, in particular highly accurate flow controllers and fast acting valves; and solid state switches capable of high current (MA), high repetition rate (up to 1-kHz), long life (? 10⁹ pulses) operation. High-voltage converters for pulsed power applications with a high-efficiency, low-complexity architecture that can be evolved into space flight hardware and survive thermal and radiation environments are desired.
- Advanced manufacturing methods for the fabrication of high power thruster components and associated systems; of particular interest is additive manufacturing for complex geometries, which may include: ceramic insulators, ion optics, and magnetic poles. Figures of merit include lower cost, rapid turnaround, and material and structural integrity comparable to or better than components or systems produced using current fabrication methods.

Proposals addressing advanced technology concepts should include a realistic and well-defined roadmap defining critical technology development milestones leading to an eventual flight system. Sub-scale, proof-of-concept experiments are highly desired for the Phase I effort. In addressing technology requirements, proposers should identify candidate thruster systems and potential mission applications that would benefit from the proposed technology.

H2.04 Cryogenic Fluid Management for In-Space Transportation

Lead Center: GRC

Participating Center(s): JSC, MSFC

This subtopic solicits technologies related to cryogenic propellant (such as hydrogen, oxygen, and methane) storage, and transfer to support NASA's exploration goals. This includes a wide range of applications, scales, and environments consistent with future NASA missions. Such missions include but are not limited to the Exploration Upper Stage (EUS), In-situ Resource Utilization in cooperation with Mars Landers, and the evolvable Mars Campaign.

Specifically, listed in order of importance:

- High Power/High Efficiency cryocoolers and cryocooler components (specifically compressors, turbines/expanders, or recuperative heat exchangers) for systems designed to reject $> 150 \text{ W}$ at 90 K with a specific power of less than $15 \text{ W (input power)/W (heat rejection)}$ and specific mass of less than 12 kg/W (of heat rejection) at the design point. The cryocooler components should be suitable for space flight.
- Novel structural solutions that can be partially disconnected post launch which the upper stage has successfully reached orbit. Full scale structural solutions ($5 - 10 \text{ m}$ diameter tanks) should be able to support $> 20 \text{ mT}$ at up to 5 g 's sustained compressive loads and have no structural modes below 50

Hz. Post disconnection, the supports should still be able to support 20 mT, but at 0.2 g's sustained compressive loads. Solutions (which do not have to be full scale at this point) should also attempt to minimize the residual heat load to the propellant tank after disconnection.

- Liquid acquisition devices (or propellant management devices) capable of preventing gas ingestion into engine feedlines in low gravity. The liquid acquisition devices should maintain bubble-free flows of 37 liters per minute while having an expulsion efficiency of 97%.
- Lightweight fluid coupling for low (< 50 psi, Cv > 5) pressure cryogenic liquids with low internal (~ 1 sccm) and external (~ 3 sccm) leakage on both halves. Coupling should be designed either for ease of use by Astronauts (i.e., bulky gloves and minimal force) or easy automation.

Life Support and Habitation Systems Topic H3

Life support and habitation encompasses the process technologies and equipment necessary to provide and maintain a livable environment within the pressurized cabin of crewed spacecraft. Functional areas of interest to this solicitation include environmental monitoring, solid waste management, crew accommodations, and water recovery systems. Technologies must be directed at long duration human missions, in microgravity, including Earth orbit and planetary transit, and planetary surfaces, including Mars. Requirements include operation in microgravity and compatibility with cabin atmospheres of up to 34% oxygen by volume and pressures ranging from 1 atmosphere to as low as 7.6 psi (52.4 kPa). Special emphasis is placed on developing technologies that will fill existing gaps, reduce requirements for consumables and other resources including mass, power, volume and crew time, and which will increase safety and reliability with respect to the state-of-the-art. Non-venting processes may be of interest for technologies that have future applicability to planetary protection. Results of a Phase I contract should demonstrate proof of concept and feasibility of the technical approach. A resulting Phase II contract should lead to development, evaluation and delivery of prototype hardware. Specific technologies of interest to this solicitation are addressed in each subtopic.

NASA is investing in technologies and techniques geared towards advancing the state of the art of spacecraft systems through the utilization of the ISS as a technology test bed. For technologies that could benefit from demonstration on the ISS, proposals should be written to indicate the intent to utilize the ISS. Research should be conducted to demonstrate technical feasibility and prototype hardware development during Phase I and show a path toward Phase II hardware and software demonstration and delivering an engineering development unit for NASA testing at the completion of the Phase II contract that could be turned into a proof-of-concept system which can be demonstrated in flight.

Sub Topics:

H3.01 Environmental Monitoring

Lead Center: JPL

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

Environmental Monitoring is comprised of the following four monitoring disciplines: Air, Water, Microbial and acoustics. ISS has employed a wide variety of analytical instruments to deal with critical items. These functional needs are required to address identified risks to crew health during Exploration-class missions. The current approach onboard ISS, if any, will serve as the logical starting point to meeting the functional needs. However, the following limitations were found common to all the current approaches on-board ISS for any missions beyond low-Earth orbit (LEO): reliance on return sample and ground analysis, require too much crew time, constraints on size, mass, and power, lack of portability, and insufficient calibration life.

Hence a concerted effort is underway to address these gaps, determine the most promising solutions, and mature those solutions to ground and flight technology demonstrations. Technologies that show improvements in miniaturization, reliability, life-time, self-calibration, and reduction of expendables are of interest.

Methods for collection and concentration for microbial surface monitoring

NASA continues to invest in the near- and mid-term development of highly-desirable systems and technologies that provide innovative ways to monitor microbial burden and enable to meet required cleanliness level of the closed habitat. To date, systematic microbial monitoring of ISS is carried out for water and not for environmental surfaces or air. The sample collection and subsequent processing for either culturing or molecular methods require sample concentration. Presently, swabs are used to collect 25 cm² area before processing and often times this outdated

technique is fraught with decreased sensitivity in removing biological materials from the surface. NASA is interested in an integrated sample collection/concentration/extraction system that could feed samples to conventional or molecular microbial monitoring techniques. Furthermore, integration of these steps and a sample delivery to the molecular instruments (such as PCR) as a single module is solicited. Required technology characteristics include a 2 year shelf-life and functionality in microgravity and low pressure environment (~8 psi). The proposed integrated sample collection/concentration/extraction delivery system for molecular microbial monitoring detection should be capable of collecting and concentrating all kinds of microorganisms including “problematic” microbial species on-board ISS (ISS MORD: SSP 50260; (<http://emits.sso.esa.int/emits-doc/ESTEC/AO6216-SoW-RD9.pdf> [2])).

Ethylene analyzer

Ethylene gas is a natural metabolite in plants and acts as a plant hormone. In closed settings, such as plant (food) production chambers, ethylene can build up to deleterious levels for the plants. NASA needs innovative concepts for monitoring ethylene on a real time or near real time basis. Detection limits should ideally be near 25 ppb to insure effective management of plant growth systems, both for fundamental space research and for using plants in bioregenerative life support applications.

Calcium, conductivity and pH monitors for urine and wastewater

A rugged calcium sensor is needed to optimize the percentage of the recovery from brine. The calcium sensor would allow engineers to process a urine batch by knowing precisely the actual calcium concentration, enabling the urine processor to approach the solubility limit of calcium species. The calcium sensor would need to be able to measure calcium at levels of 50-400 mg/L in urine that has been pretreated to a pH of 0.5-3.0. The sensor should be rugged and not require frequent calibration or replacement and should be accurate to within 10%. Rugged conductivity and pH sensors that monitor the conductivity and pH in the brine loop would allow brine to be processed more thoroughly to recover more water. As the brine becomes more concentrated during urine processing, the measurement of conductivity and pH would allow the processor to recover water just to the point of solids precipitation. The conductivity sensor should be able to measure conductivity from 10-250 mS/cm in a urine brine that has a pH of 0.5-5.0. Likewise the pH sensor should be able to measure pH from 0.5-5.0 in a urine brine that has the conductivity of 10-250 mS/cm. The sensor should not require frequent calibration or replacement and be accurate to within 15%.

H3.02 Environmental Control and Life Support for Spacecraft and Habitats

Lead Center: ARC

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

Solutions and innovations are needed for technology that supports the mass- and energy-efficient maintenance of closed air, water, and waste systems in spacecraft habitats that operate on planetary surfaces such as Mars and that operate in the microgravity environment of space. Three specific focus areas have been identified:

New Applications of the Heat Melt Compactor for Contaminant Control and Waste Management

NASA is seeking new uses for the Heat Melt Compactor (HMC) to extend its capabilities as a multipurpose/multiuse platform with a focus on addressing the needs for Mars surface and planetary protection. These may include:

- Membrane bags and/or liner inserts to initially contain unprocessed trash and other wastes within the compactor chamber but that will allow water and gas to pass through during processing. The bags/liners can melt at process temperatures >120° C but upon cooling must encapsulate the solid dry trash and waste for long-term stable storage. The encapsulation of the processed final product should prevent inoculation by external microorganisms.
- Methods and supporting hardware, including consumables such as membrane bags and/or liner inserts, for safe drying, sterilization and compaction of feces, which allow for water to pass through during processing.
- Methods and supporting hardware, including consumables such as membrane bags and/or liner inserts, for safely recovering water from urine and wastewater brines.

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- Design and demonstration of a modular subsystem that uses the existing functional capabilities of the HMC as an autoclave.

New applications of the HMC are not to be limited to the above aforementioned areas, as new and innovative uses for the HMC are welcome. Other considerations are the benefits that can arise from recycling and reutilization of materials from the trash and waste, and the recovery of useful resources such as water and oxygen. The system must work in the Mars gravity environment with micro-gravity operation highly desirable.

A detailed description of the HMC can be found in technical paper number ICES-2014-24, entitled "Generation 2 Heat Melt Compactor Development," authored by Mark Turner, John Fisher and Greg Pace, 44th International Conference on Environmental Systems, 13-17 July 2014, Tucson, Arizona. The paper is available at the following link: (<http://repositories.tdl.org/ttu-ir/handle/2346/59662> [3]). The HMC was primarily designed to compact and sterilize bulk trash and waste into a reduced volume, stable and sterile hard tile that is impregnated and encapsulated with plastics from the trash. The HMC consists of a nine inch wide cubic chamber (729 cu in) which can be heated to 180 C. Gas pressure in the chamber is controllable between 3 and 14 psia. A ram at one end of the chamber can create compression loads on materials within the chamber from 2000 to 4000 lb force. The downstream effluent processing system can collect approximately 200 ml of water per hour and oxidize noxious/toxic gases that evolve from processed materials.

Cleaning Agents and Physicochemical Treatments for Habitat Housekeeping and Laundering Clothes

Crew contact surfaces (hand rails, Velcro, acoustic blankets, racks) and food contact surfaces (utensils, table surfaces) are currently cleaned with pre-moistened wipes that are consumable intensive. A mechanism for the in-situ generation of cleaning/sanitizing solutions is needed that will enable these solutions to be applied to reusable fiber based wipes to remove particulate, food, and body oil soiling of surfaces. Solutions must be effective against a range of microbial organisms; their effectiveness against representative organisms must include, but is not limited to, food based bacteria, iodine resistant bacteria, and fecal coliform bacteria. Specific challenges include direct crew contact with cleaning/sanitizing solutions and direct off-gassing and accumulation of solutions in cabin atmosphere. Technologies that can reliably generate, provide short term storage, and dispense cleaning solutions are desired. Prepackaged cleaning solution wipe technologies are not requested.

There is currently no space based laundry technology. Traditional laundry surfactants combined with water and substantial agitation can return clothing to near original condition. However, used surfactants result in a substantial organic contaminant burden on downstream wastewater processors. Future space laundry or refreshing systems will not be required to fully restore clothing to its original condition but should enable clothing to be reused a number of times. Current clothing materials include cotton, poly blends, wool, modacrylic, elastic bands, metallic zippers, metallic snaps, Velcro®, Nomex®, Gore-Tex®, and will likely expand to include fabrics present in many current athletic garments. Generation of cleaning solutions or gases for refreshing/sanitizing clothing are needed that address particulate/dander, salts, body oils (such as squalene or other representative compound), and bacteria that cause odors (including *Staphylococcus epidermidis* and *Pseudomonas aeruginosa*). Specific challenges include capability to adequately disperse cleansing solutions through a wide range of fibers and materials, minimize mineral and organic load to wastewater processors, and minimal foam generation. Processes are desired that can recover unused cleaning solution or regenerate >70% of consumables. This request is not specifically for the laundry/sanitation device that interacts with the garments. The capabilities of the future laundry device would provide ability to agitate, partially remove liquids, and garment drying. Use of fabric brighteners, fragrances, pearlizers, and other aesthetic compounds are undesirable.

Surface treatments that limit biofilm and scaling within water processing system plumbing lines

NASA is seeking technologies or surface treatments that limit biofilm and scaling within water processing system plumbing lines. Both laboratory and flight systems have shown a strong tendency towards biofilm formation and occlusion in wastewater collection systems, particularly small diameter plumbing (3-13 mm internal diameter). Accumulation and sloughing of biofilm increases pressure drop, reduces flow rate, and can cause blockage or premature component change out within wastewater piping. Prevention technologies are sought that will limit microbial growth in piping and water recovery system components for up five years but short timeframes are also useful. Periodic inactivation or remediation technologies that use introduced compounds should be capable of being generated in-situ or recovered after use to minimize consumables. Specific challenges include high microbial and total organic carbon loads. Technologies should be effective for wastewater typical of the International Space Station (urine and humidity condensate) as well as exploration ersatz body hygiene wastewater

(see “Advanced Life Support Baseline Values and Assumptions Document”, NASA/CR-2004-208941, available at the following link: (<http://ston.jsc.nasa.gov/collections/TRS/techrep/CR-2004-208941.pdf> [4])). Proposed solutions should demonstrate compatibility with ISS type water processors, an ability to protect the wastewater system for a long quiescent period in a clean state, and the ability to withstand intermittent exposure to wastewater followed by additional quiescent periods.

Additional information on NASA needs can be found in draft 2015 NASA Technology Roadmaps including but not limited to sections TA06 6.1.4.1, TA06 6.1.3.3, TA06 6.1.4.6, TA06 6.1.4.8, and TA07 7.5.2.3. These roadmaps are available at the following link: (<http://www.nasa.gov/offices/oct/home/roadmaps/index.html> [5]).

Extra-Vehicular Activity (EVA) Topic H4

Extra-Vehicular Activity (EVA) and crew survival systems technology advancements are required to enable forecasted microgravity and planetary human exploration mission scenarios and to support potential extension of the International Space Station (ISS) mission beyond 2020. Advanced EVA systems include the portable life support system (PLSS) and airlock vehicle to suit umbilical system, as well as the power, avionics and software (PAS) systems. PAS includes communications, controls, and informative displays and the common suit system interfaces. More durable, longer-life, higher-reliability technologies for Lunar and Martian environment service are needed. Technologies suitable for working on and around near earth asteroids (NEAs) are needed. Technologies are needed that enable the range and difficulty of tasks beyond state-of-the-art to encompass those anticipated for exploration. Reductions in commodity and life-limited part consumption rates and the size/mass/power of worn systems are needed. All proposed Phase I research must lead to specific Phase II experimental development that could be integrated into a functional EVA system.

NASA is investing in technologies and techniques geared towards advancing the state of the art of spacecraft systems through the utilization of the ISS as a technology test bed. For technologies that could benefit from demonstration on ISS, proposals should be written to indicate the intent to utilize ISS. Research should be conducted to demonstrate technical feasibility and prototype hardware development during Phase I and show a path toward Phase II hardware and software demonstration and delivering an engineering development unit or software package for NASA testing at the completion of the Phase II contract that could be turned into a proof-of-concept system which can be demonstrated in flight.

Sub Topics:

H4.01 Dust Tolerant, High Pressure Oxygen Quick Disconnect for Advanced Spacesuit and Airlock Applications

Lead Center: JSC

In order to support the Extra Vehicular Activity (EVA) Systems development for more robust operation in LEO as well as enabling operation in the lunar and Martian environments, technology development is required for high pressure oxygen (3750 psia) quick disconnects. The current state of the art space suit ISS EMU Umbilical (IEU) and Service and Cooling Umbilical (SCU) connectors operate at a lower pressure and nearly zero contaminant environment. These next generation of quick disconnects (QDs) will enable the EVA systems to transfer high pressure oxygen between the vehicle and on-board tankage under adverse conditions including vacuum and dust (lunar regolith and Martian soil). The QDs expected operating thermal environment range is -50° F to 150° F. The QDs will limit dust intrusion into the internal flow such that when mated/demated 300 times with the environment per MIL-STD-810G, Method 510.5, Procedure I (Blowing Dust) using lunar soil simulant JSC Lunar-1A or JSC Mars-1A, the internal fluid flow downstream of internal filtration is maintained at Level 100A per JPR 5322.1. After those same mate/demate cycles, the fluid flow range will be 0-12 pph of gaseous oxygen at 2800-3750 psia with an allowable pressure drop of 49 psi. The allowable leakage at 3000 psia is 1 scc/hr oxygen. The QD shall exhibit low mating forces such that it can be mated by crew with gloved hands (wearing a spacesuit with a 4.3 psia or 8.3 psia operating pressure) using simple motions such as push/pull or push-twist/twist-pull. Single handed, gloved operation is preferred. A simple means of indicating positive QD engagement is preferred. The use of accessory tools to aid in QD mate/demate should be avoided if possible. The connector shall be capable of reacting a 125 lbf pull force at the strain relief. There are no specific requirements levied upon the exterior size and complexity of the QDs other to state that they are high criticality items that must be safe, practical, reliable; and a device that an exhausted crew member could operate easily and intuitively. Significant work has been done by NASA to identify a mechanical design for the basic size and operation of the device. Reference material has been attached describing existing and new designs, which NASA expects to heavily influence the general form, fit, and function of the future high pressure quick disconnect.

Research done in Phase I of these efforts should focus on technical feasibility with an emphasis on hardware development that can be further expanded in a future Phase II award cycle. Phase II products must include a demonstration unit suitable for testing by NASA. Prototyping should be tailored to applications to ongoing HEO Mission Directorate missions and possible collaborative use in both the governmental and commercial manned spaceflight disciplines. Minimum deliverables at the end of Phase I are analysis and/or test reports, with priority given to functional hardware prototypes for further evaluation. Technical maturation plans should be submitted with Phase I submittals, as well as any expected commercial applications both internal and external to the manned spaceflight enterprise.

ISS EMU UMBILICAL (IEU)

The ISS EMU Umbilical (Item 498) is an interface between the ISS Umbilical Interface Assembly (UIA) and the Extravehicular Mobility Unit (EMU). It provides electrical power and communication, water fill/drain, and water cooling capability from the International Space Station (ISS) for the EMU. The IEU consists of the following items: three water lines of which two are used for water cooling of the LCVG and one for feedwater charging and condensate draining of the PLSS, one oxygen line, one electrical harness assembly for power and communication, a tether restraint and the TMG. The Common Multiple Connector, Item 410, provides a single interface point for connecting and disconnecting the IEU from the DCM. An Umbilical Connector Manifold (UCM), which is government furnished equipment (GFE), provides a single IEU attachment point to the ISS UIA. The IEU provides recharge capability for the PLSS oxygen tank, water reservoir, and battery. In the event a decontamination EVA is needed, the umbilical is designed to withstand environments external to the Airlock.

The EMU umbilical terminates at each end with a ganged multiple connector that requires only a single operation to connect or disconnect the umbilical.

The outer layer of the IEU is a multi-layer Thermal Micrometeoroid Garment (TMG) to provide thermal insulation and protection from micrometeoroid impacts. The IEU includes a protective pouch that will provides thermal and impact protection for the IEU common multiple connector while disconnected from the EMU.

The Umbilical contains a strain relief strap which, during IV operations, attaches via a GFE tether hook to one of the Lower Torso Assembly (LTA) D-rings at the EMU end and to a separate tether ring on the Crew Lock (CL) wall. For EV operations, the hook is disengaged from the UIA panel ring and is secured to a D-ring near the UIA panel. In the event that an EVA decontamination bake out of the EMU is required, this tethering scenario will serve to ensure that UIA design loads are not exceeded.

While not in service (i.e., when completely disconnected from the UIA and EMU), the umbilical is stowed in the equipment lock. While attached to the UIA, the umbilical is restrained against the CL wall by GFE provided restraint straps.

The useful life (combination of the operational life and shelf life) of the Umbilical is 15 years from the date of PDA. The dry weight of the Umbilical does not exceed 30 lbm. This weight includes all GFE provided hardware (2 tether hooks and the UCM).

Service and Cooling Umbilical (SCU)

The Service and Cooling Umbilical (Item 400) is an 11-ft umbilical consisting of three water hoses, a high-pressure oxygen hose, electrical harness, bacteria filter assembly, and a strain relief tether. The SCU supplies the PLSS with electrical power, communications, oxygen, waste water drainage and water cooling from the Orbiter during pre- and post-EVA operations. It also supplies the EMU with recharge of the oxygen tanks, water tanks, and battery.

The end of the SCU that connects into the airlock panel, otherwise known as the vehicle end of the SCU, consists of the four fluid ECLSS connections in addition to one electrical connector that attaches the SCU to the Orbiter airlock service panel AW82. The connections remain intact between flights and do not require crewmember operation. The vehicle waste water drain and potable water fill lines are connected to the bacteria filter housing located on the airlock wall. On both the drain side and the potable water fill side, a bacteria filter of iodine-impregnated epoxy resin spheres is incorporated, along with a particulate filter made of sintered stainless steel. These filters are used to prevent contamination from passing between the Orbiter ECLSS and the EMU. During normal IVA operations, the Orbiter Waste System is off and there is no ability to dump excess condensate.

Approximately one pound of water is drained from the EMU water tanks after filling to allow room for condensate while IVA.

The common connector on the EMU end of the SCU combines the four fluid connections and one electrical circuit connector into a single unit operated by the crewmember. Disengagement of the connector is accomplished by pulling out on the SCU connector cam T-handle to retract a locking pin and then rotating the cam handle from the "locked" position approximately 180° to a detent, which is the "open" position. This rotation of the SCU connector cam disengages two pins on the mating connector. Engagement of the connector is accomplished by rotating the SCU connector cam T-handle to the "open" position, engaging the two pins on the mating connector with the cam, and then rotating the cam handle from the "open" position approximately 180° to the "locked" position, where a cam locking pin is engaged.

The SCU is stowed on the airlock wall when it is not being used. The common connector (SCU side) is attached to a mating stowage connector on the EMU mount (AAP). The SCU is unstowed and connected to the DCM during EMU donning to provide vehicle consumables for the suited EVA preparation activities in the airlock until life support from the EMU is initiated. Nominally, the SCU is disconnected at an airlock pressure of zero psia during airlock depressurization prior to an EVA and reconnected at an airlock pressure of zero psia during airlock re-pressurization after an EVA. The life support from the SCU is maintained during the suited post-EVA activities until the start of EMU doffing. The SCU is also connected to the EMU to supply Orbiter consumables for recharge of the EMU oxygen, the water tanks, and the battery.

ITAR restricted background on exploration space suit umbilical design requirements and expectations may be found at the following website (in cases where the solicitation requirements disagree with the references, the solicitation takes precedence.):

- Contract NNJ09T40C, Constellation Space Suit Systems ISS Umbilical Assembly, CSSS-T-002 Rev. DRAFT X-2, 7 July 2015. (http://sbir.gsfc.nasa.gov/SBIR/solicitations/2016/CSSS-T-002_LSS_CEL_ISS_Umbilical_Assembly_Specification.pdf [6])
- Contract NNJ09T40C, Constellation Space Suit Systems ISS Umbilical Assembly, Exploration EVA Space Suit Design Status Review, 26 August 2015. (http://sbir.gsfc.nasa.gov/SBIR/solicitations/2016/Umbilical_and_Connector_Section_CSSS_DSR_Day_2_P_M.pptx [7])

H4.02 Trace Contaminant Control for Advanced Spacesuit Applications

Lead Center: JSC

Participating Center(s): MSFC

This subtopic is in search of a trace contaminant control (TCC) technology to remove trace contaminants in an advanced spacesuit atmosphere, specifically considering power, size, and removal capability. The advanced spacesuit portable life support system (PLSS) performs the functions required to keep an astronaut alive during an extravehicular activity (EVA) including maintaining thermal control, providing a pressurized oxygen (O₂) environment, and removing carbon dioxide (CO₂). The PLSS ventilation subsystem performs the transport and provides the conditioned O₂ to the suit for pressurization and astronaut breathing. It circulates O₂ through the ventilation loop using a fan and recycles the ventilation gas, removing CO₂ and providing humidity control. The ventilation subsystem is also responsible for removing trace contaminants from the spacesuit atmosphere. The International Space Station extravehicular mobility unit uses an activated charcoal bed inside the CO₂ removal bed (lithium hydroxide (LiOH) and metal oxide (MetOx) canisters). The charcoal in the MetOx canisters can be regenerated on-orbit. The selection of the rapid cycle amine (RCA) swingbed for CO₂ removal in the baseline advanced spacesuit PLSS has added a risk for removing trace contaminants. The trace contaminants in the PLSS

ventilation subsystem and their predicted concentrations (mg/m³) at the end of an 8-hour EVA without suit leakage include the following: acetaldehyde (0.181), acetone (0.301), ammonia (564), n-Butanol (1.13), carbon monoxide (74.4), ethyl alcohol (9.03), formaldehyde (0.902), furan (0.676), hydrogen (113), methyl alcohol (3.16), methane (1352), and Toulene (1.36). The predictions are based on EVA-specific generation rates.¹ Based on these predictions ammonia and formaldehyde are the two contaminants most likely to exceed Spacecraft Maximum Allowable Concentration levels if no TCC device is in the PLSS ventilation loop. It would be beneficial for the technology to be regenerable such as vacuum swing regeneration. In particular, a vacuum-regenerable TCC device that can be regenerated in real time on the suit using a vacuum swing with 1 to 3 min of exposure would be optimum. Additional items for optimization include: reduction in expendables and incorporation into integrated CO₂ removal/reduction system. The desire is for the TCC system to be an immediate knock-down of inlet contaminants such as aldehydes which react irreversibly with the RCA sorbent. This will decrease the likelihood of losing capacity over the life of the system to these types of reactions.

Research done in Phase I of these efforts should focus on technical feasibility with an emphasis on hardware development that can be further expanded in a future Phase II award cycle. Phase II products must include a demonstration unit suitable for testing by NASA. Prototyping should be tailored to applications to ongoing HEO Mission Directorate missions and possible collaborative use in both the governmental and commercial manned spaceflight disciplines. Minimum deliverables at the end of Phase I are analysis and/or test reports, with priority given to functional hardware prototypes for further evaluation. Technical maturation plans should be submitted with Phase I submittals, as well as any expected commercial applications both internal and external to the manned spaceflight enterprise.

References:

- Paul, H., Jennings, M., and Waguespack, G., "Requirements and Sizing Investigation for Constellation Space Suit Portable Life Support System Trace Contaminant Control", 40th International Conference on Environmental Systems, Barcelona, Spain, July 2010. (http://sbir.gsfc.nasa.gov/SBIR/solicitations/2016/AIAA-2010-6065_TCC_CES_Paper_Paul-Jennings-Waguespack.pdf [8])
- James, J., "Spacecraft Maximum Allowable Concentrations for Airborne Contaminants," JSC-20584, Houston: NASA/Johnson Space Center, November 2008. (http://sbir.gsfc.nasa.gov/SBIR/solicitations/2016/Spacecraft_Maximum_Allowable_Concentrations_SMAC_JSC-20584.pdf [9])

H4.03 EVA Space Suit Power, Avionics, and Software Systems

Lead Center: JSC

Participating Center(s): GRC

Space suit power, avionics and software (PAS) advancements are needed to extend EVA capability on ISS beyond 2020, as well as future human space exploration missions. NASA is presently developing a space suit system called the Advanced Extravehicular Mobility Unit (AEMU). The AEMU PAS system is responsible for power supply and distribution for the overall EVA system, collecting and transferring several types of data to and from other mission assets, providing avionics hardware to perform numerous data display and in-suit processing functions, and furnishing information systems to supply data to enable crew members to perform their tasks with autonomy and efficiency. Current space suits are equipped with radio transmitters/receivers so that spacewalking astronauts can talk with ground controllers and/or other astronauts. The astronauts wear headsets with microphones and earphones. The transmitters/receivers are located in the backpacks worn by the astronauts only operate in the UHF band.

While a sufficient amount of radiation hardened electronics are available in areas such as serial processors, digital memory and Field Programmable Gate Arrays, certain ancillary electronic devices present a significant risk for the development of rad-hard spacesuit avionics. NASA is, therefore, seeking flight rated electronic devices needed to complement the existing inventory of flight rated parts so as to enable the creation of an advanced avionics suite for spacesuits. The suit and its corresponding avionics should be capable of being stowed inside a spacecraft

outside the low-Earth orbit (LEO) environment for periods of up to 5 years (TBR). Devices should also be capable of supporting EVA sorties of at least 8 hours and total lifetime operational durations of at least 2300 hours (TBR) for a Mars surface mission. Assumptions may be made for inherent radiation shielding provided by the primary life-support system (PLSS) and possibly the power, avionics, and software (PAS) subsystem enclosure, but proposers are welcome to include shielding technologies at the board and individual part level to reduce the radiation requirements of the actual device. Devices should be immune to single event latch-up (SEL) for particles with Linear Energy Transfer (LET) values of at least 75 Mev-cm²/mg. and maintain full functionality for total ionizing doses of at least 20 Krad (Si). Criticality 1 devices (life support) must be fully mitigated against single event errors (SEE) for all potential mission radiation environments, including solar flares. Lower criticality devices can be less tolerant of SEEs, but must still operate with acceptable error rates in all potential radiation environments. Power consumption should be no more than 2X similar COTS or mil-spec devices. Devices should be vacuum compatible and need to support conduction cooling. Need currently exists for a number of devices, as described below. However this list should not be considered to be exhaustive and proposals will be considered for other devices that are peculiar to a spacesuit avionics suite. Additionally, proposals are invited for simplified, low-cost and low-impact methods to adapt or test commercial or military-spec devices so as to yield a flight-rated part to the above levels. In order of priority, two key innovations are sought this round:

- *Safety Critical Switches and Controls* - Very low profile switches and controls for EVA Criticality 1 systems. Highly reliable and robust devices that provide traditional toggle switch, rotary dial, and linear slider control functionality in a very low profile package which permits higher packaging density compared to traditional solutions for vacuum space operations. Switches and controls must still be sized for easy operation with EVA gloves.
- *Wireless Communication* - Dual-band WLAN-class RF front-end module capable of supporting the SSCS (410 to 420 MHz) and the ISS External Wireless Communications system (5.25-5.35GHz). This module is expected to contain all RF components plus data converters. This module will interface with a baseband processing unit via high-speed digital interface. Consideration for supporting multiple antennas on the EWC band will be given, but this is not required. The front-end must be able to operate in the ISS environment.

Research done in Phase I of these efforts should focus on technical feasibility with an emphasis on hardware development that can be further expanded in a future Phase II award cycle. Phase II products must include a demonstration unit suitable for testing by NASA. Prototyping should be tailored to applications to ongoing HEO Mission Directorate missions and possible collaborative use in both the governmental and commercial manned spaceflight disciplines. Minimum deliverables at the end of Phase I are analysis and/or test reports, with priority given to functional hardware prototypes for further evaluation. Technical maturation plans should be submitted with Phase I submittals, as well as any expected commercial applications both internal and external to the manned spaceflight enterprise.

Lightweight Structures and Materials Topic H5

The SBIR topic area of Lightweight Structures and Materials centers on developing lightweight structures and advanced materials technologies for space exploration vehicles including launch vehicles, crewed vehicles and habitat systems, and in-space transfer vehicles.

Lightweight structures and advance materials have been identified as a critical need since the reduction of structural mass translates directly to additional up and down mass capability that would facilitate additional logistics capacity and increased science return for all missions. The technology drivers for exploration missions are:

- Lower mass.
- Improve efficient packaging of launch volume.
- Improve performance to reduce risk and extend life.
- Improve manufacturing and processing to reduce costs.

Because this topic covers a broad area of interests, subtopics are chosen to enhance and or fill gaps in the exploration technology development programs. These subtopics can include but are not limited to:

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- Manufacturing processes for materials.
 - Material improvements for metals, composites, ceramics, and fabrics.
 - Innovative lightweight structures.
 - Deployable structures.
 - Extreme environment materials and structures.
 - Multifunctional/multipurpose materials and structures.

This year the lightweight spacecraft materials and structures topic is seeking innovative technology for large deployable structures for smallsats, multifunctional materials and structures for integrated structural health monitoring, extreme temperature structures and in-space structural assembly. The specific needs and metrics of each of the focus areas of technology chosen for development are described in the subtopic descriptions.

Research awarded under this topic should be conducted to demonstrate technical feasibility during Phase I and show a path toward a Phase II hardware demonstration, and when possible, deliver a full-scale demonstration unit for functional and environmental testing at the completion of the Phase II contract.

Sub Topics:

H5.01 Large Deployable Structures for Smallsats

Lead Center: LaRC

Participating Center(s): GRC, MSFC

This subtopic seeks deployable structures innovations in two areas for proposed lunar and deep-space missions:

- Large solar sails with at least 85 m² of deployed surface area for 6U cubesats.
- Large solar arrays with at least 200 W of power for 6U-12U cubesats or 600 W for 50-100 kg microsats.

Design solutions must demonstrate high deployment reliability and predictability with minimum mass and launch volume and maximum strength, stiffness, stability, and durability.

Innovations are sought in the following areas for both capabilities (deployable solar sails and deployable solar arrays):

- Novel design, packaging, and deployment concepts.
- Lightweight, compact components including booms, substrates, and mechanisms.
- Validated modeling, analysis, and simulation techniques.
- Ground and in-space test methods.
- Load reduction, damping, and stiffening techniques.
- High-fidelity, functioning laboratory models.

Capability #1: Deployable Solar Sails

Solar sails provide propellant less in-space propulsion using reflected sunlight. Indefinite continuous thrust allows a wide range of advanced maneuvers including non-Keplerian orbits, efficient orbit changes, and extreme ultimate velocities. A near-term application of this technology is NASA's NEA Scout 6U cubesat missions. Larger and more capable solar sail systems are envisioned for future missions.

Square solar sails typically consist of four reflective triangular membranes supported by lightweight deployable booms, as well as mechanical sail actuation to assist attitude control. Specific innovations sought for 6U cubesat solar sails in this solicitation are: improved deployable boom technologies, novel sail designs and packaging concepts, and simpler or more-effective mechanical attitude control systems. Proposed improvements to the booms used on the LightSail mission (metallic Triangular Rollable and Collapsible (TRAC) booms) are of special interest.

Nominal solar sail requirements for 6U cubesats are:

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- Deployed reflective surface area > 85 m² (>100 m² preferred).
 - Stowed membrane volume < 10 cm x 10 cm x 20 cm.
 - Sail membrane stress > 70 kPa.
 - Minimum system deployed natural frequency > 0.1 Hz.
 - Mission life > 3 years in deep space (< 2 AU from the Sun) including lunar vicinity.
 - Deployed sail surface as flat as possible considering all thermal and mechanical loads and residual stresses.

Improvements to the deployable TRAC booms proposed for the NEA Scout solar sail should meet the following additional requirements:

- Deployed boom length: > 8 m (up to 10 m preferred).
- Stowed volume for all booms and deployment mechanisms < 5 cm x 10 cm x 20 cm.
- Boom buckling load > 3N.
- Mass of each boom < 0.25 kg (< 0.15 kg preferred).

Capability #2: Deployable Solar Arrays

Smallsats promise cost-effective solutions for diverse human spaceflight precursor missions using fuel-efficient solar electric propulsion (SEP). SEP thrust increases with electrical power, so larger solar arrays can shorten travel times and allow higher-power science and communications equipment. This subtopic seeks structures innovations for the next generation of smallsat solar arrays with at least 5x larger area than basic body-mounted solar cells or hinged pop-out panels. Scaling up electrical power for smallsats by > 5x will require game changing innovations. In particular, novel flexible-substrate solar array designs are sought that minimize structural mass and packaging volume while maximizing deployment reliability and deployed area, stiffness, strength, and longevity.

Nominal solar array requirements are:

- Beginning-of-life (BOL) power at 1 AU > 200 W for cubesats or > 600 W for microsats.
- Packaging efficiency > 50 kW/m³ BOL.
- Recurring cost < \$500/W.
- Deployment reliability > 0.999.
- Deployed stiffness > 0.5 Hz.
- Deployed strength > 0.05 g (all directions).
- Lifetime > 2 yrs.

Proposals should emphasize structural design innovations, not materials or photovoltaic innovations. Solar array designs that can be rapidly commercialized are of special interest.

For both capabilities, contractors should prove the feasibility of proposed innovations with suitable analyses and tests in Phase I. Significant hardware or software capabilities should be developed and demonstrated in Phase II. A Technology Readiness Level (TRL) at the end of Phase II of 3-4 or higher is desired.

References:

- (http://www.nasa.gov/sites/default/files/files/Small_Spacecraft_Technology_State_of_the_Art_2014.pdf [10]).
- (<http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140012882.pdf> [11]).
- (<http://www.planetary.org/blogs/jason-davis/2014/20140610-lightsail-update-boom.html> [12]).

H5.02 Extreme Temperature Structures

Lead Center: LaRC

Participating Center(s): AFRC, MSFC

This subtopic seeks to develop innovative low cost and lightweight structures for cryogenic and elevated temperature environments. The storage of cryogenic propellants and the high temperature environment during atmospheric entry require advanced materials to provide low mass, affordable, and reliable solutions. The development of durable and affordable material systems is critical to technology advances and to enabling future launch and atmospheric entry vehicles. The subtopic focuses on two main areas: highly damage-tolerant composite materials for use in cryogenic storage applications and high temperature composite materials for hot structures applications. Proposals to each area will be considered separately.

Cryogenic Storage Applications

The focus of this area is to yield material polymeric composite systems and manufacturing processes which enable the capability to store and transfer cryogenic propellants (liquid oxygen and liquid hydrogen) to orbit. Operating temperature ranges for these fluids are -183° C to -253° C. Material systems and processes proposed should be sensitive to eventual scale up and manufacturability of end use hardware. Specific areas of interest include:

- Polymeric composite systems for applications in extreme cold environments such as storage vessels and ductwork for cryogenic fluids. Performance metrics for cryogenic applications include: temperature dependent properties (fracture toughness, strength, coefficient of thermal expansion), resistance to permeability and micro-cracking under cryogenic thermal and biaxial stress state cycling.
- Reliable hatch or access door sealing technique/mechanism for cryogenic polymeric composite structures. Concepts must address seal systems for both composite to composite and composite to metal applications.

Hot Structures

The focus of this area is the development of cost effective, environmentally durable and manufacturable material systems capable of operating at temperatures from 1200° C to 2000° C, while maintaining structural integrity. Significant reductions in vehicle weight can be achieved with the application of hot structures, which do not require structurally parasitic thermal protection systems. The desired material systems are lightweight structural composites that include continuous fibers. This area seeks innovative technologies in one or more of the following:

- Material systems with significant improvements of in-plane and thru the thickness mechanical properties, compared to current high temperature laminated composites, such as stitched or 3D woven fibrous preforms.
- Decreased processing time and increased consistency for high temperature composite materials.
- Improvement in potential reusability for multiple missions.

For all above technologies, research, testing, and analysis should be conducted to demonstrate technical feasibility during Phase I and show a path towards Phase II hardware demonstration. Emphasis should be on the delivery of a manufacturing demonstration unit for NASA testing at the completion of the Phase II contract.

Phase I Deliverables - Test coupons and characterization samples for demonstrating the proposed material product. Matrix of verification/characterization testing to be performed at the end of Phase II.

Phase II Deliverables - Test coupons and manufacturing demonstration unit for proposed material product. A full report of the material development process will be provided along with the results of the conducted verification matrix from Phase I. Opportunities and plans should also be identified and summarized for potential commercialization.

References:

- Anon, "Final Report of the X-33 Liquid Hydrogen Tank Test Investigation Team," National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Huntsville, Alabama 35812, May 2000.
- Glass, D. E. "Ceramic Matrix Composites (CMC) Thermal Protection Systems (TPS) and Hot Structures for Hypersonic Vehicles," 15th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, Dayton, Ohio, AIAA-2008-2682, April 2008.

(<http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080017096.pdf> [13]).

H5.03 Multifunctional Materials and Structures: Integrated Structural Health Monitoring for Long Duration Habitats

Lead Center: LaRC

Participating Center(s): GRC, JSC, MSFC

Multifunctional and lightweight are critical attributes and technology themes required by deep space mission architectures. Multifunctional materials and structural systems will provide reductions in mass and volume for next generation vehicles. The NASA Technology Roadmap TA12, "Materials, Structures, Mechanical Systems, and Manufacturing"

(http://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_12_materials_structures_final.pdf [14]), proposed Multifunctional Structures as one of their top 5 technical challenges, and the NRC review of the roadmap recommended it as the top priority in this area stating: "... To the extent that a structure can simultaneously perform additional functions, mission capability can be increased with decreased mass. Such multifunctional materials and structures will require new design analysis tools and might exhibit new failure modes; these should be understood for use in systems design and space systems operations."

Some functional capabilities beyond structural that are in this multifunctional theme are insulating (thermal, acoustic, etc.), inflatable, protective (radiation and micrometeoroids and orbital debris), sensing, healing, in-situ inspectable (e.g., IVHM), actuating, integral cooling/heating, power generating (thermal-electric, photovoltaic, etc.), and so on.

Because of the broad scope possible in this SBIR subtopic, the intent is to vary its focus each year to address specific areas of multi-functionality:

- That have high payoff for a specific mission.
- That are broadly applicable to many missions.
- That could find broader applications outside of NASA which would allow for partnerships to leverage the development of these technologies.

For FY16, this SBIR subtopic seeks innovative, multifunctional approaches to integrating long-duration health monitoring capabilities within the range of candidate materials currently being investigated for space habitat long-duration mission concepts. These materials include, but are not limited to, thin-ply composites as well as the materials comprising the multiple soft-goods layers utilized in expandable space habitats, including the bladder, restraint and MMOD layers. Soft-goods materials, used in expandable habitats, may be packaged in an unloaded state for long periods of time prior to deployment, and then maintained at pressure for several years during a mission, while also being subjected to varying levels of thermal cycling. This creates a challenging set of conditions from which to predict the mechanical behavior of these structures over their operational life. NASA seeks the integration of robust, long-term sensing capabilities into the flexible materials (e.g., webbing, cordage, and woven fabrics) used in long-duration habitats, to provide health monitoring and evaluation of the structural integrity and properties of the multi-layer habitat structure throughout its mission life. The integration of the sensors would ideally be performed directly during manufacture; however, robust integration, post-fabrication, via non-destructive application, is also of interest. Ideally, the innovative sensing technology and integration approach should maintain the load-carrying capability or some other structural design requirement, and those technologies that enable weight reduction with similar or better structural performance when compared to traditional approaches will be considered. Sensing capabilities can include both the direct measurement of properties (strain, displacement, and load for example) and sensor fusion using multiple sensors to predict and locate critical damage areas and probable failure zones. The goal for long-duration space habitat design is fail-safe operation; providing monitoring and early prediction of failure onset via structural health monitoring and a benign, progressive failure architecture that allows for safe evacuation even at or after the first failure point.

In summary NASA seeks innovations in integrating structural health monitoring into materials for long-duration deep space habitats, including, but not limited to, state-of-the art thin-ply composites and soft-goods materials for expandable habitat structural concepts, during or after fabrication, to enable evaluation of structural properties and failure prediction over the duration of the habitat's operational life.

Contractors should prove the feasibility of proposed innovations using suitable analyses and small scale tests in Phase I. In Phase II, significant testing/fabrication or software capabilities should be developed and demonstrated. A Technology Readiness Level (TRL) at the end of Phase II of 3-4 or higher is desired.

H5.04 In-Space Structural Assembly

Lead Center: LaRC

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

In-space assembly (ISA) of spacecraft systems has been proposed and demonstrated several times as way of assembling systems too large to fit into a single launch vehicle and enabling installation of orbital replacement units. The International Space Station and the repair missions of the Hubble Space Telescope are two good examples.

Efficient structural assembly in space, namely structures with low-mass and high-stiffness and strength, can be achieved by system level design that takes advantage of robotic assembly. For deep-space exploration, the key technology gaps for a robust ISA capability are the joining and unjoining technology (mechanical and electrical), design modularity, and the reuse of components. These technologies will enable a capability that makes future long duration vehicle systems more affordable than the current single-launch, single-use approach to space vehicle design.

The need for on-orbit repair/assembly/servicing are well documented Ref. 1-3. This subtopic seeks in-space assembly and structures manufacturing innovations in two areas of special interest for proposed deep-space space exploration missions:

- Reversible joining technology for structural components and modules.
- In-space and surface systems that recycle spent metallic and composite components to produce additive manufacturing feedstock. Design solutions must minimize mass, power, and complexity while meeting all other mission requirements including contamination control, load bearing strength and stiffness of the assemblage.

Capability #1: Reversible Joining Technology

The ability to join structural and spacecraft components in-space allows for the assembly of vehicles (perhaps aggregated from multiple launches) and for re-use of vehicle subsystems. The joining technology should be reversible for maximum flexibility and utilize simple approaches (electro-mechanical or other) amenable to robotic assembly and disassembly. In addition, the joining technology must provide for mechanical, electrical and optionally thermal load transfer.

This subtopic capability seeks innovative joining technologies and capabilities for in-space assembly, disassembly, and re-use of deep-space exploration vehicle subsystems such as cargo tugs that use solar electric power for propulsion. Joining in-space of structural trusses that support multiple solar arrays for solar electric propulsion is one class of needed joining technology. The assembled truss must provide power connections either integral to the structural joint or as a non-mechanical load bearing harness with connectors. The second class of in-space joining is for modular subsystems nominally three-dimensional shapes (square or rectangular) with power, data, and mechanical load carrying connections. While these modules could represent orbital replacement units (ORUs), the modules could serve to construct an entire space vehicle.

In particular, novel reversible joining systems for robotic operations are needed that minimize mass, energy and complexity while maximizing assembled stiffness, strength and stability.

Nominal joining applications are:

- Class 1: Structural Truss Joints.
 - Strength: > 0.4 g (Mars Extensible) in all degrees of freedom assuming a fixed joint with 1 meter

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- rigid offset of a 100Kg point mass.
 - Power Transmission: > 5 kW.
 - Operating Temperature: -100° C to +100° C.
 - Assembly/Disassembly: > 20 times.
 - Class 2: Module Joints.
 - Strength: > 0.4 g (Mars Extensible) with 0.25 meter cubic module connected on one face with uniform density of 640 Kg/m³.
 - Power Transmission: > 5 kW.
 - Data Transmission: 25 low voltage lines.
 - Temperature: -100° C to +100° C.
 - Assembly/Disassembly: > 20 times.

In Phase I, contractors should prove the feasibility of proposed innovations using suitable analyses and prototype tests. In Phase II, operational joining hardware for assembly and disassembly. Technology Readiness Level (TRL) at the end of Phase II is expected to be 3-4 or higher.

Capability #2: In-situ Surface Manufacturing

Sustainable extraterrestrial presence will require innovative approaches to lightweighting launch masses. The ability to manufacture structures onsite affords an alternative to carrying components of surface systems as part of the launch mass and volume. Additive manufacturing (AM) offers the flexibility to achieve this objective since it enables the conversion of various feedstocks into functional components, especially. Maximum benefits can be realized if the AM method can take advantage of resources available onsite, including both ISRU extracted planetary metals and discarded materials.

State of the art AM techniques can process material classes ranging from metals to plastics and ceramics. Typically, AM equipment use pristine forms of these material feedstocks. This manufacturing capability will permit the construction of various surface systems using feedstock carried as part of the launch and taking advantage of AM in this manner can contribute to the reduction of volume required to carry partly or fully assembled surface systems during launch. However, the impact of AM can be maximized if it is also able to utilize a broader suite of materials, especially those generated from repurposing objects/components required only for launch and transport to the exploration destination, in-space and surface presence. For example, metallic or composite parts from vehicles needed only for transit to the planetary surface, can be recycled to construct pressure vessels for life support and propulsion. The ability to repurpose what would otherwise be discarded materials and/or fabricate with processed extracted planetary materials (such as iron, aluminum, and silicon) takes full advantage of limited resources available to make sustained presence affordable. Further, automated AM offers a means to construct surface systems ahead of the arrival of humans.

Proposals are sought for additive manufacturing concepts that can enable manufacturing from extracted planetary materials and/or the recycling/repurposing of structural components from space vehicles to produce pressure vessels. This does not include the process of ISRU to extract the materials, just the use of the extracted materials in AM. (See H1.01 In-Situ Resource Utilization for processes to extract materials.) Of interest are the following:

Design concepts for AM approaches to accommodate feedstocks that are composites of various material types including but not limited to:

- Processing techniques to recycle and repurpose structural composites having thermoset matrices and carbon fiber reinforcement to yield AM feedstocks.
- Processing techniques to recycle and repurpose structural metallic vehicle components to yield AM feedstocks.
- Approaches to join additively manufactured components from disparate materials.
- Approaches to use minimal power in the manufacture of components.
- Mobile AM methods that operate on power generated from planetary surface resources.

Nominal manufacturing applications are:

- Class 1: Pressure vessels.

- Size: > 0.25 m³.
- Strength: > 14.7 psi.
- Operating Temperature: -100° C to +100° C.
- Class 2: Two-Dimensional Platform for Mobile Carrier.
 - Size: > 3 meter X 2 meter with thickness based on strength.
 - Strength: > 0.4 g (Mars) with 300 Kg mass uniformly distributed.
 - Operating Temperature: -100° C to +100° C.

In Phase I, contractors should prove the feasibility of proposed innovations using suitable analyses and prototype tests. In Phase II, prototype manufacturing systems capable of processing multiple material classes. Technology Readiness Level (TRL) at the end of Phase II is expected to be 3-4 or higher.

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- Troutman, Patrick A.; Krizan, Shawn A; Mazanek, Daniel D.; Stillwagen, Frederic H.; Antol, Jeffrey; Sarver-Verhey Timothy R.; Chato, David J.; Saucillo, Rudolf J.; Blue, Douglas R.; and Carey, David: "Orbital Aggregation and Space Infrastructure Systems (OASIS)", IAC-02-IAA.13.2.06, 53rd International Astronautical Congress, 10-19 Oct. 2002, Houston Texas.

Autonomous and Robotic Systems Topic H6

NASA invests in the development of autonomous systems, advanced avionics, and robotics technology capabilities for the purpose of enabling complex missions and technology demonstrations supporting the Human Exploration and Operations Mission Directorate (HEOMD). The software, avionics, and robotics elements requested within this topic are critical to enhancing human spaceflight system functionality. These elements increase autonomy and system reliability; reduce system vulnerability to extreme radiation and thermal environments; and support human exploration missions with robotic assistants, precursors and caretaker robots. As key and enabling technology areas, autonomous systems, avionics and robotics are applicable to broad areas of technology use, including heavy lift launch vehicle technologies, robotic precursor platforms, utilization of the International Space Station, and spacecraft technology demonstrations performed to enable complex or long duration space missions. All of these flight applications will require unique advances in autonomy, software, robotic technologies and avionics. The exploration of space requires the best of the nation's technical community to provide the technologies, engineering, and systems to enable human exploration beyond LEO, to visit Asteroids and the Moon, and to extend our reach to Mars.

NASA is investing in technologies and techniques geared towards advancing the state of the art of spacecraft systems through the utilization of the ISS as a technology test bed. For technologies that could benefit from demonstration on ISS, proposals should be written to indicate the intent to utilize ISS. Research should be conducted to demonstrate technical feasibility and prototype hardware development during Phase I and show a path toward Phase II hardware and software demonstration and delivering an engineering development unit or software package for NASA testing at the completion of the Phase II contract that could be turned into a proof-of-concept system which can be demonstrated in flight.

Sub Topics:

H6.01 Robotic Systems - Mobility, Manipulation, and Human-System Interaction

Lead Center: JSC

Participating Center(s): ARC, JPL, KSC

The objective of this subtopic is to create autonomous systems and robotic technologies (hardware and software) to improve the human exploration of space. Robots can perform tasks to assist and off-load work from astronauts.

Robots may perform this work before, in support of, or after humans. Ground controllers and astronauts will remotely operate robots using a range of control modes (tele-operation to supervised autonomy), over multiple spatial ranges (shared-space, line-of-sight, on orbit, and interplanetary), and with a range of time-delay and communications bandwidth. Additionally, in order to build robotic systems that are cheaper, lighter, and more energy efficient than traditional devices based only on rigid assemblies, it is important to develop soft robotics technology for mobility and manipulation.

The software, avionics, and robotics elements requested within this topic are critical to increasing autonomy and system reliability; reducing system vulnerability to extreme radiation and thermal environments; and supporting human exploration missions with robotic assistants, precursors and caretaker robots. As key and enabling technology areas, autonomous systems, avionics, and soft robotics technologies are applicable to broad areas of technology use, including heavy lift launch vehicle technologies, robotic precursor platforms, utilization of the International Space Station, and spacecraft technology demonstrations performed to enable complex or long duration space missions. All of these flight applications will require unique advances in autonomy, software, robotic technologies and avionics. The exploration of space requires the best of the nation's technical community to provide the technologies, engineering, and systems to enable human exploration beyond LEO, to visit Asteroids and the Moon, and to extend our reach to Mars.

Proposals are sought to research and develop the following:

- *Mobility* - Subsystems to improve the transport of crew, instruments, and payloads on planetary surfaces, asteroids, and in-space. This includes: hazard detection sensors/perception; active suspension; grappling/anchoring; legged locomotion; robot navigation; infrastructure-free localization and sensors for deformable, flexible or active elastic mobility components.
- *Manipulation* - Subsystems to improve handling and maintenance of payloads and assets. This includes: tactile sensors; human-safe actuation active structures; dexterous grasping; modular "plug and play" mechanisms for deployment and setup; small/lightweight excavation devices; novel manipulation methods; and actuators and/or sensors for active tension control (including tendon-based manipulation and dynamic tensegrity).
- *Human-system interaction* - Subsystems that enable crew and ground controllers to better operate, monitor and supervise robots. This includes: robot user interfaces; automated performance monitoring; tactical planning software; real-time visualization/notification; software for situational awareness and modeling/simulation software for soft robotics (including design of highly compliant and/or underactuated dynamic systems).

H6.02 Requirements Management for Spacecraft Autonomy and Space Mission Automation

Lead Center: ARC

System and software requirements for autonomy have been difficult to define and test due to uncertainties in the environment in which autonomous systems might be deployed, the flexible yet safe interaction with in-situ humans that is needed, and the adaptability needed from an autonomous system for novel situations. Future human spaceflight missions will place crews and other assets at large distances and light-time delays from Earth that will need to act autonomously from mission control over significant time intervals in both nominal and emergency situations. Space missions have small crew sizes, and many mission concepts involve spacecraft and habitats that are only intermittently crewed, so automation through software will be a major portion of autonomous systems.

Proposals are solicited that provide novel methods and tools specifically targeted to defining and testing requirements for autonomy capabilities, including the definition of interactions and roles with in-situ humans. Proposals should encompass a subset of the following: methods and tools for autonomy requirement definition, refinement, verification of internal consistency, validation, and testing during subsequent development.

Proposals should compare their proposed methods and tools to conventional requirements management, and indicate why their methods and tools will result in requirements for autonomy with less ambiguity, fewer conflicts between different requirements, and more testable requirements - as compared to state of the art requirements methods. Proposals should provide metrics for measuring the quality of autonomy requirements resulting from their methods and tools compared to SOA. For example, in the aircraft industry today over half of system development

errors originate during the requirements phase, while over 75% of system development errors are caught very late in development - typically in late phases of testing. This leads to high costs and development schedule overruns due to rework. Proposers should ground their proposed research by demonstrating methods and tools on plausible design reference missions involving autonomy.

Proposals should indicate how their methods and tools will bridge the gap between requirements definition and requirements-based testing, potentially including semi-automatic test generation suitable for the autonomy attributes of flexible response in uncertain environments with uncertain situations.

Proposals can draw upon a wide range of methods, including but not limited to ontology definition, uncertainty quantification, formal approaches to requirements engineering, symbolic methods for test generation from requirements, and techniques for requirements elicitation from stakeholders. Proposals that involve natural language as a medium for autonomy system and software requirements definition should describe how the natural language will be disambiguated in subsequent phases of system development.

H6.03 Spacecraft Autonomy and Space Mission Automation for Consumables

Lead Center: ARC

Participating Center(s): JPL, JSC

Future human spaceflight missions will place crew's at large distances and light-time delays from Earth, requiring novel capabilities for crews and ground to manage spacecraft consumables and renewables such as power, water, propellant and life support systems to prevent Loss of Mission (LOM) or Loss of Crew (LOC). This capability is necessary to reconfigure spacecraft, or replan missions, in response to events such as leaks or failures leading to unexpected expenditure of consumables coupled with lack of communications. If crews in the spacecraft must manage, plan and operate much of the mission themselves, NASA must migrate operations functionality from the flight control room to the vehicle for use by the crew. Migrating flight controller tools and procedures to the crew on-board the spacecraft would, even if technically possible, overburden the crew. Enabling these same monitoring, tracking, and management capabilities on-board the spacecraft for a small crew to use will require significant automation and decision support software. Required capabilities to enable future human spaceflight to distant destinations include:

- Enable on-board crew management of vehicle consumables that are currently flight controller responsibilities.
- Increase the onboard capability to detect and respond to unexpected consumables-management related events and faults without dependence on ground.
- Reduce up-front and recurring software costs to produce flight-critical software.
- Provide more efficient and cost effective ground based operations through automation of consumables management processes, and up-front and recurring mission operations software costs.

Necessary capabilities include:

- Peer-to-peer mission operations planning.
- Mixed initiative planning systems.
- Elicitation of mission planning constraints and preferences.
- Planning system software integration.
- Space Vehicle System Automation.
- Autonomous rendezvous and docking software.
- Integrated discrete and continuous control software.
- Long-duration high-reliability autonomous system.
- Power aware computing.
- Power Systems Autonomous Control.
- Vehicle Systems Automation.
- Crew Situational Awareness of Vehicle Automation.
- Contingency Management.

The emphasis of proposed efforts should focus primarily on software systems, but emphasize hardware and operating systems the proposed software will run on (e.g., processors, sensors), and proposals must demonstrate understanding of the consumables and dependent spacecraft systems that the software is intended to manage.

Proposals may reference existing fault management techniques, but this subtopic does not solicit development of fault management capability; proposers interested in developing these capabilities are referred to the relevant H6 topic area (H6.04). While Verification, Validation and Requirements of autonomous systems is also an important area, this subtopic does not solicit development of these technologies, proposers interested in developing these capabilities are referred to the relevant H6 topic area (H6.02).

Proposals must demonstrate mission operations cost reduction by use of standards, open source software, crew workload reduction, and/or decrease of software integration costs.

Proposals must demonstrate autonomy software cost reduction by use of standards, demonstration of capability especially on long-duration missions, system integration, and/or open source software.

H6.04 Integrating ISHM with Flight Avionics Architectures for Cyber-Physical Space Systems

Lead Center: ARC

This call for SBIR proposals is for technology development of integrated flight control systems for seamless integration of flight avionics with Integrated Systems Health Management (ISHM) systems. Flight avionics, with Integrated Modular Avionics (IMA) have well-defined Caution and Warning (CW) Fault Detection Isolation and Response (FDIR) alerting systems which can in real-time detect, isolate and respond to single failures at a time. For each CW failure, a predefined mapping to a CW response procedure is defined. In this way when real time conditions occur, response can be almost immediate. However this approach suffers when more than one failure is present. Under multiple CW failures more than one CW response procedure is active. Which of the predefined procedures should you execute? A procedure execution deadlock can occur. Currently when procedure deadlock occurs a number of questions need to be addressed by flight/ground:

- At what step in each procedure should you execute first?
- Should procedure steps be removed /added?
- Should procedure steps be interleaved between procedures?
- Should an entirely new procedure be synthesized?

The determination of how to proceed from procedure deadlock under multiple failure scenarios is critically dependent upon the correct multiple failure diagnosis of the situation. ISHM supports this determination due to the fact that ISHM can extend traditional CW FDIR systems to utilize a systems view of the spacecraft which leverages all (or most) of the available sensors and command talk-back information. Whereas traditional CW FDIR logic are often small fragments of logic and code which utilize subsets of the sensors, and in general have no knowledge and/or context of the other FDIR algorithms, a global view allows for a global response but also brings additional challenges of determining that the data from all the sensors is consistent. It is also important to recognize that failure signatures/ propagation/fault masking can be the result of not only hardware but also the interaction of the myriad control loops and procedural behavior that is induced by the flight avionics. Another key aspect is to perform interpretation of fault data in the context of mission operations, and subsequent fault recovery consistent with current mission goals. Additional challenges are also to devise methods to automatically develop the ISHM fault models from system descriptions such as the schematics, procedures, etc.

To date however seamless integration of ISHM systems with flight avionics CW FDIR systems has not matured to the level such that ISHM systems are trusted to support flight avionics systems in multiple failure high stress situations such as CW storms. Prior human-rated approaches have been proposed but not baselined for similar functional situations in both the Space Shuttle domain (Enhanced Caution and Warning (ECW) as part of the Cockpit Avionics Upgrade (CAU) program) as well as the International Space Station domain (ISS 24-hour autonomy mode). The challenge is to extend the lessons learned from these efforts to achieve program insertion. Such efforts will support both crewed as well as robotic missions, both near Earth as well as deep space missions. Support will be enabled under a variety of conditions including where:

- Communication time with Earth is insufficient and/or delayed.
- Communication bandwidth is insufficient.
- The complexity of analysis is beyond human comprehension.
- The reliance on a skeleton crew requires additional computational support.

Seamless integration can be defined through many dimensions. Several dimensions of interest are:

- Allow the operator the ability to select between a palette of ISHM modules.
- Allow the operator the ability to turn on/off the ISHM module.
- Real time support for flight avionics. At least one scenario should be defined which shows the operation of the flight avionics with and without ISHM.

In order to demonstrate a technology solution, proposed work should include as baseline, a representative set of hypothetical CW events, a FDIR procedure response for each CW event, and one or more scenarios where, with multiple CW events across subsystems, the set of applicable FDIR procedures deadlocks. The proposed work should then demonstrate how the procedure deadlock is resolved through the proposed technology solution which integrates ISHM with the flight avionics.

Entry, Descent, and Landing Topic H7

In order to explore other planets or return to Earth, NASA requires various technologies to facilitate entry, descent and landing. This topic, at this time, is supported by two subtopics.

The first subtopic calls for the development, modeling, testing, and monitoring of ablative thermal protection materials, high char yield adhesives and/or systems that will support planetary entry. NASA has been developing new ablative materials, some based on a 3-D woven reinforcement, either dry woven or impregnated, and some based on felt reinforcements. In order to develop heatshield systems from these materials, joining techniques are required. As new materials are developed, improved analytical tools are required to more accurately predict material properties and thermal response in entry conditions. Light weight, low power instrumentation systems for measuring the actual surface heating, in-depth temperatures, surface recession rates during testing and/or flight are required to verify the response of the materials and to monitor the health of flight hardware.

The second subtopic calls for the development of improved diagnostics for ground test facilities providing hypervelocity flows. As we try to understand the effects of hypersonic flow fields on entry vehicles, ground testing is often used to compare test data to predicted values. Improvements in diagnostic measurements in facilities such as NASA's high enthalpy facilities, which include the Electric Arc Shock Tube (EAST), Arc Jets, Ballistic Range, Hypersonic Materials Environmental Test System (HyMETS), and 8' High Temperature Tunnel (HTT) could provide data that will be used to validate and/or calibrate predictive modeling tools which are used to design and margin EDL requirements. This will reduce uncertainty in future mission planning.

Sub Topics:

H7.01 Ablative Thermal Protection Systems Technologies

Lead Center: ARC

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

The technologies described below support the goal of developing advancements in polymers for bonding and/or gap-filling ablative materials, instrumentation systems, and analytical modeling for the higher performance Ablative Thermal Protection Systems (TPS) materials currently in development for future Exploration missions. The ablative TPS materials currently in development include felt or woven material precursors impregnated with polymers and/or additives to improve ablation and insulative performance, along with the block form of Avcoat ablator for MPCV.

Two classes of materials are currently in development for planetary aerocapture and entry. The first class is for a rigid mid L/D (lift to drag ratio) shaped vehicle with requirements to survive a dual heating exposure, with the first at heat fluxes of 400-500 W/cm² (primarily convective) and integrated heat loads of up to 55 kJ/cm², and the second at heat fluxes of 100-200 W/cm² and integrated heat loads of up to 25 kJ/cm². These materials or material systems are likely dual layer in nature, either bonded or integrally manufactured. The second class is for a deployable aerodynamic decelerator, required to survive a single or dual heating exposure, with the first (or single) pulse at

heat fluxes of 50-150 W/cm² (primarily convective) and integrated heat loads of 10 kJ/cm², and the second pulse at heat fluxes of 30-50 W/cm² and heat loads of 5 kJ/cm². These materials are either flexible or deployable.

Also currently in development is a third class of materials, for higher velocity (>11.5 km/s) Earth return, with requirements to survive heat fluxes of 1500-2500 W/cm², with radiation contributing up to 75% of that flux, and integrated heat loads from 75-150 kJ/cm². These materials are currently based upon 3-D woven architectures.

Technologies sought are:

- The development of a high char yield, flexible polymer with high strain-to-failure for used in bonding and/or gap fills for tiles of advanced TPS for extreme entry conditions. While high char yield (comparable to phenolic) and high strain-to-failure (>1%) are key requirements, additional goals would include some or all of the following: high decomposition temperatures (comparable to phenolic or higher); room temperature cure preferred; manufactured in air (inert environment not required); stable at ambient conditions (not overly sensitive to moisture in cured or un-cured state); compatible with cured epoxy, phenolic, and/or cyanate ester, extended out-time; and very low glass transition temperature to retain flexibility in space.
- Development of in-situ sensor systems including pressure sensors, heat flux sensors, surface recession diagnostics, and in-depth or structural interface thermal response measurement devices, for use on rigid and/or flexible ablative materials. Individual sensors can be proposed; however, instrumentation systems that include power, signal conditioning and data collection electronics are of particular interest. In-situ heat flux sensors and surface recession diagnostics tools are needed for flight systems to provide better traceability from the modeling and design tools to actual performance. The resultant data can lead to higher fidelity design tools, improved risk quantification, decreased heat shield mass, and increases in direct payload. The pressure sensors should be accurate to 0.5%, heat flux sensors should be accurate within 20%, surface recession diagnostic sensors should be accurate within 10%, and any temperature sensors should be accurate within 5% of actual values. These should require minimum mass, power, volume, and cost; MEMS-based, wireless, optical, acoustic, ultrasonic, and other minimally-intrusive methods are possible examples. All proposed systems should utilize low-cost, modular electronics that handle both digital and analog sensor inputs and could readily be qualified for the space environments of interest. Typical sensor frequencies are 1-10 Hz, with up to 200 channels of collected data. Consideration should be given to those sensors that will be applicable to multiple material systems.
- Advances are sought in ablation modeling, including radiation, convection, gas surface interactions, pyrolysis, coking, and charring for low and mid-density fiber based (woven or felt) ablative materials. There is a specific need for improved models for low- and mid-density as well as multi-layered charring ablators (with different chemical composition in each layer). The modeling efforts should include consideration of the non-equilibrium states of the pyrolysis gases and the surface thermochemistry, as well as the potential to couple the resulting models to a computational fluid dynamics solver.
- Advances are sought in modeling mechanical properties of 3-D woven materials. Tools that analyze and predict the effects of different fibers on the warp and fill directional properties that could help in fiber selection and weave design are sought.

Starting Technology Readiness Levels (TRL) of 2-3 or higher are sought.

For all above technologies, research should be conducted to demonstrate technical feasibility during Phase I and show a path towards Phase II hardware/software demonstration with delivery of a demonstration unit or software package for NASA testing at the completion of the Phase II contract.

Phase I Deliverables:

- *Advanced Polymer* - Polymer system with demonstration of desired char yields, along with a test plan to be executed in Phase II demonstrating its usability and compatibility with various NASA provided composite materials
- *Sensors* - Sensor system design, including electronics, with specified measurement performance, mass, power, and volume. Proposed test approach for Phase II that will demonstrate system performance in a relevant environment (arcjet or combined structural/thermal test). Plans should consider testing at the largest scale and highest fidelity that the Phase II funding constraints allow.
- *Ablator and Mechanical Modeling* - Software and architecture development plan, along with a validation test

plan, to be executed in Phase II. The Phase I report should provide evidence that the mathematical approaches will improve the state-of-the-art.

Phase II Deliverables:

- *Advanced Polymer* - Aerothermal and structural testing to validate usability and compatibility of the polymer with various NASA provided composite materials
- *Sensors* - Working engineering model of a sensor system with the proposed performance characteristics. Full report of system development, architecture, and measurement performance, including data from completed test proposed in Phase I (TRL 4-5). Potential commercialization opportunities and plans should also be identified and summarized.
- *Ablator and Mechanical Modeling* - Prototype (Beta) software and results from the validation test cases.

H7.02 Diagnostic Tools for High Velocity Testing and Analysis

Lead Center: ARC

The company will develop diagnostics for analyzing ground tests in high enthalpy, high velocity flows used to replicate vehicle entry, descent and landing conditions. Diagnostics developed will be tested in NASA's high enthalpy facilities, which include the Electric Arc Shock Tube (EAST), Arc Jets, Ballistic Range, Hypersonic Materials Environmental Test System (HyMETS), and 8' High Temperature Tunnel (HTT).

Development of improved diagnostics for hypervelocity flows allows us to better understand the composition and thermochemistry of our ground test facilities and are important for building ground-to-flight traceability. Characterizations in facilities may be used to validate and/or calibrate predictive modeling tools which are used to design and margin EDL requirements. This will reduce uncertainty in future mission planning.

Diagnostics of interest include measurement of temperature, velocity, electron number density, and information regarding byproducts of pyrolysis and ablation in CO₂ or air environments. Due to variation in facility operations, the diagnostics are required to obtain reasonable signals in test times down to approximately 4 μs with resolution on sub-μs time scales. Secondary methods of interest would relate to the detection of the shock front edge arrival to high accuracy (< 0.1 μs). Proposals should detail information such as detection limits, expected signal to noise ratios and data acquisition frequency. Data acquisition channels with up to 200 MHz sampling rate are available.

Deliverable will be in the form of a diagnostic hardware system that can be employed by NASA engineers/scientists in the test facility.

High Efficiency Space Power Topic H8

This topic solicits technology for power systems to be used for the human exploration of space. Power system needs consistent with human spaceflight include:

- Fuel cells compatible with methane-fueled landers, and electrolyzers and fuel cells compatible with materials extracted from lunar regolith and/or the Martian soil or atmosphere.
- Advanced battery cell technologies addressing NASA-unique environments and missions.
- Photovoltaic component and system technologies to power electric spacecraft and/or Mars surface systems.
- Thermal energy conversion.

Solid oxide technology is of interest for fuel cells and electrolyzers to enable:

- The operation of fuel cells using hydrocarbon reactants, including methane and fuels generated on-site at the Moon or Mars.
- Electrolysis systems capable of generating oxygen by electrolyzing CO₂ (from the Mars atmosphere, trash processing, life support, or volatiles released from soils), and/or water from either extraterrestrial soils, life

support systems, or the byproduct of Sabatier processes. Both component and system level technologies are of interest.

Breakthrough battery cell technologies that far exceed the specific energy and energy density or temperature performance of state-of-the-art lithium-based cell technologies are sought to achieve NASA-unique energy storage goals for human missions to cis-lunar space and Mars. Applications include extravehicular activities, human-rated landers, and Mars ascent vehicles. The sub-topic solicitation describes the NASA-unique metrics being sought for new energy storage technologies.

Advanced photovoltaic (PV) power generation and enabling power system technologies are sought with improvements in power system performance (conversion efficiency, mass, stowed volume, etc.), mission operation capability, and reliability for PV power systems supporting NASA human exploration missions using solar electric propulsion (SEP) or on the surface of Mars. The sub-topic solicitation describes the specific metrics being sought for new photovoltaic technologies and systems.

Sub Topics:

H8.01 Thermal Energy Conversion

Lead Center: GRC

Participating Center(s): JPL, JSC, MSFC

NASA needs innovative technologies that convert thermal energy into electricity for space power generation on orbiting platforms, extraterrestrial surfaces, and space transportation vehicles. The thermal energy could be supplied by nuclear reactors, radioisotope heat sources, solar concentrators, chemical reactions, or as waste heat from other space systems. The focus of this subtopic is the energy conversion subsystem. Proposals are requested on thermal energy conversion approaches that offer high efficiency, low mass, high reliability, long life, and low cost. Candidate technologies include thermodynamic heat engines such as Stirling, Brayton, and Rankine as well as thermoelectric and thermionic devices. Ancillary components used to deliver heat (e.g., heat transport loops, heat pipes) to the energy conversion and reject waste heat (e.g., heat pipes, radiators) are also of interest.

The primary mission pull is providing electric power for human Mars surface missions that require kilowatts for remote science stations and rovers, or 10s of kilowatts for crew habitats and in-situ resource utilization plants. A secondary mission pull is providing electric power for Mars transportation vehicles that require 10s of kilowatts for crew life support and vehicle subsystems. The Mars missions may be preceded by human precursor missions to near earth objects, cis-lunar space, and the lunar surface during which the Mars technologies could be demonstrated. The anticipated heat source temperature ranges are 800 to 1300 K for nuclear, solar, and chemical sources and less than 400 to 500 K for waste heat. The expected operating lifetime ranges from several years to greater than 10 years.

The proposals should focus on energy conversion subsystems and components with a current technology readiness level of 2 or 3. The Phase I effort should include conceptual design with analytical or experimental proof-of-concept based on the expected operating environment and system interfaces (e.g., heat source, heat rejection).

The Phase II effort should include development of breadboards or prototypes that can be operated at the contractor's facility to demonstrate functionality in a laboratory environment. If the contractor testing is successful, the hardware will be considered for integration into NASA ground tests and flight experiments with representative system interfaces and relevant operating environments. Upon completion of successful integrated system tests at NASA, Phase III projects would be pursued to infuse the technologies into flight projects.

H8.02 Solid Oxide Fuel Cells and Electrolyzers

Lead Center: GRC

Participating Center(s): JPL, JSC

Technologies are sought that improve the durability, efficiency, and reliability of solid oxide systems. Of particular interest are those technologies that address challenges common to both fuel cells fed by oxygen and methane and electrolyzers fed by carbon dioxide and/or water. Hydrocarbon fuels of interest include methane and fuels generated by processing lunar and Mars soils. Primary solid oxide components and systems of interest are:

- Solid oxide fuel cell, stack, materials and system development for operation on propellant grade direct methane in designs scalable to 1 to 3 kW at maturity. Strong preference for high power density configurations.
- Cell and stack development capable of Mars atmosphere electrolysis should consider feasibility at 0.4 to 0.8 kg/hr O₂; scalable to 2 to 3.5 kg/hr O₂ at maturity. CO₂ electrolysis or co-electrolysis designs must have demonstrated capability of withstanding 15 psid in Phase I with pathway to up to 50 psid in Phase II.

Proposed technologies should demonstrate the following characteristics:

- The developed systems are expected to operate as specified after at least 20 thermal cycles during Phase I and greater than 70 thermal cycles for Phase II. The heat up rate must be stated in the proposal.
- The developed systems are expected to operate with less than five percent degradation after at least 500 hours of steady state operation on propellant-grade methane and oxygen. Operation for 2500 hours and less than five percent degradation is expected of a mature system.
- Fuel reforming must be water neutral. Integrated systems that minimize components and complexity are favored.
- Minimal cooling is available for power applications. Some cooling in the final application will be provided by means of conduction through the stack to a radiator exposed to space or other company proposed solution that minimizes resources required.
- Minimal power (heating plus electrolysis) required for CO₂ electrolysis applications.
- Demonstrate electrolysis of the following input gases: 100% CO₂, Mars atmosphere mixture (95.7% CO₂, 2.7% N₂, 1.6% Ar), 100% water vapor, and 0.7 to 1.6:1 CO₂:H₂O mass ratio. A final test using pure CO₂ of 500 hours (or stopping at 40% voltage degradation) is required. Description of technical path to achieve up to 11,000 hrs for human missions is requested.

H8.03 Advanced Photovoltaic Systems

Lead Center: GRC

Participating Center(s): JSC

Advanced photovoltaic (PV) power generation and enabling power system technologies are sought with improvements in power system performance (conversion efficiency, mass, stowed volume, etc.), mission operation capability, and reliability for PV power systems supporting NASA human exploration missions. Power levels may cover ranges of 25-250 kWe to MegaWatt-class systems. Component technologies and array concept designs are sought that can address all or parts of the following: improved efficiency (>30% cell conversion efficiency at Air Mass zero), cost (50% reduction compared to state-of-the-art (SOA) through modularization, automated manufacturing, and reduced material costs), improved reliability, reduced mass (50% reduction compared to SOA designs), reduced stowed volume (designs capable of accommodating 100kW power levels within a single launch), high array bus voltages (> 250 V), and long-lived, reliable operation within the expected space environment (i.e., high radiation environments, both high and low temperature and light intensity extremes, planetary surface dust conditions, electric propulsion plume impingement erosion, and minimal arcing/degradation due to interactions with the space plasma). The technologies being sought should enable or enhance the ability to provide low-cost, low mass, and higher efficiency solar power systems that support high power Solar Electric Propulsion (SEP), high radiation/extreme environments, and Mars surface NASA missions. Areas of particular emphasis include:

- Advanced PV blanket and component technology with designs that support very high power and high voltage (> 250 V) applications.
- Array structures and blankets optimized for Mars surface gravity and maximum wind loading conditions while still preserving the low mass, low stowed volume, high reliability, and possible retraction/redeployment capabilities.
- Array/blanket designs capable of operating in high dust environments.
- PV blanket, component technology, and arrays optimized for extreme environment conditions (high radiation, low/high temperature extremes, exposure to SEP plume environments, etc.).
- PV module/component technologies that emphasize low mass and cost reduction (via materials, fabrication, and reduced testing).
- Improvements to solar cell efficiency consistent with low cost, high volume fabrication techniques that are

applicable to HEOMD missions.

- Automated/modular fabrication methods for PV panels/modules on flexible blankets (includes cell laydown, interconnects, shielding and high voltage operation mitigation techniques).

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

H8.04 Advanced Next Generation Batteries

Lead Center: GRC

Participating Center(s): JPL, JSC

Breakthrough battery cell technologies that far exceed the specific energy and energy density or temperature performance of state-of-the-art lithium-based cell technologies are required to achieve far-term energy storage goals for human and robotic missions to the moon, Near Earth Orbit, Venus, and Mars. NASA is seeking innovative, advanced electrochemical cell and battery technologies that can aggressively address requirements for these future missions. Proposed chemistries and components must meet performance goals while simultaneously delivering a high level of safety. Components and systems that can enable one of the following sets of cell-level performance goals (simultaneously, within the same system) are sought for specific missions:

- Extravehicular Activities. 450 Wh/kg, 1000-1500 Wh/L, >100 full cycles, >5 year calendar life, up to C/5 rate capability, operation at 0 to 40° C, retention of at least 90% of room temperature capacity during operation at 0°C, and tolerant to electrical and mechanical abuse (i.e., abuse does not result in fire or thermal runaway).
- Human Lunar and Mars Landers and Rovers. 300-375 Wh/kg, 1000-1500 Wh/L, up to 2000 full cycles, >10 year calendar life, >C/2 rate capability, operation at -60 to 30°C, and retention of at least 80% of room temperature capacity during operation at -60° C.
- Mars Ascent Vehicle - Quiescent capability. >250-300 Wh/kg, 1000-1500 Wh/L, few cycles, >15 year shelf life after activation and very limited cycling, and C-rate capability. Extremely high reliability and very low irreversible capacity loss required after 15 year quiescent period. Calendar life and reliable operation after quiescent period are paramount.

Offerors may propose to develop a single or multiple components, or a full cell system. Phase I proposals shall include quantitative analysis, scientific evidence, and technical rationale that clearly demonstrates how the proposed component or components will meet or contribute to the cell performance goals by the end of a Phase II effort. If a single component(s) is proposed rather than full cells, the Offeror shall also include in their justification of the proposed technology the performance that other advanced cell components must achieve in order to meet the claimed cell-level goals. Additionally, Phase I proposals shall describe the technical path that will be followed to achieve the claimed goals. Where possible, laboratory scale prototype hardware should be proposed as deliverables to NASA in Phase I.

Phase I Deliverables - Laboratory scale prototype hardware.

Phase II Deliverables - Incremental hardware deliverables and breadboard demonstration.

Space Communications and Navigation Topic H9

Space Communication and Navigation (SCaN) technologies support all NASA space missions with the development of new capabilities and services that make our missions possible. Communication links are the lifelines that provide the command, telemetry, science data transfers, and navigation support to our spacecraft.

Advancement in communication and navigation technology will allow future missions to implement new and more capable science instruments, greatly enhance human missions beyond Earth orbit, and enable entirely new mission concepts. NASA's communication and navigation capability is based on the premise that communications shall enable and not constrain missions. This topic supports development of technologies to fundamentally change the paradigm of communications and navigation. They include greatly increased data rates via optical communications; cognition in Software Defined Radios (SDR); advanced guidance, control, and navigation; and

advanced RF systems. For more details, see: (<http://www.nasa.gov/scan> [15]).

Sub Topics:

H9.01 Long Range Optical Telecommunications

Lead Center: JPL

Participating Center(s): GRC, GSFC

The Long Range Optical Communications subtopic seeks innovative technologies in free-space optical communications for increased data volume returns from space missions in multiple domains [1]:

- >100 gigabit/s cis-lunar (Earth or lunar orbit to ground).
- >10 gigabit/s Earth-sun L1 and L2.
- >1 gigabit/s per A.U.-squared deep space.
- >100 megabit/s planetary lander to orbiter.

Proposals are sought in the following specific areas (TRL3 Phase I to mature to TRL4 to 5 in Phase II):

- *Low-mass large apertures for high-EIRP laser transceivers [2]* - 30 to 100 cm diameter laser communications telescopes massing less than 65 kg/square-meter with wavefront errors less than 1/25th of a wavelength at 1550 nm and a cumulative wavefront error and transmission loss of <3dB in the far field that can survive direct sun-pointing. Operational range of -20° C to +50° C without active thermal control is desired.
- *High-gigabit/s laser transmitter and receiver optical-electronic subsystems* - space qualifiable 1550 nm laser transmitter and receiver optoelectronic modulator, detection, and Forward-Error-Correction assemblies for data rates from 1 gigabits/s to >200 gigabits/s with power efficiencies better than 10W per gigabit/s and mass efficiencies better than 100 g per gigabit/s. Radiation tolerance better than 100 Krad is required. Technologies for efficient waveform modulation, detection, and synchronization and on-board low-gap-to-capacity forward-error-correction decoding are of interest; also of interest are hybrid RF-optical technologies. Integrated photonic circuit solutions are strongly desired. Highly efficient (>20% DC-to-optical, including support electronics) and space qualifiable (including resilience to photo-darkening) multi-watt Erbium Doped Fiber Amplifier with high gain bandwidth (> 30nm, 0.5 dB flatness) concepts will also be considered. Detailed description of approaches to achieve the stated efficiency is a must.
- *Waveform signal processing technologies [3]* - **CCSDS White Book, "High Photon Efficiency Optical Communications -- Coding & Modulation," March 2015,** <http://www.nasa.gov/directorates/heo/scan/engineering/datastandards/index.html> [16] - 100 Mb/s and higher hardware/firmware implementation of the coding and synchronization layer of the proposed Consultative Committee for Space Data Systems (CCSDS) high-photon-efficiency optical signaling waveform, including transmitter and receiver functions. Supported features are to include CCSDS Transfer Frame ingestion and slicing; attached frame sync markers; CRC; serially concatenated convolutional coding with accumulate pulse position modulation (SCPPM), including a constraint length 3 convolutional code of rates 1/3, 1/2, and 2/3, code interleaver, accumulator, and PPM of orders 4, 8, ..., 256; randomizer; 1 s channel interleaver; codeblock sync marker repeat/spreader, and guard slot insertion.
- *Large aperture ground receiver subsystem technologies [4]* - Demonstrate innovative subsystem technologies for >10 m diameter ground receiver capable of operating to within 3 degrees of solar limb with a better than 10 microradian spot size (excluding atmospheric seeing contribution). Desire demonstration of low-cost primary mirror segment fabrication to meet a cost goal of less than \$35K per square meter and low-cost techniques for segment alignment and control, including daytime operations. Also desired are cryogenic optical filters for operation at 40K with noise equivalent bandwidths of a few nm in the 1550 nm spectral region, transmission losses < 0.25 dB, clear aperture >35 mm, and acceptance angle >40 milliradians with out-of-band rejection of >65 dB from 0.4 to 5 microns.
- *Superconducting magnesium diboride (MgB₂) thin films for ground receiver detectors [5]* - 5 to 20 nm thick MgB₂ films with critical temperature T_c > 35 K and critical current density J_c > 5 MA / cm² at 20 K The preferred substrates are SiC, Sapphire or MgO. The substrate size should be at least 4 in². There is also strong interest in MgB₂ films deposited on buffered Si wafers. The MgB₂ films should be passivated with SiO₂ or Au.
- *Cryogenic read-out electronics for large format superconducting nanowire arrays [6]* - 64 to 1024 channel

DC coupled amplifier arrays for mounting onto a 40K cryocooler stage with 50 to 110 Ohm input impedance, <0.5 dB noise figure, DC to >4 GHz bandwidth, >40 dB gain, <1 dB compression with -47 dBm input, < 5 ps additive jitter, and less than 20 mW per channel power dissipation; strongly desired is an integrated per-channel leading-edge detect discriminator with LVDS-compatible output signal levels. Also of great interest is development of an read-out integrated circuit for direct bump-bonding to superconducting nanowire arrays operating in the 1 to 3 K range, with <0.5 dB noise figure, DC to >4 GHz bandwidth, >20 dB gain, <1 dB compression with -47 dBm input, < 5 ps additive jitter, and less than 1 mW per channel power dissipation.

- *Beaconless pointing subsystems for operations beyond 3 A.U.* - Point 20 to 100 cm lasercomm transmitter aperture to an Earth-based receiver with a 1-sigma accuracy of better than 100 nanoradians with an assumed integrated spacecraft micro-vibration angular disturbance of 150 micro-radians (<0.1 Hz to ~500 Hz) without requiring a dedicated laser beacon transmission from Earth; lowest subsystem mass and power is a primary selection factor.
- *Low mass / low power / cold survivable optical transceivers for planetary lander to orbiter links [7]* - Bi-directional optical terminals with data rates from >100 megabit/second at a nominal link range of 1000 km, with an individual terminal mass <5 kg and operational power < 25W, including a pointing system for at least full hemisphere coverage. Terminals shall be capable of operationally surviving >500 cycles of unpowered temperature cycling from -40° C to +40° C and a 100 krad TID. Discussion of acquisition and tracking con-ops and requirements is a must.

Research must convincingly prove technical feasibility (proof-of-concept) during Phase I, ideally with hardware deliverables that can be tested to validate performance claims, with a clear path to demonstrating and delivering functional hardware meeting all objectives and specifications in Phase II.

References:

- [1] - (<http://ssed.gsfc.nasa.gov/IPM/PDF/1010.pdf> [17]).
- [2] - W. Farr, W, et al. "Overview and Design of the DOT Flight Laser Transceiver," IPN Progress Report 42-185, (2011).
- [3] - CCSDS White Book, "High Photon Efficiency Optical Communications -- Coding & Modulation," March 2015.
- [4] - Birnbaum, K., et al., "DOT Ground Laser Receiver: Overview and Major Trades," IPN Progress Report 42-182, (2010).
- [5] - Wolak, M. A. et al., IEEE Trans. Appl. Supercond. 25, 1-5 (2015).
- [6] - Dauler, E., et al., "Review of Superconducting Nanowire Single-Photon Detector System Design Options and Demonstrated Performance." Opt. Eng 53 (2014).
- [7] - Biswas, A., et al., "Future Planetary Optical Access Links", 2011 International Conference on Space Optical Systems and Applications.

H9.02 Advanced Space Communication Systems

Lead Center: GRC

Participating Center(s): GSFC, JPL

NASA's future systems require increased levels of adaptive, cognitive, and autonomous system technologies to improve mission communication capabilities for science and exploration. Goals of this capability are to improve communications efficiency, mitigate impairments (e.g., scintillation, interference), and reduce operations complexity and costs through intelligent and autonomous communications and data handling. These goals are further described in the TA05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems Roadmap, Sections 5.1, 5.2, 5.3 and 5.5.

Over the past 10 years software defined radio platforms and their applications have emerged and demonstrated the applicability of reconfigurable platforms and applications to space missions. This solicitation seeks advancements in cognitive and automation communication systems, networks, waveforms and components. While there are a number of acceptable definitions of cognitive systems/radio, for simplicity, a cognitive system should sense, detect, adapt, and learn from its environment to improve the communications capabilities and situation for the mission. Cognitive systems naturally lead to advanced multi-function RF platforms; platforms that serve more

than one user or function and are reconfigurable, on-demand, either autonomously or by the user for arbitrary applications. NASA can leverage these systems, techniques, hardware, algorithms and waveforms for use in space applications to maximize science data return, enable substantial efficiencies, reduce operations costs, or adapt to unplanned scenarios. While much interest in cognitive radio in other domains focuses on dynamic spectrum access, this subtopic is primarily interested in much broader ways to apply cognition and automation. Areas of interest to develop and/or demonstrate are as follows:

- *System wide intelligence* – While much of the current research often describes negotiations and improvements between two radio nodes, the subtopic seeks solutions to understand system wide aspects and impacts of this new technology. Areas of interest include (but not limited to) -cognitive architectures considering mission spacecraft, relay satellites, other user spacecraft, and ground stations, system wide effects to decisions made by one or more communication/navigation elements, handling unexpected or undesired decisions, self-configuring networks, coordination among multiple spacecraft nodes in a multiple access scheme, cooperation and planning among networked space elements to efficiently and securely move data through the system, and automated link planning and scheduling to optimize data throughput and reduce operations costs. Capabilities may include interference mitigation, maximizing data throughput and efficiency, and intelligent network routing (best route) and disruptive tolerant networking over cognitive links. The focus here is on a cognitive understanding of, and adaptation to, temporally or spatially non-contiguous communications paths.
- *Advanced waveform development in the digital domain. Specifically* - The foundation has been laid through prior NASA investments in the area of generating the infrastructure for software-based algorithms. These investments led to the development and demonstration of the Space Telecommunication Radio System (STRS) architectural standard for software-defined radios. STRS based advanced backend platforms generate (for transmission) or process (from reception) the appropriate waveform at a common Intermediate Frequency (IF) for transmission to, or reception from, an appropriate RF front-end. In addition, the backend processor is reconfigurable, by the user, for a specific application at a given time (radar vs. short range communications link, etc.).
- *Flexible and adaptive hardware systems* - Signal processing platforms, wideband and multi-band adaptive front ends for RF (particularly at S-, X-, and Ka-bands) or optical communications, and other intelligent electronics that advance or enable flexible, cognitive, and intelligent operations. The development and demonstration of advanced RF Front-Ends that cover NASA RF bands of interest; specifically S-Band, X-Band and/or Ka-Band. These RF front-ends may support time-multiplexed waveforms such as radar or (digitized) half-duplex voice transmissions as well as frequency duplexed waveforms such as full-duplex two-way navigation and data communications. Specifically, these front-ends are expected to leverage state-of-the-art RF materials (e.g., GaN, SiC, CMOS, etc.), packaging (e.g., MIC, SMT, etc.), device (e.g., MMIC, MEMS, etc.) and component techniques to minimize mass, volume and energy resource usage while supporting multi-functionality
- *Autonomous Ka-band and/or optical communications antenna pointing* - Future mission spacecraft in low Earth orbit may need to access both shared relay satellites in geosynchronous orbit (GEO) and direct to ground stations via Ka-band (25.5-27.0 GHz) and/or optical (1550 nm) communications for high capacity data return. To maximize the use of this capacity, user spacecraft will need to point autonomously and communicate on a coordinated, non-interfering basis along with other spacecraft using these same space- and ground-based assets. Included here are electronically steered antennas, especially at Ka-Band. Applications include large, high-performance electronically-steered antennas required for a dedicated communications relay spacecraft with multiple simultaneous connections, advanced multifunction antennas to support science missions that utilize a multifunction antenna to both communicate and conduct science, and small, lightweight antennas for communications only that provide moderate gain without the use of mechanical steering. Antennas that are reconfigurable in frequency, polarization, and radiation pattern that reduce the number of antennas needed to meet the communication requirements of NASA missions are desired.

For all technologies, Phase I will emphasize research aspects for technical feasibility, clear and achievable benefits (e.g., 2x-5x increase in throughput, 25-50% reduction in bandwidth, improved quality of service or efficiency, reduction in operations staff or costs) and show a path towards Phase II hardware/software development with delivery of hardware or software product for NASA. Proposals should demonstrate and explain how and where cognitive and automation technologies could be applied to NASA space systems and be discussed in the proposal.

Phase I Deliverables - Feasibility study and concept of operations of the research topic, including simulations and

measurements, proving the proposed approach to develop a given product (TRL 3-4). Early development and delivery of the simulation and prototype software and platform(s) to NASA. Plan for further development and verification of specific capabilities or products to be performed at the end of Phase II.

Phase II Deliverables - Working engineering model of proposed product/platform or software delivery, along with documentation of development, capabilities, and measurements (showing specific improvement metrics). User's guide and other documents and tools as necessary for NASA to recreate, modify, and use the cognitive software capability or hardware component(s). Opportunities and plans should also be identified and summarized for potential commercialization or NASA infusion.

Software applications and platform/infrastructure deliverables for SDR platforms shall be compliant with the NASA standard for software defined radios, the Space Telecommunications Radio System (STRS), NASA-STD-4009 and NASA-HNBK-4009, found at: (<https://standards.nasa.gov/documents/detail/3315910> [18]).

H9.03 Flight Dynamics and Navigation Systems

Lead Center: GSFC

Participating Center(s): GRC, JPL

NASA is investing in the advancement of software algorithm/stools, systems, and devices to enhance and extend its capabilities for providing position, attitude, and velocity estimates of its spacecraft as well as improve navigation, guidance and control functions to these same spacecraft. Efforts must demonstrate significant risk or cost reduction, significant performance benefit, or enabling capability.

Proposals can support mission engineering activities at any stage of development from the concept-phase/pre-formulation through operations and disposal. Applications in low Earth orbit, lunar, and deep space are in scope for this sub-topic. Proposals that could lead to the replacement of the Goddard Trajectory Determination System (GTDS), or leverage state-of-the-art capabilities already developed by NASA such as the General Mission Analysis Tool (<http://sourceforge.net/projects/gmat/> [19]), GPS-Inferred Positioning System and Orbit Analysis Simulation Software, (<http://gipsy.jpl.nasa.gov/orms/goa/> [20]), Optimal Trajectories by Implicit Simulation (<http://otis.grc.nasa.gov/> [21]) are especially encouraged. Proposers who contemplate licensing NASA technologies are highly encouraged to coordinate with the appropriate NASA technology transfer offices prior to submission of their proposals.

In particular, this solicitation is primarily focused on NASA's needs in the following focused areas:

Guidance and Control

- Advanced optimal control methodologies for chemical and electric space flight guidance and control systems.
- Numerical methods and solvers for robust targeting, and non-linear, constrained optimization problems.
- Applications of advanced dynamical theories to space mission design and analysis, in the context of unstable orbital trajectories in the vicinity of small bodies and libration points.
- Advanced guidance and control techniques that support autonomous, on-board applications.

Navigation

- Applications of cutting-edge estimation techniques to spaceflight navigation problems.
- Applications of estimation techniques that have an expanded state vector (beyond position, velocity, and/or attitude components) or that employ data fusion.
- Advanced autonomous navigation techniques including devices and systems that support significant advances in independence from Earth supervision while minimizing spacecraft burden by requiring low power and minimal mass and volume.
- Advanced time and frequency keeping and dissemination

Software

-
- Addition of novel guidance, navigation, and control improvements to existing NASA software that is either freely available via NASA Open Source Agreements, or that is licensed by the proposer.
 - Interface improvements, tool modularization, APIs, workflow improvements, and cross platform interfaces for software that is either freely available via NASA Open Source Agreements, or that is licensed by the proposer that provide significant cost or performance benefits

Phase I research should be conducted to demonstrate technical feasibility, with preliminary software being delivered for NASA testing, as well as show a plan towards Phase II integration. For proposals that include hardware development, delivery of a prototype under the Phase I contract is preferred, but not necessary.

With the exception listed below for heritage software modifications, Phase II new technology development efforts shall deliver components at the TRL 5-6 level with mature algorithms and software components complete and preliminary integration and testing in an operational environment. For efforts that extend or improve existing NASA software tools, the TRL of the deliverable shall be consistent with the TRL of the heritage software. Note, for some existing software systems (see list above) this requires delivery at TRL 8. Final software, test plans, test results, and documentation shall be delivered to NASA.

Ground Processing Topic H10

Ground processing technology development prepares the agency to test, process and launch the next generation of rockets and spacecraft in support of NASA's exploration objectives by developing the necessary ground systems, infrastructure and operational approaches.

This topic seeks innovative concepts and solutions for both addressing long-term ground processing and test complex operational challenges and driving down the cost of government and commercial access to space. Technology infusion and optimization of existing and future operational programs, while concurrently maintaining continued operations, are paramount for cost effectiveness, safety assurance, and supportability.

A key aspect of NASA's approach to long term sustainability and affordability is to make test, processing and launch infrastructure available to commercial and other government entities, thereby distributing the fixed cost burden among multiple users and reducing the cost of access to space for the United States.

Unlike previous work focusing on a single kind of launch vehicle such as the Saturn V rocket or the Space Shuttle, NASA is preparing common infrastructure to support several different kinds of spacecraft and rockets that are in development. Products and systems devised at a NASA center could be used at other launch sites on earth and eventually on other planets or moons.

Sub Topics:

H10.01 Improved Test and Launch Operations via Interface Design

Lead Center: KSC

Participating Center(s): SSC

This subtopic seeks to improve ground and surface processing in both the operational and test environments through improved interface design concepts. A substantial portion of pre-launch processing involves the integration of spacecraft assemblies to each other or to the ground/surface systems that supply the commodities, power or data. Each assembly requires an interface that connects it to the adjacent hardware which includes flight critical seals or connectors and other components. The impact of these interface-driven tasks are of particular concern for surface systems where the additional work must be accomplished by crew performing Extra-Vehicular Activities (EVAs) or by purpose-built robotic systems.

The interfaces between payloads, boosters and ground/surface support equipment have historically been drivers of numerous delays and unplanned work prior to launch. The developmental impact of interface design and requirements development includes extensive design labor and validation for any new integrated launch system. Finally, the historical trend of having unique interface types for different launch systems has hampered recent efforts to establish a multi-user capability for existing launch infrastructure.

Development and adoption of improved, standardized interfaces holds the potential of reducing the cost and

complexity of future space systems and their related design and implementation, which can increase the funding available for flight hardware and drive down the cost of government and commercial access to space.

Standardization of interfaces used during testing or launch processing also provides eventual benefits to autonomous servicing, a key space technology for future missions. Future in-space and surface servicing of multiple spacecraft/user types such as satellites becomes more feasible if a common interface approach can be developed and widely adopted.

Technologies sought for interface design are grouped in the following two focus areas:

Physical Interfaces

- Modular architectures of expandable surface systems that minimize the adverse impact of interface connections.
 - Interfaces suitable for modular, reliable, cryogenic propellant liquefaction architectures that enable incremental system approaches for increasing capacities as needed.
 - Dust-tolerant interface approaches that drive highly reliable and/or autonomous connections.
- Development of earth based analog test hardware to test and validate these surface system interface concepts (module equipment interfaces and/or surface to vehicle interfaces).
 - Connector technologies including ports, disconnects or couplers that enable standardization across the industry for the transfer of cryogenic and storable propellants or other servicing fluids, power, and/or data for Governmental and Commercial launch providers and/or future surface system analog testing.
 - Interface concepts that simplify or standardize future Interface Requirements Documents (IRDs) or enable increased use of off-the-shelf hardware for future flight and exploration support systems.
 - Solutions that promote standardization of key payload to launch vehicle and subsystem interface standards to reduce the cost associated with analysis, design, configure, integration, and preparation of space systems for launch and reusability through standard servicing interfaces.
 - Novel concepts for adaptation of common interface architectures from relevant industries and the analysis and development required to adapt them to space and exploration architectures. Adaptation should include providing the relevant certification planning required for acceptance by government and industry.

Software/Data Interfaces

- Concepts for embedded intelligence within interfaces that include software attributes to enhance the usage of interface data for tasks such as self-testing, diagnostics, configuration verification and/or management of the interface.
- Concepts for the use of industry standards and/or open source software to reduce or eliminate the need for dedicated interfaces by more efficiently managing system configurations. Software addressable interfaces conducting fault isolation and recovery, and decrease of software integration costs.
- Interface concepts that simplify or standardize future Interface Requirements Documents (IRDs) or enable increased use of off-the-shelf hardware for future flight and exploration support systems.

For all above technologies, research should be conducted to demonstrate technical feasibility during Phase I and show a path toward Phase II demonstration, and delivering a demonstration package for NASA testing at the completion of the Phase II contract.

Phase I Deliverables - Research to identify and evaluate candidate technology applications, demonstrate the technical feasibility, and show a path towards a demonstration. Concept methodology should include the path for adaptation of the technology, infusion strategies (including risk trades), and business model. Identify improvements over the current state of the art for both operations and systems development and the feasibility of the approach in a multi-customer environment. Bench or lab-level demonstrations are desirable.

Phase II Deliverables - Emphasis should be placed on developing and demonstrating the technology under simulated operational conditions with analog earth-based systems including dynamic events such as commodity loading, disconnect or engine testing. The proposal shall outline a path showing how the technology could be

developed into or applied to mission-worthy systems. The contract should deliver demonstration hardware for functional and environmental testing at the completion of the Phase II contract. The technology concept at the end of Phase II should be at a TRL of 5 or higher.

H10.02 Advanced Propulsion Systems Ground Test Technology

Lead Center: SSC

Participating Center(s): KSC

Rocket propulsion development is enabled by rigorous ground testing in order to mitigate the propulsion system risks that are inherent in spaceflight. This is true for virtually all propulsive devices of a space vehicle including liquid and solid rocket propulsion, chemical and non-chemical propulsion, boost stage and in-space propulsion and so forth. It involves a combination of component-level and engine-level testing to demonstrate the propulsion devices were designed to meet the specified requirements for a specified operational envelope and over robust margins and shown to be sufficiently reliable, prior to its first flight.

This topic area seeks to develop advanced ground test technology components and system level ground test systems that enhance Chemical and Advanced Propulsion technology development and certification. The goal is to advanced propulsion ground test technologies to enhance environment simulation, minimize test program time, cost and risk and meet existing environmental and safety regulations. It is focused on near-term products that augment and enhance proven, state-of-the-art propulsion test facilities.

In particular, technology needs includes producing large quantities of hot hydrogen, and develop robust materials, advanced instruments and monitoring systems capable of operating in extreme temperature and harsh environments.

This subtopic seeks innovative technologies in the following areas:

- Efficient generation of high temperature (>2500°R), high flowrate (<60 lb/sec) hydrogen.
- Devices for measurement of pressure, temperature, strain and radiation in a high temperature and/or harsh environment.
- Development of innovative rocket test facility components (e.g., valves, flowmeters, actuators, tanks, etc.) for ultra-high pressure (>8000 psi), high flow rate (>100 lbm/sec) and cryogenic environments.
- Robust and reliable component designs which are oxygen compatible and can operate efficiency in high vibro-acoustic, environments.
- Advanced materials to resist high-temperature (<4400° F), hydrogen embrittlement and harsh environments.

- Tools using computational methods to accurately model and predict system performance are required that integrate simple interfaces with detailed design and/or analysis software. SSC is interested in improving capabilities and methods to accurately predict and model the transient fluid structure interaction between cryogenic fluids and immersed components to predict the dynamic loads, frequency response of facilities.
- Improved capabilities to predict and model the behavior of components (valves, check valves, chokes, etc.) during the facility design process are needed. This capability is required for modeling components in high pressure (to 12,000 psi), with flow rates up to several thousand lb/sec, in cryogenic environments and must address two-phase flows. Challenges include: accurate, efficient, thermodynamic state models; cavitation models for propellant tanks, valve flows, and run lines; reduction in solution time; improved stability; acoustic interactions; fluid-structure interactions in internal flows.
- Improved capability for monitoring environmental conditions for ground and launch facilities supporting test and launch operations. Instrumentation should provide a remote sensing capability to measure atmospheric data with respect to altitude from 300 meters to at least 10 km. The technology must have a vertical measurement resolution of 150 m or smaller and a full vertical profile multiple times an hour in both cloudy and clear environments.
- Improved capability for cryogenic leak and fire detection to support ground test or launch operations.
- Non-instrusive instrumentation for measuring rocket engine plume velocities including a volumetric assessment of plume extent, volume and turbulence.

For all above technologies, research should be conducted to demonstrate technical feasibility during Phase I and show a path towards Phase II hardware/software demonstration with delivery of a demonstration unit or software package for NASA testing at the completion of the Phase II contract.

Radiation Protection Topic H11

The SBIR Topic area of Radiation Protection focuses on the development of computational tools that enable the evaluation of the transport of space radiation through highly complex vehicle architectures as represented in detailed computer-aided design (CAD) models. All space radiation environments in which humans may travel in the foreseeable future are considered, including geosynchronous orbit (GEO), Moon, Mars, and the Asteroids. Advances are needed in mitigation schema for the next generation of exploration vehicles and structures technologies to protect humans from the hazards of space radiation during NASA missions. As NASA continues to form plans for long duration exploration, it has become clear that the ability to mitigate the risks posed to crews by the space radiation environment is of central importance. Advanced computer codes are needed to model and predict the transport of radiation through materials and subsystems, as well as to predict the effects of radiation on the physiological performance, health, and well-being of humans in space radiation environments.

A number of codes and computational packages currently exist that can be used to assess the transport of the diverse particle and energy spectra of the space environment through shielding materials. However, using these transport codes on geometry represented by complex CAD models requires considerable human intervention. Computational tools that automate vehicle ray tracing for use with the NASA-developed HZETRN space radiation transport code are needed to enable vehicle dose mapping and a larger vehicle optimization capability. Tools that enable the use of Monte-Carlo transport codes with native CAD geometry could also make it possible to perform radiation analyses for space architectures using multiple transport codes. Research under this topic should be conducted to demonstrate technical feasibility during Phase I and show a path forward to Phase II software demonstration. Phase I deliverables are alpha-tested computer codes. Phase II deliverables are beta-tested computer codes.

Sub Topics:

H11.01 Radiation Shielding Technologies - Transport Codes

Lead Center: LaRC

Participating Center(s): MSFC

Advanced radiation shielding technologies are needed to protect humans from the hazards of space radiation during future NASA missions. All space radiation environments in which humans may travel in the foreseeable future are considered, including the Moon, Mars, asteroids, geosynchronous orbit (GEO), and low Earth orbit (LEO). All particulate radiations are considered, particularly galactic cosmic radiation (GCR), solar energetic particles (SEP), and secondary neutrons. For this 2016 solicitation, the special interest is in advanced space radiation transport codes. Mid-TRL (3 to 5) technologies of specific interest include, but are not limited to, the following:

- Computational tools that enable the evaluation of the transport of space radiation through highly complex vehicle architectures as represented in detailed computer-aided design (CAD) models are needed. A number of codes and computational packages currently exist that can be used to assess the transport of the diverse particle and energy spectra of the space environment through shielding materials. However, using these transport codes on geometry represented by complex CAD models requires considerable human intervention. Computational tools that automate vehicle ray tracing for use with the NASA-developed HZETRN space radiation transport code are needed to enable vehicle dose mapping and a larger vehicle optimization capability.
- Tools that enable the use of Monte-Carlo transport codes with native CAD geometry could also make it possible to perform radiation analyses for space architectures using multiple transport codes.
- Phase I deliverables are alpha-tested computer codes.
- Phase II deliverables are beta-tested computer codes.

For additional information, please see the following link:

(http://www.nasa.gov/pdf/500436main_TA06-ID_rev6a_NRC_wTASR.pdf [22]).

Human Research and Health Maintenance Topic H12

NASA's Human Research Program (HRP) investigates and mitigates the highest risks to astronaut health and performance in exploration missions. The goal of the HRP is to provide human health and performance countermeasures, knowledge, technologies, and tools to enable safe, reliable, and productive human space exploration, and to ensure safe and productive human spaceflight. The scope of these goals includes both the successful completion of exploration missions and the preservation of astronaut health over the life of the astronaut. HRP developed an Integrated Research Plan (IRP) to describe the requirements and notional approach to understanding and reducing the human health and performance risks. The IRP describes the Program's research activities that are intended to address the needs of human space exploration and serve HRP customers. The IRP illustrates the program's research plan through the timescale of exploration missions of extended duration. The Human Research Roadmap (<http://humanresearchroadmap.nasa.gov> [23]) is a web-based version of the IRP that allows users to search HRP risks, gaps, and tasks.

The HRP is organized into Program Elements:

- Human Health Countermeasures.
- Behavioral Health and Performance.
- Exploration Medical Capability.
- Space Human Factors and Habitability.
- Space Radiation.
- ISS Medical Projects.

Each HRP Element addresses a subset of the risks, with ISS Medical Projects responsible for the implementation of the research on various space and ground analog platforms. The HRP subtopics in this year's solicitation address risks from the Behavioral Health and Performance, Exploration Medical Capability, and Space Human Factors and Habitability Elements.

NASA is investing in technologies and techniques geared towards advancing the state of the art of spacecraft systems through the utilization of the ISS as a technology test bed. For technologies that could benefit from demonstration on ISS, proposals should be written to indicate the intent to utilize ISS. Research should be conducted to demonstrate technical feasibility and prototype hardware development during Phase I and show a path toward Phase II hardware and software demonstration and delivering an engineering development unit or software package for NASA testing at the completion of the Phase II contract that could be turned into a proof-of-concept system which can be demonstrated in flight.

Sub Topics:

H12.01 Task Analysis Visualization and Data Management Tool

Lead Center: JSC

Participating Center(s): ARC

Task analysis (TA) is a method within the Human-Centered Design process that represents tasks as sequences or concurring steps and actions that are necessary to accomplish goals. It is used to understand and document the sequence of tasks, steps, and the relationship among these in order to indicate how the user or uses performing them. Furthermore, most major NASA programs, such as Orion, call for TA in the verification process. The output of the TA is a Master Task List (MTL) that feeds into design, models, and databases. Designers use the MTL to design systems, subsystems, and components to accommodate crew tasks. Operations personnel use the MTL for operations concepts and crew procedures development. This solicitation invites proposals intending to develop methods and technologies to manage and visualize TA information.

Although recognized as a critical function in design, task analysis is often erroneously overlooked until final design phases when hardware, system, and software designs are too costly to change. It is essential that task analysis be conducted as early in the design process as possible. Task analysis should be conducted iteratively and should be frequently evaluated throughout the design and development process to allow for proper verification of crew task and system design. Furthermore, task analysis should be performed to identify the "critical" tasks, i.e., those tasks that are necessary to successfully accomplish operations and mission objectives. Function allocation is also an important part of task analysis: deciding whether a particular function will be accomplished by the human or the system, or by some combination of humans and systems.

Task analyses for long-duration missions will result in a complex structure of tasks and sub-tasks. Master task lists can contain thousands of tasks that have complex temporal and sequential relations among them that need to be visualized. In order to use the results of a complex task analysis efficiently, there is a need for a robust visualization tool that helps with overviewing, sorting, and interpreting the results. Available commercial tools are not able to deal with the complexity of long-duration mission task analysis data due to the following limitations: cannot easily show simultaneous tasks and tasks performed by multiple operators, difficult to track changes, difficult to search for tasks, few/no summary options, and few/no file export options.

The tool should improve task design and system design by relating tasks and sequences of tasks in an efficient way, making the data more usable and ultimately improving overall design.

Phase I Deliverables - Conceptual prototype of a task analysis data management and visualization tool and final report detailing the conceptual prototype and software development plan including feature and display requirements.

Phase II Deliverables - Completed, usability-tested software tool along with the source code, user's guide, and final report on the development and testing of the tool.

H12.02 Passive Vital Sign Monitoring

Lead Center: ARC

Participating Center(s): JSC

Human exploration missions beyond low earth orbit (LEO) require physiologic monitoring of the crew. These highly mass, volume, and power constrained missions require significant leveraging of resources by all vehicle subsystems. To date, research and development resources involving physiologic monitoring have been allocated to crew worn devices to measure these physiologic parameters. NASA recognizes that there are numerous worn devices that provide monitoring, but all of these devices still require mass, volume, power, and crew time to operate. The exploration vehicle, however, will already provide a variety of technologies that could potentially be used to extrapolate human physiologic data in a more passive and continuous manner that does not require additional mass, volume, power, and crew time to operate. Examples of technology embedded within the vehicle include, but are not limited to, high quality video and audio, wireless networks, radio frequency identification, and other electromagnetic (EM) sources/detectors.

NASA requires new technologies that will exploit vehicle infrastructure to passively and continuously monitor the crew's physiologic parameters. NASA is amenable to improving existing vehicle technologies to extract crew data, but also for incorporating novel and innovative technologies that could be added to the vehicle or the crew. Examples of technology developments can include, but are not limited to, heart and respiration rate detection via HD video, temperature detection via infrared camera, or circadian rhythm phase detection via automated urine analysis. Some of the parameters that would be desirable for monitoring include:

- Heart Rate.
- Oxygen Saturation Level.
- Respiration Rate.
- Blood Pressure (diastolic/systolic).
- Core and/or Skin Temperature.
- Urinary 6-sulfatoxymelatonin.

A list of anticipated medical conditions that would require monitoring can be found on the Exploration Medical Condition list (EMCL), which may be found on NASA's Human Research Wiki:

(<https://humanresearchwiki.jsc.nasa.gov/index.php?title=ExMC> [24]).

Phase I Deliverables - Conceptual prototype of a monitoring device/algorithm and final report detailing the conceptual prototype and hardware/software development plans.

Phase II Deliverables - Completed monitoring device/algorithm, and final report on the development, testing, and

validation of the tool.

H12.03 Novel Imaging Technologies for Space Medicine

Lead Center: GRC

Participating Center(s): JSC

NASA is seeking novel medical imaging techniques in two areas: software-based ultrasound and portable x-ray.

Software-Based Ultrasound

Ultrasound has been, and will continue to be for the foreseeable future, NASA's workhorse modality for internal imaging in space. Ultrasound's smaller footprint, lower power consumption and lower emissions across the electromagnetic spectrum make it particularly well-suited for space medicine. Ultrasound also provides additional medically useful capabilities outside the realm of imaging, such as quantitative ultrasound diagnostic techniques, and therapeutic techniques that utilize the energy in the ultrasound signal itself. NASA's commitment to ultrasound has led to the development of the Flexible Ultrasound System (FUS), which is a software-based, state of the art clinical scanner specially adapted to support the development of novel research in ultrasound. The FUS may be thought of as an "ultrasound development platform". It features software-based beam forming, scanning and receiving on up to 192 channels, dual-probe operation, high power support, and full access to the radio frequency (RF) data. Developers using the FUS may implement their algorithms and techniques in an Application Programming Interface (API) that supports both Matlab and C++.

The ground-based demonstration of the FUS will begin in April of 2016 and will potentially last for several years. NASA requires novel ultrasound-based diagnostic and therapeutic techniques for diagnosing and/or treating conditions on the Exploration Medical Condition List (EMCL), which can be found on NASA's Human Research Wiki at – (<https://humanresearchwiki.jsc.nasa.gov/index.php?title=ExMC> [24]).

NASA is amenable to improving existing uses of ultrasound for both diagnostic and therapeutic purposes, but also for completely novel and innovative uses of ultrasound for diagnosis or treatment of any conditions on the EMCL. These novel techniques, which can include both hardware and software, should be developed with integration onto the FUS in mind, either by direct development on a system loaned to the developer by NASA or by porting the application from another system to the FUS at a later stage in the grant. Current examples of FUS integration include novel probe and algorithm development to quantify bone density and efforts to move/break up renal stones.

Portable X-Ray

Although ultrasound remains NASA's workhorse modality for internal imaging of body parts on spaceflight missions, there are gaps in ultrasound's ability to diagnose certain medical conditions that might arise during spaceflight, particularly to deep space destinations. Ultrasound is not as well suited to diagnosing dental conditions and certain musculoskeletal (MSK) injuries as traditional radiographic (x-ray) techniques. A set of limiting factors have precluded the use of x-ray devices on-orbit. These limitations include the relatively higher volumetric footprint, higher power requirements and higher electromagnetic (EM) emissions (particularly ionizing radiation, both in terms of dosage delivered to the crew and stray emissions) of x-ray devices and other imaging devices.

NASA needs new technology developments to overcome these limitations and ensure the diagnosis of dental and MSK conditions are more compatible with human spaceflight. NASA is amenable to improvements in existing x-ray devices and/or other novel and innovative imaging technologies. Example technology developments include, but are not limited to, those leading to more efficient x-ray sources, more sensitive detector technologies, improving image quality, reducing delivered EM dosage, and expanding the usefulness of handheld portable x-ray devices and other imaging devices to address dental and MSK conditions. A complete list of dental and MSK conditions can be found on the Exploration Medical Condition list (EMCL), which may be found on NASA's Human Research Wiki -

(<https://humanresearchwiki.jsc.nasa.gov/index.php?title=ExMC> [24]).

Proposals should address one of the two aforementioned technology areas.

The expected deliverables for Phase I for the software-based ultrasound are:

- Conceptual prototype of a novel device/algorithm.
- Final report detailing the conceptual prototype and hardware/software development plans.

The expected deliverables for Phase II are:

- Completed FUS device/algorithm.
- Integrated testing on FUS platform.
- Final report on the development, testing, and validation of the tool.

The expected deliverables for Phase I for the portable x-ray are:

- Conceptual prototype of an imaging device.
- Final report detailing the conceptual prototype and hardware/software development plans.

The expected deliverables for Phase II are:

- Completed imaging device.
- Final report on the development and testing of the tool.

Non-Destructive Evaluation (NDE) Topic H13

Future manned space missions will require technologies that enable detection and monitoring of the space flight vehicles during deep space missions. Development of these systems will also benefit the safety of current missions such as the International Space Station and Aerospace as a whole. Technologies sought under this SBIR Topic can be defined as advanced sensors, sensor systems, sensor techniques or software that enhance or expand NASA's Nondestructive Evaluation (NDE) and NDE modeling capabilities beyond the current State of the Art.

Sensors and Sensor systems sought under this topic can include but are not limited to techniques that include the development of quantum, meta- and nano sensor technologies for deployment. Technologies enabling the ability to perform inspections on large complex structures will be encouraged. Technologies should provide reliable assessments of the location and extent of damage. Advanced processing and displays are needed to reduce the complexity of operations for astronaut crews who need to make important assessments quickly. Examples of structural components that will require sensor and sensor systems are multi-wall pressure vessels, batteries, thermal tile, thermal blankets, micrometeoroid shielding, International Space Station (ISS) Radiators or aerospace structural components.

Technologies sought under the modeling SBIR include near real-time large scale nondestructive evaluation (NDE) and structural health monitoring (SHM) simulations and automated data reduction/analysis methods for large data sets. Simulation techniques will seek to expand NASA's use of physics based models to predict inspection coverage for complex aerospace components and structures. Analysis techniques should include optimized automated reduction of NDE/SHM data for enhanced interpretation appropriate for detection/characterization of critical flaws in space flight structures and components. Space flight structures will include light weight structural materials such as composites and thin metals. Future purposes will include application to long duration space vehicles, as well as validation of SHM systems. Techniques sought include advanced material-energy interaction simulation in high-strength lightweight material systems and include energy interaction with realistic damage types in complex 3D component geometries (such as bonded/built-up structures). Primary material systems can include metals but it is highly desirable to target composite structures. NDE/SHM techniques for simulation can include ultrasonic, laser, micro-wave, terahertz, eddy current, infra-red, backscatter X-Ray, X-ray computed tomography and fiber optic.

Sub Topics:

H13.01 NDE Simulation and Analysis

Lead Center: LaRC

Participating Center(s): ARC, JSC

Technologies sought under this SBIR include near real-time large scale nondestructive evaluation (NDE) and structural health monitoring (SHM) simulations and automated data reduction/analysis methods for large data sets. Simulation techniques will seek to expand NASA's use of physics based models to predict inspection coverage for complex aerospace components and structures. Analysis techniques should include optimized automated reduction of NDE/SHM data for enhanced interpretation appropriate for detection/characterization of critical flaws in space flight structures and components. Space flight structures will include light weight structural materials such as composites and thin metals. Future purposes will include application to long duration space vehicles, as well as validation of SHM systems.

Techniques sought include advanced material-energy interaction simulation in high-strength lightweight material systems and include energy interaction with realistic damage types in complex 3D component geometries (such as bonded/built-up structures). Primary material systems can include metals but it is highly desirable to target composite structures. NDE/SHM techniques for simulation can include ultrasonic, Laser, Micro-wave, Terahertz, Infra-red, X-ray, X-ray Computed Tomography, Fiber Optic, backscatter X-Ray and eddy current. It is assumed that all systems will have high resolution high volume data. Modeling efforts should be physics based and account for changes in energy interaction due to material aging and induced damage such as micrometeoroid impact. Examples of damage states of interest include delamination, microcracking, porosity, fiber breakage. Techniques sought for data reduction/interpretation will yield automated and accurate results to improve quantitative data interpretation to reduce large amounts of NDE/SHM data into a meaningful characterization of the structure. Realistic computational methods for validating SHM systems are also desirable. It is advantageous to use co-processor configurations for simulation and data reduction. Co-Processor configurations can include graphics processing units (GPU), system on a chip (SOC), field-programmable gate array (FPGA) and Intel's Many Integrated Core (MIC) Architecture. Combined simulation and data reduction/interpretation techniques should demonstrate ability to guide the development of optimized NDE/SHM techniques, lead to improved inspection coverage predictions, and yield quantitative data interpretation for damage characterization.

Phase I Deliverables - Feasibility study, including demonstration simulations and data interpretation algorithms, proving the proposed approach to develop a given product (TRL 2-4). Plan for Phase II including proposed verification methods.

Phase II Deliverables - Software of proposed product, along with full report of development and test results, including verification methods (TRL 5-6). Opportunities and plans should also be identified and summarized for potential commercialization.

H13.02 NDE Sensors

Lead Center: LaRC

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

Technologies sought under this SBIR program can be defined as advanced sensors, sensor systems, sensor techniques or software that enhance or expand NASA's current sensor capability. It is desirable but not necessary to target structural components of space flight hardware. Examples of space flight hardware will include light weight structural materials including composites and thin metals.

Technologies sought include modular, smart, advanced Nondestructive Evaluation (NDE) sensor systems and associated capture and analysis software. It is advantageous for techniques to include the development on quantum, meta- and nano sensor technologies for deployment. Technologies enabling the ability to perform inspections on large complex structures will be encouraged. Technologies should provide reliable assessments of the location and extent of damage. Methods are desired to perform inspections in areas with difficult access in pressurized habitable compartments and external environments for flight hardware. Many applications require the ability to see through assembled conductive and/or thermal insulating materials without contacting the surface. Techniques that can dynamically and accurately determine position and orientation of the NDE sensor are needed to automatically register NDE results to precise locations on the structure. Advanced processing and displays are needed to reduce the complexity of operations for astronaut crews who need to make important assessments

quickly. NDE inspection sensors are needed for potential use on free-flying inspection platforms. Integration of wireless systems with NDE may be of significant utility. It is strongly encouraged to provide explanation of how proposed techniques and sensors will be applied to a complex structure. Examples of structural components include but are not limited to multi-wall pressure vessels, batteries, tile, thermal blankets, micrometeoroid shielding, International Space Station (ISS) Radiators or aerospace structural components.

Phase I Deliverables - Lab prototype, feasibility study or software package including applicable data or observation of a measureable phenomenon on which the prototype will be built. Inclusion of a proposed approach to develop a given methodology to Technology Readiness Level (TRL) of 2-4. All Phase I's will include minimum of short description for Phase II prototype. It will be highly favorable to include description of how the Phase II prototype or methodology will be applied to structures.

Phase II Deliverables - Working prototype or software of proposed product, along with full report of development and test results. Prototype or software of proposed product should be of Technology Readiness Level (TRL 5-6). Proposal should include plan of how to apply prototype or software on applicable structure or material system. Opportunities and plans should also be identified and summarized for potential commercialization.

International Space Station (ISS) Demonstration & Development of Improved Exploration Technologies and Increased ISS Utilization Topic H14

The Human Exploration and Operations Mission Directorate (HEOMD) provides mission critical space exploration services to both NASA customers and to other partners within the U.S. and throughout the world: operating the International Space Station (ISS); ensuring safe and reliable access to space; maintaining secure and dependable communications between platforms across the solar system; and ensuring the health and safety of astronauts. Additionally, the HEOMD is chartered with the development of the core transportation elements, key systems, and enabling technologies required for beyond-Low Earth Orbit (LEO) human exploration that will provide the foundation for the next half-century of American leadership in space exploration. In this topic area, NASA is seeking technologies that address how to improve and lower costs related to use of flight assets; maximize the utilization of the ISS for in-situ research and as a test bed for development of improved space exploration technologies; and utilize the ISS as a platform for in-space commercial science and technology opportunities.

NASA seeks to accomplish these objectives by achieving following goals:

- Investing in the near- and mid-term development of highly-desirable system and technologies that provide innovative ways to leverage existing ISS facilities for new scientific payloads.
- Increasing investments in Human Operations and research to prepare for long-duration missions in deep space.
- Conducting technology development and demonstrations to reduce cost and prove required capabilities for future human exploration.
- Developing exploration precursor robotic missions to multiple destinations to cost-effectively scout human exploration targets.
- Developing communication and navigation technologies.
- Enabling U.S. commercial spaceflight opportunities.

Through the potential projects spurred by this topic, NASA hopes to incorporate SBIR-developed technologies into current and future systems to contribute to the expansion of humanity across the solar system while providing continued cost effective ISS operations and utilization for its customers, with a high standard of safety, reliability, and affordability.

NASA is investing in technologies and techniques geared towards advancing the state of the art of spacecraft systems through the utilization of the ISS as a technology test bed. For technologies that could benefit from demonstration on ISS, proposals should be written to indicate the intent to utilize ISS. Research should be conducted to demonstrate technical feasibility and prototype hardware development during Phase I and show a path toward Phase II hardware and software demonstration and delivering an engineering development unit or software package for NASA testing at the completion of the Phase II contract that could be turned into a proof-of-concept system which can be demonstrated in flight.

Sub Topics:

H14.01 International Space Station (ISS) Utilization

Lead Center: JSC

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

NASA continues to invest in the near- and mid-term development of highly-desirable systems and technologies that provide innovative ways to leverage existing ISS facilities for new scientific payloads and to provide on orbit analysis to enhance capabilities. Additionally, NASA is supporting commercial science, engineering, and technology to provide low earth orbit commercial opportunities utilizing the ISS. Utilization of the ISS is limited by available up-mass, down-mass, and crew time as well as by the capabilities of the interfaces and hardware already developed and in use. Innovative interfaces between existing hardware and systems, which are common to ground research, could facilitate both increased and faster payload development and subsequent utilization. Technologies that are portable and that can be matured rapidly for flight demonstration on the International Space Station are of particular interest.

Desired capabilities that will continue to enhance improvements to existing ISS research and support hardware, with the potential of reducing crew time needs, and those that promote commercial enterprise ventures include but are not limited to, the below examples:

- Providing additional on-orbit analytical tools. Development of instruments for on-orbit analysis of plants, cells, small mammals and model organisms including *Drosophila*, *C. elegans*, and yeast. Instruments to support studies of bone and muscle loss, multi-generational species studies and cell and plant tissue are desired. Providing flight qualified hardware that is similar to commonly used tools in biological and material science laboratories could allow for an increased capacity of on-orbit analysis thereby reducing the number of samples which must be returned to Earth.
- Instruments that can be used as infrared inspection tools for locating and diagnosing material defects, leaks of fluids and gases, and abnormal heating or electrical circuits. The technology should be suitable for hand-held portable use. Battery powered wireless operation is desirable. Specific issues to be addressed include: pitting from micro-meteoroid impacts, stress fractures, leaking of cooling gases and liquids and detection of abnormal hot spots in power electronics and circuit boards.
- Innovative technologies and flight projects that can enable significant terrestrial applications from microgravity development or in-space manufacturing and lead to private sector and/or government agency product development within a number of discipline areas, including biotechnology, medical applications, material sciences, electronics, and pharmaceuticals. This includes modifications to existing flight instruments as well as the development of novel flight hardware for deployment on the ISS.

For the above, research should be conducted to demonstrate technical feasibility and prototype hardware development during Phase I and show a path toward Phase II hardware and software demonstration and delivering an engineering development unit or software package for NASA testing at the completion of the Phase II contract that could be turned into a proof-of-concept system which can be demonstrated in flight.

Phase I Deliverables - Written report detailing evidence of demonstrated prototype technology in the laboratory or in a relevant environment and stating the future path toward hardware and software demonstration on orbit. Bench or lab-level demonstrations are desirable. The technology concept at the end of Phase I should be at a TRL of 3-6.

Phase II Deliverables - Emphasis should be placed on developing and demonstrating hardware and/or software prototype that can be demonstrated on orbit (TRL 8), or in some cases under simulated flight conditions. The proposal shall outline a path showing how the technology could be developed into space-worthy systems. The contract should deliver an engineering development unit for functional and environmental testing at the completion of the Phase II contract. The technology at the end of Phase II should be at a TRL of 6-7.

In situ Resource Utilization - Production of Feedstock for Manufacturing and Construction Topic H1.01
The overall goal of in-situ Resource Utilization (ISRU) is to transform available resources, both natural and man-made, on extraterrestrial surfaces into usable materials and products that assist in sustaining and growing human exploration capabilities. ISRU involves all the steps associated with identifying, collecting, and converting local resources into products that can reduce mission mass, cost, and/or risk. It is imperative that novel technologies be developed to effectively utilize these resources for mission critical consumables, as well as to produce feedstock for additive manufacturing of replacement parts, construction for habitat, and infrastructure expansion. In the case of

Mars, carbon dioxide and other atmospheric constituents, along with regolith and water/ice can be harvested for basic elements that could be utilized to generate various simple and complex organic and inorganic compounds, composites and products. The subtopic seeks proposals for critical technologies associated with the design, fabrication, and testing of hardware associated with one or more of the areas of interest below:

- *Plastic production for in-space additive manufacturing* - Production of plastic that can be fed into in space manufacturing devices. Define and demonstrate all steps required for conversion of some or all of the following in-situ constituents (H₂, CO, CO₂, O₂, N₂, and CH₄) into a final plastic product. It is expected that intermediate products, such as longer chain hydrocarbons, alcohols, aromatics, etc. will be required to achieve final plastic production. Proposals will need to identify all the steps and intermediate products. Phase I proposals will need to demonstrate critical steps, especially the first step from the list of starting constituents. Each step in Phase I can be performed/demonstrated individually. Phase II proposals will need to demonstrate all steps in an integrated manner. Production rates for plastic production will initially be low at 1 to 5 kg/day. Ability to breakdown and recycle the plastic produced is desired but not required. If additional constituents are required to make in-situ plastic, proposer can include them but will need to identify whether the constituents can be obtained in-situ or needs to be brought from Earth. Information on thermoplastic feedstock glass transition temperature and melting point properties for 3D printer plastic feedstocks that might be useful can be found at: (<http://3dprintingfromscratch.com/common/3d-printer-filament-types-overview/> [1]). Since the loads and environments of the parts made using the feedstock are not known at this time, it is recommended that the properties be commensurate with commercially available feedstocks. Some desired characteristics of the parts made from the feedstock are high temperature resistance, low moisture adsorption, and ability to bond using adhesives. Feedstock produced must be tested in a commercially available additive manufacturing device in Phase II.
- *Metal extraction from extraterrestrial material for additive manufacturing* - Metal extraction from extraterrestrial material including lunar regolith, Mars soil, and ordinary and carbonaceous chondrites asteroidal material. Regeneration of any reactants used in the metal extraction process is required. Metals found in extraterrestrial material such as iron, aluminum, silicon, magnesium, and nickel are desired for future in-situ additive manufacturing. It is not expected that the quality and purity of the extracted metals will be to the same standard obtained from terrestrial processes so proposer needs to consider the possible extraction method and subsequent purity of the feedstock. In Phase I, the proposer is required to demonstrate the feasibility of extracting the desired feedstock. Methods used for extraction can be physical/chemical or biological. In Phase II, these feed stocks should be ready for introduction into a fabrication process by being pre-processed to have appropriate physical properties and forms (e.g., granulated, spooled wire, plate, billet, ingots, etc.). Manufacturing processes should be identified and feasibility demonstrated using the regolith derived feed stocks in partial and/or micro gravity environments. Regolith acquisition and delivery of up to 100 kg/hour can be assumed as an input material stream. Using a waste stream from another ISRU process to produce feedstock for fabrication may be considered such as regolith that has already been processed to extract water or oxygen from minerals.
- *ISRU for additive construction techniques* - Bulk or modified regolith can also be used as a construction material (with or without a binder) to form a material that can be extruded to produce a floor, structural wall, or ceiling, or into bricks or slabs for landing pads, roads, and shielding. These construction material can be used for making structures, shelters, radiation shielding, and thermal shading and for micrometeorite protection. Binders and additives must be less than 10% by mass of the construction material feedstock. Use of binders that can also be produced in-situ are preferred. Use of water is not excluded, but steps to be taken mitigate losses and amounts used and lost must be clarified to compare to non-water based construction materials. In Phase II, demonstration of the feasibility of additive construction using construction material feedstock is required (demonstration in partial or micro gravity environments is desired). For extruded materials a linear printing rates 30 to 100 cm/minute is desired. Bricks and slabs should have ability to be joined or interlocked.

All proposals need to identify the state-of-the-art of applicable technologies and processes. Proposals must address the physical/mineral properties of the regolith/soil used. Proposers must specify whether the process is performed in batches or by continuous processing with appropriate sealing techniques to minimize reactant/product losses identified.

Sub Topics:

LOX/Methane In-Space Propulsion Topic H2.01

NASA is developing high thrust in-space chemical propulsion capabilities to enable human and robotic missions into the proving ground (Mars and beyond). Successful proposals are sought for focused investments on key technologies and design concepts that may transform the path for future exploration of Mars, while providing component and system-level cost and mass savings. In-space propulsion is defined as the development and demonstration of technologies for ascent, orbit transfer, pulsing attitude/reaction control (RCS), and descent engines.

The goal of this subtopic is to examine novel technology options that include the use of additive manufacturing or other low cost processes which save mass and/or cost compared to current state-of-the-art (SOA) technologies and fabrication methods. Technologies of interest for operation with liquid oxygen and methane specifically are sought.

Proposers shall show how their technology works and provide the following:

- Assessment of SOA with the key performance parameters (KPP) of their choosing (such as performance, mass, response time, etc.), including specifics which may be referenced in backup material - provide SOA for each major technology element in the proposal.
- Address the outstanding technology performance being promised and the degree to which the concept is new, different, and important. Particularly how the technology and/or fabrication technique proposed saves cost and/or mass is desired.
- Provide quantitative assertions (e.g., x% improvement of y, z kg of mass savings, xx% in cost savings, etc.) to the advancement over the SOA.

Phase I Deliverables - Research to identify and evaluate candidate technology applications to demonstrate the technical feasibility and show a path towards a demonstration. Bench or lab-level demonstrations are desirable. The technology concept at the end of Phase I should be at a TRL of 4 to 5.

Phase II Deliverables - Emphasis should be placed on developing and demonstrating the technology under simulated mission conditions. The proposal shall outline a path showing how the technology could be developed into mission-worthy systems. The contract should deliver a demonstration unit for functional and environmental testing at the completion of the Phase II contract. The technology concept at the end of Phase II should be at a TRL of 5 to 6.

For reference, current anticipated performance goals for liquid oxygen/liquid methane systems are:

- Reaction control thruster development in the 100-800 lbf thrust class. The reaction control engines would operate cryogenic liquid-liquid for applications requiring integration with main engine propellants; or would operate gas-gas or gas-liquid for small total impulse type applications. RCEs operating on liquid cryogenic propellant(s) should be able to tolerate operation for limited duty cycles with gaseous or saturated propellants of varying quality. Integrated RCS (IRCS) capability desired (common propellant tanks for RCS and main engines).
- Descent pump-fed engine development with 50,000 lbf thrust and a minimum vacuum specific impulse of 360-sec. The propulsion system should be capable of stable throttling to 5:1 (20% power). Space survival time of greater than 3 years.
- Ascent pump-fed engine development with 25,000 lbf thrust and a minimum vacuum specific impulse of 360-sec. The propulsion system should be capable of stable throttling to 5:1 (20% power). Space survival time of greater than 4 years.
- Integrated Propulsion and Feed System technologies, such as for integrated reaction control systems (RCS). This would include thermal conditioning features, self-pressurization/re-pressurization control, and system isolation control.

For reference, some specific propulsion technologies of interest are included below. In all cases – interest in using additive manufacturing or novel fabrication methods to save cost and mass are desired to achieve the specific component objectives identified below:

- Injector concepts with throttle range greater than 4:1 while maintaining stable combustion over the range of

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- operation and inlet conditions and meeting performance goals at full throttle condition.
 - Regenerative cooled combustion chamber technologies which offer improved performance, especially at sub-critical or trans-critical conditions, and provide adequate chamber life. This includes methods for addressing differential boiling within regenerative channels and/or start up transients (gas/gas, to two-phase, to high-quality liquid/liquid) for both fuel and oxidizer circuits.
 - Turbopump technologies specific to liquid methane that are lightweight with a long shelf life that can meet deep-throttle requirements, including small durable high speed turbines, high speed lightweight electric direct current (DC) motor driven pumps, high fatigue life impellers, zero net positive suction head (NPSH) inducers, low leakage seals, and long life in-situ propellant fed bearings.
 - Engine valves with a focus on light-weight (at the system level, considering supporting pneumatics, batteries, etc.), fast-acting, low-leakage throttle valves, which meet the following performance considerations: Maintain consistent mixture ratio (MR) over the throttle range, 50% (minimum) force margin, cold and warm operations, easily chilled in, with leakage in the 10^{-4} to 10^{-6} standard cubic centimeters per second (SCCS) range (gaseous phase oxygen and methane).

Sub Topics:

Nuclear Thermal Propulsion (NTP) Topic H2.02

Solid core NTP has been identified as an advanced propulsion concept which could provide the fastest trip times with fewer SLS launches than other propulsion concepts for human missions to Mars over a variety of mission years. The current NASA Strategic Space Technology Investment Plan states NTP is a high priority technology needed for future human exploration of Mars. NTP had major technical work done between 1955-1973 as part of the Rover and Nuclear Engine for Rocket Vehicle Application (NERVA) programs. A few other NTP programs followed including the Space Nuclear Thermal Propulsion (SNTP) program in the early 1990's. The NTP concept is similar to a liquid chemical propulsion system, except instead of combustion in the thrust chamber, a monopropellant is heated with a fission reactor (heat exchanger) in the thrust chamber. In addition, the engine components and surrounding structures are exposed to a radiation environment formed by the reactor during operation.

This solicitation will examine a range of modern technologies associated with NTP using solid core nuclear fission reactors and technologies needed to ground test the engine system and components. The engines are pump fed ~15,000-35,000 lbf with a specific impulse goal of 900 seconds (using hydrogen), and are used individually or in clusters for the spacecraft's primary propulsion system. The NTP can have multiple start-ups (>4) with cumulative run time >100 minutes in a single mission, which can last a few years. The Rover/NERVA program ground tested a variety of engine sizes, for a variety of burn durations and start-ups with the engine exhaust released to the open air. Current regulations require exhaust filtering of any radioactive noble gases and particulates. The NTP primary test requirements can have multiple start-ups (>8) with the longest single burn time ~50 minutes.

Specific technologies of interest to meet the proposed requirements include:

- Reactor fuel element designs with high temperature (> 2600K), high power density (>5 MW/L) to maximize hydrogen propellant heating. New additive manufacturing processes to quickly manufacture the fuel with uniform channel coatings and/or claddings to reduce fission product gas release and particulates into the engine's exhaust stream.
 - Composite or carbide designs with low burn-up coating technology.
 - Ceramic-metallic (cermet) based nuclear fuels need improved methods to apply W coatings on small UO₂ spheres and the best way to bond W-UO₂ wafers with integral claddings.
- Concepts to cool down the reactor decay heat after shutdown to minimize the amount of open cycle propellant used in each engine shutdown. Depending on the engine run time for a single burn, cool down time can take many hours.
- Low risk reactor design features which allow more flexible criticality control during burns beyond the reactor circumferential rotating control drums, and/or provide nuclear safety for ground processing, launch, and possible launch aborts.
 - Control of criticality with water submersion and compaction accidents.
 - Concept for quick restart of reactor (2-6 hours) after 30-40 minute burns and accounting for Xe135 buildup.
- Ground test engine effluent processing technologies for efficient containment and/or filtering of radioactive particles and noble gases, and management of high temperature, high flow hydrogen exhausts (16-39

lbs/sec). In particular, to produce large quantities of hot hydrogen, and develop robust materials, advanced instruments and monitoring systems capable of operating in extreme temperature and radiation environments.

- Advanced materials to resist high-temperature (<4400° F), hydrogen embrittlement and radiation environment.
- Efficient non-nuclear generation of high temperature (<5000° F), high flow rate hydrogen (<39 lb/sec).
- Effluent processing technologies for efficient filtering and management of high temperature, high flow hydrogen exhausts. Specific interests include:
 - Filtering of radioactive particles and debris from exhaust stream having an efficiency rating greater than 99.9%.
 - Removal of radioactive halogens, noble gases and vapor phase contaminants from a high flow exhaust stream with an efficiency rating greater than 99.5%
- Applicable Integrated System Health Monitoring and autonomous test operations control systems that provide diagnostic capability to detect reactor fuel degradation in the engine exhaust.
- Technologies providing an affordable low power (<20 MW) nuclear furnace to ground test a variety of fuel elements at conditions replicating a full scale NTP engine.

For all above technologies, research should be conducted to demonstrate technical feasibility during Phase I and show a path towards Phase II hardware/software demonstration with delivery of a demonstration unit or software package for NASA testing at the completion of the Phase II contract.

Phase I Deliverables - Feasibility study, including simulations and measurements, proving the proposed approach to develop a given product (TRL 2-3). Verification matrix of measurements to be performed at the end of Phase II, along with specific quantitative pass-fail ranges for each quantity listed.

Phase II Deliverables - Working engineering model of proposed product, along with full report of component and/or breadboard validation measurements, including populated verification matrix from Phase I (TRL 4-5). Opportunities and plans should also be identified and summarized for potential commercialization.

Sub Topics:

High Power Electric Propulsion Topic H2.03

The goal of this subtopic is to develop innovative, high-power (>100-kW) electric propulsion systems. High-power solar or nuclear electric propulsion may enable dramatic mass and cost savings for lunar and Mars cargo missions, including Earth escape and near-Earth space maneuvers, at power levels that enable a wide range of exploration missions. Innovations and advancements leading to improvements in the end-to-end performance of high power electric propulsion systems are of interest. Methods are sought to increase overall system efficiency; improve system and/or component life or durability; reduce system and/or component mass, complexity, and development issues; or provide other definable benefits. In general, thruster systems providing total impulse values greater than 10^7 N-sec are desired. Specific impulse values of interest range from a minimum of 1500-sec for Earth-orbit transfers to over 6000-sec for planetary missions.

Advanced high-power concepts that provide quantifiable benefits over state-of-the-art electric propulsion systems are to be developed. Key figures of merit include: thrust density (to decrease thruster footprint), thruster efficiency (>60%), lifetime (>10³ hrs), reliability, and scalability. A practical and affordable method of performing relevant ground testing should be discussed, taking into account the pumping capabilities of state-of-the-art vacuum facilities. The proposed propulsion system should be mindful of the development of an efficient, low specific mass power processing unit, with an emphasis on reducing complexity and cost. Specific technologies of interest include but are not limited to:

- Nesting/clustering moderately powered thrusters to reach a desired total throughput: This component development can include: an assessment of system performance and plasma plume interactions, a thermal characterization of the system, and an assessment of the system lifetime during multi-thruster operation. The impact of multi-thruster operation on the power processing unit and feed system performance should also be addressed.
- High-current electromagnetic accelerators that directly addresses thruster efficiency and lifetime. This component development can include an investigation of electrode geometries, thermal management designs, and material selection to mitigate electrode erosion, the major lifetime limiter. Innovative, high efficiency power processor architectures/convertors for high-amperage thrusters that can be evolved into

space flight hardware and survive thermal and radiation environments are desired.

- Scalable, high-perveance gridded ion engines with thrust densities that significantly exceed the current state-of-the-art ($\sim 3 \text{ N/m}^2$ for the NEXT ion engine). This component development can include the development of novel designs of the discharge chamber and ion optics for maximizing anode current and beam extraction capability, respectively.
- Long-life hollow cathode technologies for use with high-power electrostatic engines. The cathodes should be tested in a relevant environment (e.g., comparable magnetic field environment) and provide sufficient current densities for high-power thruster operation.
- Components for inductively pulsed plasma thrusters, in particular highly accurate flow controllers and fast acting valves; and solid state switches capable of high current (MA), high repetition rate (up to 1-kHz), long life (? 10⁹ pulses) operation. High-voltage converters for pulsed power applications with a high-efficiency, low-complexity architecture that can be evolved into space flight hardware and survive thermal and radiation environments are desired.
- Advanced manufacturing methods for the fabrication of high power thruster components and associated systems; of particular interest is additive manufacturing for complex geometries, which may include: ceramic insulators, ion optics, and magnetic poles. Figures of merit include lower cost, rapid turnaround, and material and structural integrity comparable to or better than components or systems produced using current fabrication methods.

Proposals addressing advanced technology concepts should include a realistic and well-defined roadmap defining critical technology development milestones leading to an eventual flight system. Sub-scale, proof-of-concept experiments are highly desired for the Phase I effort. In addressing technology requirements, proposers should identify candidate thruster systems and potential mission applications that would benefit from the proposed technology.

Sub Topics:

Cryogenic Fluid Management for In-Space Transportation Topic H2.04

This subtopic solicits technologies related to cryogenic propellant (such as hydrogen, oxygen, and methane) storage, and transfer to support NASA's exploration goals. This includes a wide range of applications, scales, and environments consistent with future NASA missions. Such missions include but are not limited to the Exploration Upper Stage (EUS), In-situ Resource Utilization in cooperation with Mars Landers, and the evolvable Mars Campaign.

Specifically, listed in order of importance:

- High Power/High Efficiency cryocoolers and cryocooler components (specifically compressors, turbines/expanders, or recuperative heat exchangers) for systems designed to reject $>150 \text{ W}$ at 90 K with a specific power of less than $15 \text{ W (input power)/W (heat rejection)}$ and specific mass of less than 12 kg/W (of heat rejection) at the design point. The cryocooler components should be suitable for space flight.
- Novel structural solutions that can be partially disconnected post launch which the upper stage has successfully reached orbit. Full scale structural solutions ($5 - 10 \text{ m}$ diameter tanks) should be able to support $> 20 \text{ mT}$ at up to 5 g's sustained compressive loads and have no structural modes below 50 Hz . Post disconnection, the supports should still be able to support 20 mT , but at 0.2 g's sustained compressive loads. Solutions (which do not have to be full scale at this point) should also attempt to minimize the residual heat load to the propellant tank after disconnection.
- Liquid acquisition devices (or propellant management devices) capable of preventing gas ingestion into engine feedlines in low gravity. The liquid acquisition devices should maintain bubble-free flows of $37 \text{ liters per minute}$ while having an expulsion efficiency of 97% .
- Lightweight fluid coupling for low ($< 50 \text{ psi}$, $\text{Cv} > 5$) pressure cryogenic liquids with low internal ($\sim 1 \text{ sccm}$) and external ($\sim 3 \text{ sccm}$) leakage on both halves. Coupling should be designed either for ease of use by Astronauts (i.e., bulky gloves and minimal force) or easy automation.

Sub Topics:

Environmental Monitoring Topic H3.01

Environmental Monitoring is comprised of the following four monitoring disciplines: Air, Water, Microbial and acoustics. ISS has employed a wide variety of analytical instruments to deal with critical items. These functional needs are required to address identified risks to crew health during Exploration-class missions. The current approach onboard ISS, if any, will serve as the logical starting point to meeting the functional needs. However, the following limitations were found common to all the current approaches on-board ISS for any missions beyond low-

Earth orbit (LEO): reliance on return sample and ground analysis, require too much crew time, constraints on size, mass, and power, lack of portability, and insufficient calibration life.

Hence a concerted effort is underway to address these gaps, determine the most promising solutions, and mature those solutions to ground and flight technology demonstrations. Technologies that show improvements in miniaturization, reliability, life-time, self-calibration, and reduction of expendables are of interest.

Methods for collection and concentration for microbial surface monitoring

NASA continues to invest in the near- and mid-term development of highly-desirable systems and technologies that provide innovative ways to monitor microbial burden and enable to meet required cleanliness level of the closed habitat. To date, systematic microbial monitoring of ISS is carried out for water and not for environmental surfaces or air. The sample collection and subsequent processing for either culturing or molecular methods require sample concentration. Presently, swabs are used to collect 25 cm² area before processing and often times this outdated technique is fraught with decreased sensitivity in removing biological materials from the surface. NASA is interested in an integrated sample collection/concentration/extraction system that could feed samples to conventional or molecular microbial monitoring techniques. Furthermore, integration of these steps and a sample delivery to the molecular instruments (such as PCR) as a single module is solicited. Required technology characteristics include a 2 year shelf-life and functionality in microgravity and low pressure environment (~8 psi). The proposed integrated sample collection/concentration/extraction delivery system for molecular microbial monitoring detection should be capable of collecting and concentrating all kinds of microorganisms including “problematic” microbial species on-board ISS (ISS MORD: SSP 50260; (<http://emits.sso.esa.int/emits-doc/ESTEC/AO6216-SoW-RD9.pdf> [2])).

Ethylene analyzer

Ethylene gas is a natural metabolite in plants and acts as a plant hormone. In closed settings, such as plant (food) production chambers, ethylene can build up to deleterious levels for the plants. NASA needs innovative concepts for monitoring ethylene on a real time or near real time basis. Detection limits should ideally be near 25 ppb to insure effective management of plant growth systems, both for fundamental space research and for using plants in bioregenerative life support applications.

Calcium, conductivity and pH monitors for urine and wastewater

A rugged calcium sensor is needed to optimize the percentage of the recovery from brine. The calcium sensor would allow engineers to process a urine batch by knowing precisely the actual calcium concentration, enabling the urine processor to approach the solubility limit of calcium species. The calcium sensor would need to be able to measure calcium at levels of 50-400 mg/L in urine that has been pretreated to a pH of 0.5-3.0. The sensor should be rugged and not require frequent calibration or replacement and should be accurate to within 10%. Rugged conductivity and pH sensors that monitor the conductivity and pH in the brine loop would allow brine to be processed more thoroughly to recover more water. As the brine becomes more concentrated during urine processing, the measurement of conductivity and pH would allow the processor to recover water just to the point of solids precipitation. The conductivity sensor should be able to measure conductivity from 10-250 mS/cm in a urine brine that has a pH of 0.5-5.0. Likewise the pH sensor should be able to measure pH from 0.5-5.0 in a urine brine that has the conductivity of 10-250 mS/cm. The sensor should not require frequent calibration or replacement and be accurate to within 15%.

Sub Topics:

Environmental Control and Life Support for Spacecraft and Habitats Topic H3.02

Solutions and innovations are needed for technology that supports the mass- and energy-efficient maintenance of closed air, water, and waste systems in spacecraft habitats that operate on planetary surfaces such as Mars and that operate in the microgravity environment of space. Three specific focus areas have been identified:

New Applications of the Heat Melt Compactor for Contaminant Control and Waste Management

NASA is seeking new uses for the Heat Melt Compactor (HMC) to extend its capabilities as a multipurpose/multiuse platform with a focus on addressing the needs for Mars surface and planetary protection. These may include:

- Membrane bags and/or liner inserts to initially contain unprocessed trash and other wastes within the compactor chamber but that will allow water and gas to pass through during processing. The bags/liners can melt at process temperatures $>120^{\circ}\text{C}$ but upon cooling must encapsulate the solid dry trash and waste for long-term stable storage. The encapsulation of the processed final product should prevent inoculation by external microorganisms.
- Methods and supporting hardware, including consumables such as membrane bags and/or liner inserts, for safe drying, sterilization and compaction of feces, which allow for water to pass through during processing.
- Methods and supporting hardware, including consumables such as membrane bags and/or liner inserts, for safely recovering water from urine and wastewater brines.
- Design and demonstration of a modular subsystem that uses the existing functional capabilities of the HMC as an autoclave.

New applications of the HMC are not to be limited to the above aforementioned areas, as new and innovative uses for the HMC are welcome. Other considerations are the benefits that can arise from recycling and reutilization of materials from the trash and waste, and the recovery of useful resources such as water and oxygen. The system must work in the Mars gravity environment with micro-gravity operation highly desirable.

A detailed description of the HMC can be found in technical paper number ICES-2014-24, entitled "Generation 2 Heat Melt Compactor Development," authored by Mark Turner, John Fisher and Greg Pace, 44th International Conference on Environmental Systems, 13-17 July 2014, Tucson, Arizona. The paper is available at the following link: (<http://repositories.tdl.org/ttu-ir/handle/2346/59662> [3]). The HMC was primarily designed to compact and sterilize bulk trash and waste into a reduced volume, stable and sterile hard tile that is impregnated and encapsulated with plastics from the trash. The HMC consists of a nine inch wide cubic chamber (729 cu in) which can be heated to 180 C. Gas pressure in the chamber is controllable between 3 and 14 psia. A ram at one end of the chamber can create compression loads on materials within the chamber from 2000 to 4000 lb force. The downstream effluent processing system can collect approximately 200 ml of water per hour and oxidize noxious/toxic gases that evolve from processed materials.

Cleaning Agents and Physicochemical Treatments for Habitat Housekeeping and Laundering Clothes

Crew contact surfaces (hand rails, Velcro, acoustic blankets, racks) and food contact surfaces (utensils, table surfaces) are currently cleaned with pre-moistened wipes that are consumable intensive. A mechanism for the in-situ generation of cleaning/sanitizing solutions is needed that will enable these solutions to be applied to reusable fiber based wipes to remove particulate, food, and body oil soiling of surfaces. Solutions must be effective against a range of microbial organisms; their effectiveness against representative organisms must include, but is not limited to, food based bacteria, iodine resistant bacteria, and fecal coliform bacteria. Specific challenges include direct crew contact with cleaning/sanitizing solutions and direct off-gassing and accumulation of solutions in cabin atmosphere. Technologies that can reliably generate, provide short term storage, and dispense cleaning solutions are desired. Prepackaged cleaning solution wipe technologies are not requested.

There is currently no space based laundry technology. Traditional laundry surfactants combined with water and substantial agitation can return clothing to near original condition. However, used surfactants result in a substantial organic contaminant burden on downstream wastewater processors. Future space laundry or refreshing systems will not be required to fully restore clothing to its original condition but should enable clothing to be reused a number of times. Current clothing materials include cotton, poly blends, wool, modacrylic, elastic bands, metallic zippers, metallic snaps, Velcro®, Nomex®, Gore-Tex®, and will likely expand to include fabrics present in many current athletic garments. Generation of cleaning solutions or gases for refreshing/sanitizing clothing are needed that address particulate/dander, salts, body oils (such as squalene or other representative compound), and bacteria that cause odors (including *Staphylococcus epidermidis* and *Pseudomonas aeruginosa*). Specific challenges include capability to adequately disperse cleansing solutions through a wide range of fibers and materials, minimize mineral and organic load to wastewater processors, and minimal foam generation. Processes are desired that can recover unused cleaning solution or regenerate $>70\%$ of consumables. This request is not specifically for the laundry/sanitation device that interacts with the garments. The capabilities of the future laundry device would provide ability to agitate, partially remove liquids, and garment drying. Use of fabric brighteners, fragrances, pearlizers, and other aesthetic compounds are undesirable.

Surface treatments that limit biofilm and scaling within water processing system plumbing lines

NASA is seeking technologies or surface treatments that limit biofilm and scaling within water processing system

plumbing lines. Both laboratory and flight systems have shown a strong tendency towards biofilm formation and occlusion in wastewater collection systems, particularly small diameter plumbing (3-13 mm internal diameter). Accumulation and sloughing of biofilm increases pressure drop, reduces flow rate, and can cause blockage or premature component change out within wastewater piping. Prevention technologies are sought that will limit microbial growth in piping and water recovery system components for up five years but short timeframes are also useful. Periodic inactivation or remediation technologies that use introduced compounds should be capable of being generated in-situ or recovered after use to minimize consumables. Specific challenges include high microbial and total organic carbon loads. Technologies should be effective for wastewater typical of the International Space Station (urine and humidity condensate) as well as exploration ersatz body hygiene wastewater (see "Advanced Life Support Baseline Values and Assumptions Document", NASA/CR-2004-208941, available at the following link: (<http://ston.jsc.nasa.gov/collections/TRS/techrep/CR-2004-208941.pdf> [4])). Proposed solutions should demonstrate compatibility with ISS type water processors, an ability to protect the wastewater system for a long quiescent period in a clean state, and the ability to withstand intermittent exposure to wastewater followed by additional quiescent periods.

Additional information on NASA needs can be found in draft 2015 NASA Technology Roadmaps including but not limited to sections TA06 6.1.4.1, TA06 6.1.3.3, TA06 6.1.4.6, TA06 6.1.4.8, and TA07 7.5.2.3. These roadmaps are available at the following link: (<http://www.nasa.gov/offices/oct/home/roadmaps/index.html> [5]).

Sub Topics:

Dust Tolerant, High Pressure Oxygen Quick Disconnect for Advanced Spacesuit and Airlock Applications Topic H4.01

In order to support the Extra Vehicular Activity (EVA) Systems development for more robust operation in LEO as well as enabling operation in the lunar and Martian environments, technology development is required for high pressure oxygen (3750 psia) quick disconnects. The current state of the art space suit ISS EMU Umbilical (IEU) and Service and Cooling Umbilical (SCU) connectors operate at a lower pressure and nearly zero contaminant environment. These next generation of quick disconnects (QDs) will enable the EVA systems to transfer high pressure oxygen between the vehicle and on-board tankage under adverse conditions including vacuum and dust (lunar regolith and Martian soil). The QDs expected operating thermal environment range is -50° F to 150° F. The QDs will limit dust intrusion into the internal flow such that when mated/demated 300 times with the environment per MIL-STD-810G, Method 510.5, Procedure I (Blowing Dust) using lunar soil simulant JSC Lunar-1A or JSC Mars-1A, the internal fluid flow downstream of internal filtration is maintained at Level 100A per JPR 5322.1. After those same mate/demate cycles, the fluid flow range will be 0-12 pph of gaseous oxygen at 2800-3750 psia with an allowable pressure drop of 49 psi. The allowable leakage at 3000 psia is 1 scc/hr oxygen. The QD shall exhibit low mating forces such that it can be mated by crew with gloved hands (wearing a spacesuit with a 4.3 psia or 8.3 psia operating pressure) using simple motions such as push/pull or push-twist/twist-pull. Single handed, gloved operation is preferred. A simple means of indicating positive QD engagement is preferred. The use of accessory tools to aid in QD mate/demate should be avoided if possible. The connector shall be capable of reacting a 125 lbf pull force at the strain relief. There are no specific requirements levied upon the exterior size and complexity of the QDs other to state that they are high criticality items that must be safe, practical, reliable; and a device that an exhausted crew member could operate easily and intuitively. Significant work has been done by NASA to identify a mechanical design for the basic size and operation of the device. Reference material has been attached describing existing and new designs, which NASA expects to heavily influence the general form, fit, and function of the future high pressure quick disconnect.

Research done in Phase I of these efforts should focus on technical feasibility with an emphasis on hardware development that can be further expanded in a future Phase II award cycle. Phase II products must include a demonstration unit suitable for testing by NASA. Prototyping should be tailored to applications to ongoing HEO Mission Directorate missions and possible collaborative use in both the governmental and commercial manned spaceflight disciplines. Minimum deliverables at the end of Phase I are analysis and/or test reports, with priority given to functional hardware prototypes for further evaluation. Technical maturation plans should be submitted with Phase I submittals, as well as any expected commercial applications both internal and external to the manned spaceflight enterprise.

ISS EMU UMBILICAL (IEU)

The ISS EMU Umbilical (Item 498) is an interface between the ISS Umbilical Interface Assembly (UIA) and the Extravehicular Mobility Unit (EMU). It provides electrical power and communication, water fill/drain, and water cooling capability from the International Space Station (ISS) for the EMU. The IEU consists of the following items: three water lines of which two are used for water cooling of the LCVG and one for feedwater charging and

condensate draining of the PLSS, one oxygen line, one electrical harness assembly for power and communication, a tether restraint and the TMG. The Common Multiple Connector, Item 410, provides a single interface point for connecting and disconnecting the IEU from the DCM. An Umbilical Connector Manifold (UCM), which is government furnished equipment (GFE), provides a single IEU attachment point to the ISS UIA. The IEU provides recharge capability for the PLSS oxygen tank, water reservoir, and battery. In the event a decontamination EVA is needed, the umbilical is designed to withstand environments external to the Airlock.

The EMU umbilical terminates at each end with a ganged multiple connector that requires only a single operation to connect or disconnect the umbilical.

The outer layer of the IEU is a multi-layer Thermal Micrometeoroid Garment (TMG) to provide thermal insulation and protection from micrometeoroid impacts. The IEU includes a protective pouch that will provides thermal and impact protection for the IEU common multiple connector while disconnected from the EMU.

The Umbilical contains a strain relief strap which, during IV operations, attaches via a GFE tether hook to one of the Lower Torso Assembly (LTA) D-rings at the EMU end and to a separate tether ring on the Crew Lock (CL) wall. For EV operations, the hook is disengaged from the UIA panel ring and is secured to a D-ring near the UIA panel. In the event that an EVA decontamination bake out of the EMU is required, this tethering scenario will serve to ensure that UIA design loads are not exceeded.

While not in service (i.e., when completely disconnected from the UIA and EMU), the umbilical is stowed in the equipment lock. While attached to the UIA, the umbilical is restrained against the CL wall by GFE provided restraint straps.

The useful life (combination of the operational life and shelf life) of the Umbilical is 15 years from the date of PDA. The dry weight of the Umbilical does not exceed 30 lbm. This weight includes all GFE provided hardware (2 tether hooks and the UCM).

Service and Cooling Umbilical (SCU)

The Service and Cooling Umbilical (Item 400) is an 11-ft umbilical consisting of three water hoses, a high-pressure oxygen hose, electrical harness, bacteria filter assembly, and a strain relief tether. The SCU supplies the PLSS with electrical power, communications, oxygen, waste water drainage and water cooling from the Orbiter during pre- and post-EVA operations. It also supplies the EMU with recharge of the oxygen tanks, water tanks, and battery.

The end of the SCU that connects into the airlock panel, otherwise known as the vehicle end of the SCU, consists of the four fluid ECLSS connections in addition to one electrical connector that attaches the SCU to the Orbiter airlock service panel AW82. The connections remain intact between flights and do not require crewmember operation. The vehicle waste water drain and potable water fill lines are connected to the bacteria filter housing located on the airlock wall. On both the drain side and the potable water fill side, a bacteria filter of iodine-impregnated epoxy resin spheres is incorporated, along with a particulate filter made of sintered stainless steel. These filters are used to prevent contamination from passing between the Orbiter ECLSS and the EMU. During normal IVA operations, the Orbiter Waste System is off and there is no ability to dump excess condensate. Approximately one pound of water is drained from the EMU water tanks after filling to allow room for condensate while IVA.

The common connector on the EMU end of the SCU combines the four fluid connections and one electrical circuit connector into a single unit operated by the crewmember. Disengagement of the connector is accomplished by pulling out on the SCU connector cam T-handle to retract a locking pin and then rotating the cam handle from the "locked" position approximately 180° to a detent, which is the "open" position. This rotation of the SCU connector cam disengages two pins on the mating is accomplished by pulling out on the SCU connector cam T-handle to retract a locking pin and then rotating the cam handle from the "locked" position approximately 180° to a detent, which is the "open" position. This rotation of the SCU connector cam disengages two pins on the mating connector. Engagement of the connector is accomplished by rotating the SCU connector cam T-handle to the "open" position, engaging the two pins on the mating connector with the cam, and then rotating the cam handle from the "open" position approximately 180° to the "locked" position, where a cam locking pin is engaged.

The SCU is stowed on the airlock wall when it is not being used. The common connector (SCU side) is attached to a mating stowage connector on the EMU mount (AAP). The SCU is unstowed and connected to the DCM during

EMU donning to provide vehicle consumables for the suited EVA preparation activities in the airlock until life support from the EMU is initiated. Nominally, the SCU is disconnected at an airlock pressure of zero psia during airlock depressurization prior to an EVA and reconnected at an airlock pressure of zero psia during airlock re-pressurization after an EVA. The life support from the SCU is maintained during the suited post-EVA activities until the start of EMU doffing. The SCU is also connected to the EMU to supply Orbiter consumables for recharge of the EMU oxygen, the water tanks, and the battery.

ITAR restricted background on exploration space suit umbilical design requirements and expectations may be found at the following website (in cases where the solicitation requirements disagree with the references, the solicitation takes precedence.):

- Contract NNJ09T40C, Constellation Space Suit Systems ISS Umbilical Assembly, CSSS-T-002 Rev. DRAFT X-2, 7 July 2015. (http://sbir.gsfc.nasa.gov/SBIR/solicitations/2016/CSSS-T-002_LSS_CEI_ISS_Umbilical_Assembly_Specification.pdf [6])
- Contract NNJ09T40C, Constellation Space Suit Systems ISS Umbilical Assembly, Exploration EVA Space Suit Design Status Review, 26 August 2015. (http://sbir.gsfc.nasa.gov/SBIR/solicitations/2016/Umbilical_and_Connector_Section_CSSS_DSR_Day_2_P_M.pptx [7])

Sub Topics:

Trace Contaminant Control for Advanced Spacesuit Applications Topic H4.02

This subtopic is in search of a trace contaminant control (TCC) technology to remove trace contaminants in an advanced spacesuit atmosphere, specifically considering power, size, and removal capability. The advanced spacesuit portable life support system (PLSS) performs the functions required to keep an astronaut alive during an extravehicular activity (EVA) including maintaining thermal control, providing a pressurized oxygen (O₂) environment, and removing carbon dioxide (CO₂). The PLSS ventilation subsystem performs the transport and provides the conditioned O₂ to the suit for pressurization and astronaut breathing. It circulates O₂ through the ventilation loop using a fan and recycles the ventilation gas, removing CO₂ and providing humidity control. The ventilation subsystem is also responsible for removing trace contaminants from the spacesuit atmosphere. The International Space Station extravehicular mobility unit uses an activated charcoal bed inside the CO₂ removal bed (lithium hydroxide (LiOH) and metal oxide (MetOx) canisters). The charcoal in the MetOx canisters can be regenerated on-orbit. The selection of the rapid cycle amine (RCA) swingbed for CO₂ removal in the baseline advanced spacesuit PLSS has added a risk for removing trace contaminants. The trace contaminants in the PLSS ventilation subsystem and their predicted concentrations (mg/m³) at the end of an 8-hour EVA without suit leakage include the following: acetaldehyde (0.181), acetone (0.301), ammonia (564), n-Butanol (1.13), carbon monoxide (74.4), ethyl alcohol (9.03), formaldehyde (0.902), furan (0.676), hydrogen (113), methyl alcohol (3.16), methane (1352), and Toulene (1.36). The predictions are based on EVA-specific generation rates.¹ Based on these predictions ammonia and formaldehyde are the two contaminants most likely to exceed Spacecraft Maximum Allowable Concentration levels if no TCC device is in the PLSS ventilation loop. It would be beneficial for the technology to be regenerable such as vacuum swing regeneration. In particular, a vacuum-regenerable TCC device that can be regenerated in real time on the suit using a vacuum swing with 1 to 3 min of exposure would be optimum. Additional items for optimization include: reduction in expendables and incorporation into integrated CO₂ removal/reduction system. The desire is for the TCC system to be an immediate knock-down of inlet contaminants such as aldehydes which react irreversibly with the RCA sorbent. This will decrease the likelihood of losing capacity over the life of the system to these types of reactions.

Research done in Phase I of these efforts should focus on technical feasibility with an emphasis on hardware development that can be further expanded in a future Phase II award cycle. Phase II products must include a demonstration unit suitable for testing by NASA. Prototyping should be tailored to applications to ongoing HEO Mission Directorate missions and possible collaborative use in both the governmental and commercial manned spaceflight disciplines. Minimum deliverables at the end of Phase I are analysis and/or test reports, with priority given to functional hardware prototypes for further evaluation. Technical maturation plans should be submitted with Phase I submittals, as well as any expected commercial applications both internal and external to the manned spaceflight enterprise.

References:

- Paul, H., Jennings, M., and Waguespack, G., "Requirements and Sizing Investigation for Constellation Space Suit Portable Life Support System Trace Contaminant Control", 40th International Conference on Environmental Systems, Barcelona, Spain, July 2010. (http://sbir.gsfc.nasa.gov/SBIR/solicitations/2016/AIAA-2010-6065_TCC_CES_Paper_Paul-Jennings-Waguespack.pdf [8])
- James, J., "Spacecraft Maximum Allowable Concentrations for Airborne Contaminants," JSC-20584, Houston: NASA/Johnson Space Center, November 2008. (http://sbir.gsfc.nasa.gov/SBIR/solicitations/2016/Spacecraft_Maximum_Allowable_Concentrations_SMAC_JSC-20584.pdf [9])

Sub Topics:

EVA Space Suit Power, Avionics, and Software Systems Topic H4.03

Space suit power, avionics and software (PAS) advancements are needed to extend EVA capability on ISS beyond 2020, as well as future human space exploration missions. NASA is presently developing a space suit system called the Advanced Extravehicular Mobility Unit (AEMU). The AEMU PAS system is responsible for power supply and distribution for the overall EVA system, collecting and transferring several types of data to and from other mission assets, providing avionics hardware to perform numerous data display and in-suit processing functions, and furnishing information systems to supply data to enable crew members to perform their tasks with autonomy and efficiency. Current space suits are equipped with radio transmitters/receivers so that spacewalking astronauts can talk with ground controllers and/or other astronauts. The astronauts wear headsets with microphones and earphones. The transmitters/receivers are located in the backpacks worn by the astronauts only operate in the UHF band.

While a sufficient amount of radiation hardened electronics are available in areas such as serial processors, digital memory and Field Programmable Gate Arrays, certain ancillary electronic devices present a significant risk for the development of rad-hard spacesuit avionics. NASA is, therefore, seeking flight rated electronic devices needed to complement the existing inventory of flight rated parts so as to enable the creation of an advanced avionics suite for spacesuits. The suit and its corresponding avionics should be capable of being stowed inside a spacecraft outside the low-Earth orbit (LEO) environment for periods of up to 5 years (TBR). Devices should also be capable of supporting EVA sorties of at least 8 hours and total lifetime operational durations of at least 2300 hours (TBR) for a Mars surface mission. Assumptions may be made for inherent radiation shielding provided by the primary life-support system (PLSS) and possibly the power, avionics, and software (PAS) subsystem enclosure, but proposers are welcome to include shielding technologies at the board and individual part level to reduce the radiation requirements of the actual device. Devices should be immune to single event latch-up (SEL) for particles with Linear Energy Transfer (LET) values of at least 75 Mev-cm²/mg. and maintain full functionality for total ionizing doses of at least 20 Krad (Si). Criticality 1 devices (life support) must be fully mitigated against single event errors (SEE) for all potential mission radiation environments, including solar flares. Lower criticality devices can be less tolerant of SEEs, but must still operate with acceptable error rates in all potential radiation environments. Power consumption should be no more than 2X similar COTS or mil-spec devices. Devices should be vacuum compatible and need to support conduction cooling. Need currently exists for a number of devices, as described below. However this list should not be considered to be exhaustive and proposals will be considered for other devices that are peculiar to a spacesuit avionics suite. Additionally, proposals are invited for simplified, low-cost and low-impact methods to adapt or test commercial or military-spec devices so as to yield a flight-rated part to the above levels. In order of priority, two key innovations are sought this round:

- *Safety Critical Switches and Controls* - Very low profile switches and controls for EVA Criticality 1 systems. Highly reliable and robust devices that provide traditional toggle switch, rotary dial, and linear slider control functionality in a very low profile package which permits higher packaging density compared to traditional solutions for vacuum space operations. Switches and controls must still be sized for easy operation with EVA gloves.
- *Wireless Communication* - Dual-band WLAN-class RF front-end module capable of supporting the SSCS (410 to 420 MHz) and the ISS External Wireless Communications system (5.25-5.35GHz). This module is

expected to contain all RF components plus data converters. This module will interface with a baseband processing unit via high-speed digital interface. Consideration for supporting multiple antennas on the EWC band will be given, but this is not required. The front-end must be able to operate in the ISS environment.

Research done in Phase I of these efforts should focus on technical feasibility with an emphasis on hardware development that can be further expanded in a future Phase II award cycle. Phase II products must include a demonstration unit suitable for testing by NASA. Prototyping should be tailored to applications to ongoing HEO Mission Directorate missions and possible collaborative use in both the governmental and commercial manned spaceflight disciplines. Minimum deliverables at the end of Phase I are analysis and/or test reports, with priority given to functional hardware prototypes for further evaluation. Technical maturation plans should be submitted with Phase I submittals, as well as any expected commercial applications both internal and external to the manned spaceflight enterprise.

Sub Topics:

Large Deployable Structures for Smallsats Topic H5.01

This subtopic seeks deployable structures innovations in two areas for proposed lunar and deep-space missions:

- Large solar sails with at least 85 m² of deployed surface area for 6U cubesats.
- Large solar arrays with at least 200 W of power for 6U-12U cubesats or 600 W for 50-100 kg microsats.

Design solutions must demonstrate high deployment reliability and predictability with minimum mass and launch volume and maximum strength, stiffness, stability, and durability.

Innovations are sought in the following areas for both capabilities (deployable solar sails and deployable solar arrays):

- Novel design, packaging, and deployment concepts.
- Lightweight, compact components including booms, substrates, and mechanisms.
- Validated modeling, analysis, and simulation techniques.
- Ground and in-space test methods.
- Load reduction, damping, and stiffening techniques.
- High-fidelity, functioning laboratory models.

Capability #1: Deployable Solar Sails

Solar sails provide propellant less in-space propulsion using reflected sunlight. Indefinite continuous thrust allows a wide range of advanced maneuvers including non-Keplerian orbits, efficient orbit changes, and extreme ultimate velocities. A near-term application of this technology is NASA's NEA Scout 6U cubesat missions. Larger and more capable solar sail systems are envisioned for future missions.

Square solar sails typically consist of four reflective triangular membranes supported by lightweight deployable booms, as well as mechanical sail actuation to assist attitude control. Specific innovations sought for 6U cubesat solar sails in this solicitation are: improved deployable boom technologies, novel sail designs and packaging concepts, and simpler or more-effective mechanical attitude control systems. Proposed improvements to the booms used on the LightSail mission (metallic Triangular Rollable and Collapsible (TRAC) booms) are of special interest.

Nominal solar sail requirements for 6U cubesats are:

- Deployed reflective surface area > 85 m² (>100 m² preferred).
- Stowed membrane volume < 10 cm x 10 cm x 20 cm.
- Sail membrane stress > 70 kPa.
- Minimum system deployed natural frequency > 0.1 Hz.
- Mission life > 3 years in deep space (< 2 AU from the Sun) including lunar vicinity.

-
- Deployed sail surface as flat as possible considering all thermal and mechanical loads and residual stresses.

Improvements to the deployable TRAC booms proposed for the NEA Scout solar sail should meet the following additional requirements:

- Deployed boom length: > 8 m (up to 10 m preferred).
- Stowed volume for all booms and deployment mechanisms < 5 cm x 10 cm x 20 cm.
- Boom buckling load > 3N.
- Mass of each boom < 0.25 kg (< 0.15 kg preferred).

Capability #2: Deployable Solar Arrays

Smallsats promise cost-effective solutions for diverse human spaceflight precursor missions using fuel-efficient solar electric propulsion (SEP). SEP thrust increases with electrical power, so larger solar arrays can shorten travel times and allow higher-power science and communications equipment. This subtopic seeks structures innovations for the next generation of smallsat solar arrays with at least 5x larger area than basic body-mounted solar cells or hinged pop-out panels. Scaling up electrical power for smallsats by > 5x will require game changing innovations. In particular, novel flexible-substrate solar array designs are sought that minimize structural mass and packaging volume while maximizing deployment reliability and deployed area, stiffness, strength, and longevity.

Nominal solar array requirements are:

- Beginning-of-life (BOL) power at 1 AU > 200 W for cubesats or > 600 W for microsats.
- Packaging efficiency > 50 kW/m³ BOL.
- Recurring cost < \$500/W.
- Deployment reliability > 0.999.
- Deployed stiffness > 0.5 Hz.
- Deployed strength > 0.05 g (all directions).
- Lifetime > 2 yrs.

Proposals should emphasize structural design innovations, not materials or photovoltaic innovations. Solar array designs that can be rapidly commercialized are of special interest.

For both capabilities, contractors should prove the feasibility of proposed innovations with suitable analyses and tests in Phase I. Significant hardware or software capabilities should be developed and demonstrated in Phase II. A Technology Readiness Level (TRL) at the end of Phase II of 3-4 or higher is desired.

References:

- (http://www.nasa.gov/sites/default/files/files/Small_Spacecraft_Technology_State_of_the_Art_2014.pdf [10]).
- (<http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140012882.pdf> [11]).
- (<http://www.planetary.org/blogs/jason-davis/2014/20140610-lightsail-update-boom.html> [12]).

Sub Topics:

Extreme Temperature Structures Topic H5.02

This subtopic seeks to develop innovative low cost and lightweight structures for cryogenic and elevated temperature environments. The storage of cryogenic propellants and the high temperature environment during atmospheric entry require advanced materials to provide low mass, affordable, and reliable solutions. The development of durable and affordable material systems is critical to technology advances and to enabling future launch and atmospheric entry vehicles. The subtopic focuses on two main areas: highly damage-tolerant composite materials for use in cryogenic storage applications and high temperature composite materials for hot structures applications. Proposals to each area will be considered separately.

Cryogenic Storage Applications

The focus of this area is to yield material polymeric composite systems and manufacturing processes which enable the capability to store and transfer cryogenic propellants (liquid oxygen and liquid hydrogen) to orbit. Operating temperature ranges for these fluids are -183° C to -253° C. Material systems and processes proposed should be sensitive to eventual scale up and manufacturability of end use hardware. Specific areas of interest include:

- Polymeric composite systems for applications in extreme cold environments such as storage vessels and ductwork for cryogenic fluids. Performance metrics for cryogenic applications include: temperature dependent properties (fracture toughness, strength, coefficient of thermal expansion), resistance to permeability and micro-cracking under cryogenic thermal and biaxial stress state cycling.
- Reliable hatch or access door sealing technique/mechanism for cryogenic polymeric composite structures. Concepts must address seal systems for both composite to composite and composite to metal applications.

Hot Structures

The focus of this area is the development of cost effective, environmentally durable and manufacturable material systems capable of operating at temperatures from 1200° C to 2000° C, while maintaining structural integrity. Significant reductions in vehicle weight can be achieved with the application of hot structures, which do not require structurally parasitic thermal protection systems. The desired material systems are lightweight structural composites that include continuous fibers. This area seeks innovative technologies in one or more of the following:

- Material systems with significant improvements of in-plane and thru the thickness mechanical properties, compared to current high temperature laminated composites, such as stitched or 3D woven fibrous preforms.
- Decreased processing time and increased consistency for high temperature composite materials.
- Improvement in potential reusability for multiple missions.

For all above technologies, research, testing, and analysis should be conducted to demonstrate technical feasibility during Phase I and show a path towards Phase II hardware demonstration. Emphasis should be on the delivery of a manufacturing demonstration unit for NASA testing at the completion of the Phase II contract.

Phase I Deliverables - Test coupons and characterization samples for demonstrating the proposed material product. Matrix of verification/characterization testing to be performed at the end of Phase II.

Phase II Deliverables - Test coupons and manufacturing demonstration unit for proposed material product. A full report of the material development process will be provided along with the results of the conducted verification matrix from Phase I. Opportunities and plans should also be identified and summarized for potential commercialization.

References:

- Anon, "Final Report of the X-33 Liquid Hydrogen Tank Test Investigation Team," National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Huntsville, Alabama 35812, May 2000.
- Glass, D. E. "Ceramic Matrix Composites (CMC) Thermal Protection Systems (TPS) and Hot Structures for Hypersonic Vehicles," 15th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, Dayton, Ohio, AIAA-2008-2682, April 2008.
(<http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080017096.pdf> [13]).

Sub Topics:

Multifunctional Materials and Structures: Integrated Structural Health Monitoring for Long Duration Habitats Topic H5.03

Multifunctional and lightweight are critical attributes and technology themes required by deep space mission architectures. Multifunctional materials and structural systems will provide reductions in mass and volume for next generation vehicles. The NASA Technology Roadmap TA12, "Materials, Structures, Mechanical Systems, and

Manufacturing”

(http://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_12_materials_structures_final.pdf [14]), proposed Multifunctional Structures as one of their top 5 technical challenges, and the NRC review of the roadmap recommended it as the top priority in this area stating: “... To the extent that a structure can simultaneously perform additional functions, mission capability can be increased with decreased mass. Such multifunctional materials and structures will require new design analysis tools and might exhibit new failure modes; these should be understood for use in systems design and space systems operations.”

Some functional capabilities beyond structural that are in this multifunctional theme are insulating (thermal, acoustic, etc.), inflatable, protective (radiation and micrometeoroids and orbital debris), sensing, healing, in-situ inspectable (e.g., IVHM), actuating, integral cooling/heating, power generating (thermal-electric, photovoltaic, etc.), and so on.

Because of the broad scope possible in this SBIR subtopic, the intent is to vary its focus each year to address specific areas of multi-functionality:

- That have high payoff for a specific mission.
- That are broadly applicable to many missions.
- That could find broader applications outside of NASA which would allow for partnerships to leverage the development of these technologies.

For FY16, this SBIR subtopic seeks innovative, multifunctional approaches to integrating long-duration health monitoring capabilities within the range of candidate materials currently being investigated for space habitat long-duration mission concepts. These materials include, but are not limited to, thin-ply composites as well as the materials comprising the multiple soft-goods layers utilized in expandable space habitats, including the bladder, restraint and MMOD layers. Soft-goods materials, used in expandable habitats, may be packaged in an unloaded state for long periods of time prior to deployment, and then maintained at pressure for several years during a mission, while also being subjected to varying levels of thermal cycling. This creates a challenging set of conditions from which to predict the mechanical behavior of these structures over their operational life. NASA seeks the integration of robust, long-term sensing capabilities into the flexible materials (e.g., webbing, cordage, and woven fabrics) used in long-duration habitats, to provide health monitoring and evaluation of the structural integrity and properties of the multi-layer habitat structure throughout its mission life. The integration of the sensors would ideally be performed directly during manufacture; however, robust integration, post-fabrication, via non-destructive application, is also of interest. Ideally, the innovative sensing technology and integration approach should maintain the load-carrying capability or some other structural design requirement, and those technologies that enable weight reduction with similar or better structural performance when compared to traditional approaches will be considered. Sensing capabilities can include both the direct measurement of properties (strain, displacement, and load for example) and sensor fusion using multiple sensors to predict and locate critical damage areas and probable failure zones. The goal for long-duration space habitat design is fail-safe operation; providing monitoring and early prediction of failure onset via structural health monitoring and a benign, progressive failure architecture that allows for safe evacuation even at or after the first failure point.

In summary NASA seeks innovations in integrating structural health monitoring into materials for long-duration deep space habitats, including, but not limited to, state-of-the art thin-ply composites and soft-goods materials for expandable habitat structural concepts, during or after fabrication, to enable evaluation of structural properties and failure prediction over the duration of the habitat’s operational life.

Contractors should prove the feasibility of proposed innovations using suitable analyses and small scale tests in Phase I. In Phase II, significant testing/fabrication or software capabilities should be developed and demonstrated. A Technology Readiness Level (TRL) at the end of Phase II of 3-4 or higher is desired.

Sub Topics:

In-Space Structural Assembly Topic H5.04

In-space assembly (ISA) of spacecraft systems has been proposed and demonstrated several times as way of assembling systems too large to fit into a single launch vehicle and enabling installation of orbital replacement units. The International Space Station and the repair missions of the Hubble Space Telescope are two good examples.

Efficient structural assembly in space, namely structures with low-mass and high-stiffness and strength, can be

achieved by system level design that takes advantage of robotic assembly. For deep-space exploration, the key technology gaps for a robust ISA capability are the joining and unjoining technology (mechanical and electrical), design modularity, and the reuse of components. These technologies will enable a capability that makes future long duration vehicle systems more affordable than the current single-launch, single-use approach to space vehicle design.

The need for on-orbit repair/assembly/servicing are well documented Ref. 1-3. This subtopic seeks in-space assembly and structures manufacturing innovations in two areas of special interest for proposed deep-space space exploration missions:

- Reversible joining technology for structural components and modules.
- In-space and surface systems that recycle spent metallic and composite components to produce additive manufacturing feedstock. Design solutions must minimize mass, power, and complexity while meeting all other mission requirements including contamination control, load bearing strength and stiffness of the assemblage.

Capability #1: Reversible Joining Technology

The ability to join structural and spacecraft components in-space allows for the assembly of vehicles (perhaps aggregated from multiple launches) and for re-use of vehicle subsystems. The joining technology should be reversible for maximum flexibility and utilize simple approaches (electro-mechanical or other) amenable to robotic assembly and disassembly. In addition, the joining technology must provide for mechanical, electrical and optionally thermal load transfer.

This subtopic capability seeks innovative joining technologies and capabilities for in-space assembly, disassembly, and re-use of deep-space exploration vehicle subsystems such as cargo tugs that use solar electric power for propulsion. Joining in-space of structural trusses that support multiple solar arrays for solar electric propulsion is one class of needed joining technology. The assembled truss must provide power connections either integral to the structural joint or as a non-mechanical load bearing harness with connectors. The second class of in-space joining is for modular subsystems nominally three-dimensional shapes (square or rectangular) with power, data, and mechanical load carrying connections. While these modules could represent orbital replacement units (ORUs), the modules could serve to construct an entire space vehicle.

In particular, novel reversible joining systems for robotic operations are needed that minimize mass, energy and complexity while maximizing assembled stiffness, strength and stability.

Nominal joining applications are:

- Class 1: Structural Truss Joints.
 - Strength: > 0.4 g (Mars Extensible) in all degrees of freedom assuming a fixed joint with 1 meter rigid offset of a 100Kg point mass.
 - Power Transmission: > 5 kW.
 - Operating Temperature: -100° C to +100° C.
 - Assembly/Disassembly: > 20 times.
- Class 2: Module Joints.
 - Strength: > 0.4 g (Mars Extensible) with 0.25 meter cubic module connected on one face with uniform density of 640 Kg/m³.
 - Power Transmission: > 5 kW.
 - Data Transmission: 25 low voltage lines.
 - Temperature: -100° C to +100° C.
 - Assembly/Disassembly: > 20 times.

In Phase I, contractors should prove the feasibility of proposed innovations using suitable analyses and prototype tests. In Phase II, operational joining hardware for assembly and disassembly. Technology Readiness Level (TRL) at the end of Phase II is expected to be 3-4 or higher.

Capability #2: In-situ Surface Manufacturing

Sustainable extraterrestrial presence will require innovative approaches to lightweighting launch masses. The ability to manufacture structures onsite affords an alternative to carrying components of surface systems as part of the launch mass and volume. Additive manufacturing (AM) offers the flexibility to achieve this objective since it enables the conversion of various feedstocks into functional components, especially. Maximum benefits can be realized if the AM method can take advantage of resources available onsite, including both ISRU extracted planetary metals and discarded materials.

State of the art AM techniques can process material classes ranging from metals to plastics and ceramics. Typically, AM equipment use pristine forms of these material feedstocks. This manufacturing capability will permit the construction of various surface systems using feedstock carried as part of the launch and taking advantage of AM in this manner can contribute to the reduction of volume required to carry partly or fully assembled surface systems during launch. However, the impact of AM can be maximized if it is also able to utilize a broader suite of materials, especially those generated from repurposing objects/components required only for launch and transport to the exploration destination, in-space and surface presence. For example, metallic or composite parts from vehicles needed only for transit to the planetary surface, can be recycled to construct pressure vessels for life support and propulsion. The ability to repurpose what would otherwise be discarded materials and/or fabricate with processed extracted planetary materials (such as iron, aluminum, and silicon) takes full advantage of limited resources available to make sustained presence affordable. Further, automated AM offers a means to construct surface systems ahead of the arrival of humans.

Proposals are sought for additive manufacturing concepts that can enable manufacturing from extracted planetary materials and/or the recycling/repurposing of structural components from space vehicles to produce pressure vessels. This does not include the process of ISRU to extract the materials, just the use of the extracted materials in AM. (See H1.01 In-Situ Resource Utilization for processes to extract materials.) Of interest are the following:

Design concepts for AM approaches to accommodate feedstocks that are composites of various material types including but not limited to:

- Processing techniques to recycle and repurpose structural composites having thermoset matrices and carbon fiber reinforcement to yield AM feedstocks.
- Processing techniques to recycle and repurpose structural metallic vehicle components to yield AM feedstocks.
- Approaches to join additively manufactured components from disparate materials.
- Approaches to use minimal power in the manufacture of components.
- Mobile AM methods that operate on power generated from planetary surface resources.

Nominal manufacturing applications are:

- Class 1: Pressure vessels.
 - Size: > 0.25 m³.
 - Strength: > 14.7 psi.
 - Operating Temperature: -100° C to +100° C.
- Class 2: Two-Dimensional Platform for Mobile Carrier.
 - Size: > 3 meter X 2 meter with thickness based on strength.
 - Strength: > 0.4 g (Mars) with 300 Kg mass uniformly distributed.
 - Operating Temperature: -100° C to +100° C.

In Phase I, contractors should prove the feasibility of proposed innovations using suitable analyses and prototype tests. In Phase II, prototype manufacturing systems capable of processing multiple material classes. Technology Readiness Level (TRL) at the end of Phase II is expected to be 3-4 or higher.

References:

- Barnhart, David; Will, Peter; Sullivan, Brook; Hunter, Roger; and Hill, Lisa: "Creating a Sustainable Assembly Architecture for Next-Gen Space: The Phoenix Effect," 30th Space Symposium, May 2014,

Colorado Springs CO.

- Erkorkmaz, Catherine; Nimelman, Menachem; and Ogilvie, Andrew: "Spacecraft Payload Modularization for Operationally Responsive Space," 6th Responsive Space Conference, April 28-May 1, 2008, Los Angeles, CA.
- Troutman, Patrick A.; Krizan, Shawn A; Mazanek, Daniel D.; Stillwagen, Frederic H.; Antol, Jeffrey; Sarver-Verhey Timothy R.; Chato, David J.; Saucillo, Rudolf J.; Blue, Douglas R.; and Carey, David: "Orbital Aggregation and Space Infrastructure Systems (OASIS)", IAC-02-IAA.13.2.06, 53rd International Astronautical Congress, 10-19 Oct. 2002, Houston Texas.

Sub Topics:

Robotic Systems - Mobility, Manipulation, and Human-System Interaction Topic H6.01

The objective of this subtopic is to create autonomous systems and robotic technologies (hardware and software) to improve the human exploration of space. Robots can perform tasks to assist and off-load work from astronauts. Robots may perform this work before, in support of, or after humans. Ground controllers and astronauts will remotely operate robots using a range of control modes (tele-operation to supervised autonomy), over multiple spatial ranges (shared-space, line-of-sight, on orbit, and interplanetary), and with a range of time-delay and communications bandwidth. Additionally, in order to build robotic systems that are cheaper, lighter, and more energy efficient than traditional devices based only on rigid assemblies, it is important to develop soft robotics technology for mobility and manipulation.

The software, avionics, and robotics elements requested within this topic are critical to increasing autonomy and system reliability; reducing system vulnerability to extreme radiation and thermal environments; and supporting human exploration missions with robotic assistants, precursors and caretaker robots. As key and enabling technology areas, autonomous systems, avionics, and soft robotics technologies are applicable to broad areas of technology use, including heavy lift launch vehicle technologies, robotic precursor platforms, utilization of the International Space Station, and spacecraft technology demonstrations performed to enable complex or long duration space missions. All of these flight applications will require unique advances in autonomy, software, robotic technologies and avionics. The exploration of space requires the best of the nation's technical community to provide the technologies, engineering, and systems to enable human exploration beyond LEO, to visit Asteroids and the Moon, and to extend our reach to Mars.

Proposals are sought to research and develop the following:

- *Mobility* - Subsystems to improve the transport of crew, instruments, and payloads on planetary surfaces, asteroids, and in-space. This includes: hazard detection sensors/perception; active suspension; grappling/anchoring; legged locomotion; robot navigation; infrastructure-free localization and sensors for deformable, flexible or active elastic mobility components.
- *Manipulation* - Subsystems to improve handling and maintenance of payloads and assets. This includes: tactile sensors; human-safe actuation active structures; dexterous grasping; modular "plug and play" mechanisms for deployment and setup; small/lightweight excavation devices; novel manipulation methods; and actuators and/or sensors for active tension control (including tendon-based manipulation and dynamic tensegrity).
- *Human-system interaction* - Subsystems that enable crew and ground controllers to better operate, monitor and supervise robots. This includes: robot user interfaces; automated performance monitoring; tactical planning software; real-time visualization/notification; software for situational awareness and modeling/simulation software for soft robotics (including design of highly compliant and/or underactuated dynamic systems).

Sub Topics:

Requirements Management for Spacecraft Autonomy and Space Mission Automation Topic H6.02

System and software requirements for autonomy have been difficult to define and test due to uncertainties in the environment in which autonomous systems might be deployed, the flexible yet safe interaction with in-situ humans that is needed, and the adaptability needed from an autonomous system for novel situations. Future human spaceflight missions will place crews and other assets at large distances and light-time delays from Earth that will need to act autonomously from mission control over significant time intervals in both nominal and emergency situations. Space missions have small crew sizes, and many mission concepts involve spacecraft and habitats that are only intermittently crewed, so automation through software will be a major portion of autonomous systems.

Proposals are solicited that provide novel methods and tools specifically targeted to defining and testing requirements for autonomy capabilities, including the definition of interactions and roles with in-situ humans. Proposals should encompass a subset of the following: methods and tools for autonomy requirement definition, refinement, verification of internal consistency, validation, and testing during subsequent development.

Proposals should compare their proposed methods and tools to conventional requirements management, and indicate why their methods and tools will result in requirements for autonomy with less ambiguity, fewer conflicts between different requirements, and more testable requirements - as compared to state of the art requirements methods. Proposals should provide metrics for measuring the quality of autonomy requirements resulting from their methods and tools compared to SOA. For example, in the aircraft industry today over half of system development errors originate during the requirements phase, while over 75% of system development errors are caught very late in development - typically in late phases of testing. This leads to high costs and development schedule overruns due to rework. Proposers should ground their proposed research by demonstrating methods and tools on plausible design reference missions involving autonomy.

Proposals should indicate how their methods and tools will bridge the gap between requirements definition and requirements-based testing, potentially including semi-automatic test generation suitable for the autonomy attributes of flexible response in uncertain environments with uncertain situations.

Proposals can draw upon a wide range of methods, including but not limited to ontology definition, uncertainty quantification, formal approaches to requirements engineering, symbolic methods for test generation from requirements, and techniques for requirements elicitation from stakeholders. Proposals that involve natural language as a medium for autonomy system and software requirements definition should describe how the natural language will be disambiguated in subsequent phases of system development.

Sub Topics:

Spacecraft Autonomy and Space Mission Automation for Consumables Topic H6.03

Future human spaceflight missions will place crew's at large distances and light-time delays from Earth, requiring novel capabilities for crews and ground to manage spacecraft consumables and renewables such as power, water, propellant and life support systems to prevent Loss of Mission (LOM) or Loss of Crew (LOC). This capability is necessary to reconfigure spacecraft, or replan missions, in response to events such as leaks or failures leading to unexpected expenditure of consumables coupled with lack of communications. If crews in the spacecraft must manage, plan and operate much of the mission themselves, NASA must migrate operations functionality from the flight control room to the vehicle for use by the crew. Migrating flight controller tools and procedures to the crew on-board the spacecraft would, even if technically possible, overburden the crew. Enabling these same monitoring, tracking, and management capabilities on-board the spacecraft for a small crew to use will require significant automation and decision support software. Required capabilities to enable future human spaceflight to distant destinations include:

- Enable on-board crew management of vehicle consumables that are currently flight controller responsibilities.
- Increase the onboard capability to detect and respond to unexpected consumables-management related events and faults without dependence on ground.
- Reduce up-front and recurring software costs to produce flight-critical software.
- Provide more efficient and cost effective ground based operations through automation of consumables management processes, and up-front and recurring mission operations software costs.

Necessary capabilities include:

- Peer-to-peer mission operations planning.
- Mixed initiative planning systems.
- Elicitation of mission planning constraints and preferences.
- Planning system software integration.
- Space Vehicle System Automation.
- Autonomous rendezvous and docking software.
- Integrated discrete and continuous control software.
- Long-duration high-reliability autonomous system.

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- Power aware computing.
 - Power Systems Autonomous Control.
 - Vehicle Systems Automation.
 - Crew Situational Awareness of Vehicle Automation.
 - Contingency Management.

The emphasis of proposed efforts should focus primarily on software systems, but emphasize hardware and operating systems the proposed software will run on (e.g., processors, sensors), and proposals must demonstrate understanding of the consumables and dependent spacecraft systems that the software is intended to manage.

Proposals may reference existing fault management techniques, but this subtopic does not solicit development of fault management capability; proposers interested in developing these capabilities are referred to the relevant H6 topic area (H6.04). While Verification, Validation and Requirements of autonomous systems is also an important area, this subtopic does not solicit development of these technologies, proposers interested in developing these capabilities are referred to the relevant H6 topic area (H6.02).

Proposals must demonstrate mission operations cost reduction by use of standards, open source software, crew workload reduction, and/or decrease of software integration costs.

Proposals must demonstrate autonomy software cost reduction by use of standards, demonstration of capability especially on long-duration missions, system integration, and/or open source software.

Sub Topics:

Integrating ISHM with Flight Avionics Architectures for Cyber-Physical Space Systems Topic H6.04
This call for SBIR proposals is for technology development of integrated flight control systems for seamless integration of flight avionics with Integrated Systems Health Management (ISHM) systems. Flight avionics, with Integrated Modular Avionics (IMA) have well-defined Caution and Warning (CW) Fault Detection Isolation and Response (FDIR) alerting systems which can in real-time detect, isolate and respond to single failures at a time. For each CW failure, a predefined mapping to a CW response procedure is defined. In this way when real time conditions occur, response can be almost immediate. However this approach suffers when more than one failure is present. Under multiple CW failures more than one CW response procedure is active. Which of the predefined procedures should you execute? A procedure execution deadlock can occur. Currently when procedure deadlock occurs a number of questions need to be addressed by flight/ground:

- At what step in each procedure should you execute first?
- Should procedure steps be removed /added?
- Should procedure steps be interleaved between procedures?
- Should an entirely new procedure be synthesized?

The determination of how to proceed from procedure deadlock under multiple failure scenarios is critically dependent upon the correct multiple failure diagnosis of the situation. ISHM supports this determination due to the fact that ISHM can extend traditional CW FDIR systems to utilize a systems view of the spacecraft which leverages all (or most) of the available sensors and command talk-back information. Whereas traditional CW FDIR logic are often small fragments of logic and code which utilize subsets of the sensors, and in general have no knowledge and/or context of the other FDIR algorithms, a global view allows for a global response but also brings additional challenges of determining that the data from all the sensors is consistent. It is also important to recognize that failure signatures/ propagation/fault masking can be the result of not only hardware but also the interaction of the myriad control loops and procedural behavior that is induced by the flight avionics. Another key aspect is to perform interpretation of fault data in the context of mission operations, and subsequent fault recovery consistent with current mission goals. Additional challenges are also to devise methods to automatically develop the ISHM fault models from system descriptions such as the schematics, procedures, etc.

To date however seamless integration of ISHM systems with flight avionics CW FDIR systems has not matured to the level such that ISHM systems are trusted to support flight avionics systems in multiple failure high stress situations such as CW storms. Prior human-rated approaches have been proposed but not baselined for similar functional situations in both the Space Shuttle domain (Enhanced Caution and Warning (ECW) as part of the Cockpit Avionics Upgrade (CAU) program) as well as the International Space Station domain (ISS 24-hour autonomy mode). The challenge is to extend the lessons learned from these efforts to achieve program insertion. Such efforts will support both crewed as well as robotic missions, both near Earth as well as deep space missions.

Support will be enabled under a variety of conditions including where:

- Communication time with Earth is insufficient and/or delayed.
- Communication bandwidth is insufficient.
- The complexity of analysis is beyond human comprehension.
- The reliance on a skeleton crew requires additional computational support.

Seamless integration can be defined through many dimensions. Several dimensions of interest are:

- Allow the operator the ability to select between a palette of ISHM modules.
- Allow the operator the ability to turn on/off the ISHM module.
- Real time support for flight avionics. At least one scenario should be defined which shows the operation of the flight avionics with and without ISHM.

In order to demonstrate a technology solution, proposed work should include as baseline, a representative set of hypothetical CW events, a FDIR procedure response for each CW event, and one or more scenarios where, with multiple CW events across subsystems, the set of applicable FDIR procedures deadlocks. The proposed work should then demonstrate how the procedure deadlock is resolved through the proposed technology solution which integrates ISHM with the flight avionics.

Sub Topics:

Ablative Thermal Protection Systems Technologies Topic H7.01

The technologies described below support the goal of developing advancements in polymers for bonding and/or gap-filling ablative materials, instrumentation systems, and analytical modeling for the higher performance Ablative Thermal Protection Systems (TPS) materials currently in development for future Exploration missions. The ablative TPS materials currently in development include felt or woven material precursors impregnated with polymers and/or additives to improve ablation and insulative performance, along with the block form of Avcoat ablator for MPCV.

Two classes of materials are currently in development for planetary aerocapture and entry. The first class is for a rigid mid L/D (lift to drag ratio) shaped vehicle with requirements to survive a dual heating exposure, with the first at heat fluxes of 400-500 W/cm² (primarily convective) and integrated heat loads of up to 55 kJ/cm², and the second at heat fluxes of 100-200 W/cm² and integrated heat loads of up to 25 kJ/cm². These materials or material systems are likely dual layer in nature, either bonded or integrally manufactured. The second class is for a deployable aerodynamic decelerator, required to survive a single or dual heating exposure, with the first (or single) pulse at heat fluxes of 50-150 W/cm² (primarily convective) and integrated heat loads of 10 kJ/cm², and the second pulse at heat fluxes of 30-50 W/cm² and heat loads of 5 kJ/cm². These materials are either flexible or deployable.

Also currently in development is a third class of materials, for higher velocity (>11.5 km/s) Earth return, with requirements to survive heat fluxes of 1500-2500 W/cm², with radiation contributing up to 75% of that flux, and integrated heat loads from 75-150 kJ/cm². These materials are currently based upon 3-D woven architectures.

Technologies sought are:

- The development of a high char yield, flexible polymer with high strain-to-failure for used in bonding and/or gap fills for tiles of advanced TPS for extreme entry conditions. While high char yield (comparable to phenolic) and high strain-to-failure (>1%) are key requirements, additional goals would include some or all of the following: high decomposition temperatures (comparable to phenolic or higher); room temperature cure preferred; manufactured in air (inert environment not required); stable at ambient conditions (not overly sensitive to moisture in cured or un-cured state); compatible with cured epoxy, phenolic, and/or cyanate ester, extended out-time; and very low glass transition temperature to retain flexibility in space.
- Development of in-situ sensor systems including pressure sensors, heat flux sensors, surface recession diagnostics, and in-depth or structural interface thermal response measurement devices, for use on rigid and/or flexible ablative materials. Individual sensors can be proposed; however, instrumentation systems that include power, signal conditioning and data collection electronics are of particular interest. In-situ heat flux sensors and surface recession diagnostics tools are needed for flight systems to provide better traceability from the modeling and design tools to actual performance. The resultant data can lead to higher

fidelity design tools, improved risk quantification, decreased heat shield mass, and increases in direct payload. The pressure sensors should be accurate to 0.5%, heat flux sensors should be accurate within 20%, surface recession diagnostic sensors should be accurate within 10%, and any temperature sensors should be accurate within 5% of actual values. These should require minimum mass, power, volume, and cost; MEMS-based, wireless, optical, acoustic, ultrasonic, and other minimally-intrusive methods are possible examples. All proposed systems should utilize low-cost, modular electronics that handle both digital and analog sensor inputs and could readily be qualified for the space environments of interest. Typical sensor frequencies are 1-10 Hz, with up to 200 channels of collected data. Consideration should be given to those sensors that will be applicable to multiple material systems.

- Advances are sought in ablation modeling, including radiation, convection, gas surface interactions, pyrolysis, coking, and charring for low and mid-density fiber based (woven or felt) ablative materials. There is a specific need for improved models for low- and mid-density as well as multi-layered charring ablators (with different chemical composition in each layer). The modeling efforts should include consideration of the non-equilibrium states of the pyrolysis gases and the surface thermochemistry, as well as the potential to couple the resulting models to a computational fluid dynamics solver.
- Advances are sought in modeling mechanical properties of 3-D woven materials. Tools that analyze and predict the effects of different fibers on the warp and fill directional properties that could help in fiber selection and weave design are sought.

Starting Technology Readiness Levels (TRL) of 2-3 or higher are sought.

For all above technologies, research should be conducted to demonstrate technical feasibility during Phase I and show a path towards Phase II hardware/software demonstration with delivery of a demonstration unit or software package for NASA testing at the completion of the Phase II contract.

Phase I Deliverables:

- *Advanced Polymer* - Polymer system with demonstration of desired char yields, along with a test plan to be executed in Phase II demonstrating its usability and compatibility with various NASA provided composite materials
- *Sensors* - Sensor system design, including electronics, with specified measurement performance, mass, power, and volume. Proposed test approach for Phase II that will demonstrate system performance in a relevant environment (arcjet or combined structural/thermal test). Plans should consider testing at the largest scale and highest fidelity that the Phase II funding constraints allow.
- *Ablator and Mechanical Modeling* - Software and architecture development plan, along with a validation test plan, to be executed in Phase II. The Phase I report should provide evidence that the mathematical approaches will improve the state-of-the-art.

Phase II Deliverables:

- *Advanced Polymer* - Aerothermal and structural testing to validate usability and compatibility of the polymer with various NASA provided composite materials
- *Sensors* - Working engineering model of a sensor system with the proposed performance characteristics. Full report of system development, architecture, and measurement performance, including data from completed test proposed in Phase I (TRL 4-5). Potential commercialization opportunities and plans should also be identified and summarized.
- *Ablator and Mechanical Modeling* - Prototype (Beta) software and results from the validation test cases.

Sub Topics:

Diagnostic Tools for High Velocity Testing and Analysis Topic H7.02

The company will develop diagnostics for analyzing ground tests in high enthalpy, high velocity flows used to replicate vehicle entry, descent and landing conditions. Diagnostics developed will be tested in NASA's high enthalpy facilities, which include the Electric Arc Shock Tube (EAST), Arc Jets, Ballistic Range, Hypersonic Materials Environmental Test System (HyMETS), and 8' High Temperature Tunnel (HTT).

Development of improved diagnostics for hypervelocity flows allows us to better understand the composition and thermochemistry of our ground test facilities and are important for building ground-to-flight traceability.

Characterizations in facilities may be used to validate and/or calibrate predictive modeling tools which are used to design and margin EDL requirements. This will reduce uncertainty in future mission planning.

Diagnostics of interest include measurement of temperature, velocity, electron number density, and information regarding byproducts of pyrolysis and ablation in CO₂ or air environments. Due to variation in facility operations, the diagnostics are required to obtain reasonable signals in test times down to approximately 4 μ s with resolution on sub- μ s time scales. Secondary methods of interest would relate to the detection of the shock front edge arrival to high accuracy (< 0.1 μ s). Proposals should detail information such as detection limits, expected signal to noise ratios and data acquisition frequency. Data acquisition channels with up to 200 MHz sampling rate are available.

Deliverable will be in the form of a diagnostic hardware system that can be employed by NASA engineers/scientists in the test facility.

Sub Topics:

Thermal Energy Conversion Topic H8.01

NASA needs innovative technologies that convert thermal energy into electricity for space power generation on orbiting platforms, extraterrestrial surfaces, and space transportation vehicles. The thermal energy could be supplied by nuclear reactors, radioisotope heat sources, solar concentrators, chemical reactions, or as waste heat from other space systems. The focus of this subtopic is the energy conversion subsystem. Proposals are requested on thermal energy conversion approaches that offer high efficiency, low mass, high reliability, long life, and low cost. Candidate technologies include thermodynamic heat engines such as Stirling, Brayton, and Rankine as well as thermoelectric and thermionic devices. Ancillary components used to deliver heat (e.g., heat transport loops, heat pipes) to the energy conversion and reject waste heat (e.g., heat pipes, radiators) are also of interest.

The primary mission pull is providing electric power for human Mars surface missions that require kilowatts for remote science stations and rovers, or 10s of kilowatts for crew habitats and in-situ resource utilization plants. A secondary mission pull is providing electric power for Mars transportation vehicles that require 10s of kilowatts for crew life support and vehicle subsystems. The Mars missions may be preceded by human precursor missions to near earth objects, cis-lunar space, and the lunar surface during which the Mars technologies could be demonstrated. The anticipated heat source temperature ranges are 800 to 1300 K for nuclear, solar, and chemical sources and less than 400 to 500 K for waste heat. The expected operating lifetime ranges from several years to greater than 10 years.

The proposals should focus on energy conversion subsystems and components with a current technology readiness level of 2 or 3. The Phase I effort should include conceptual design with analytical or experimental proof-of-concept based on the expected operating environment and system interfaces (e.g., heat source, heat rejection).

The Phase II effort should include development of breadboards or prototypes that can be operated at the contractor's facility to demonstrate functionality in a laboratory environment. If the contractor testing is successful, the hardware will be considered for integration into NASA ground tests and flight experiments with representative system interfaces and relevant operating environments. Upon completion of successful integrated system tests at NASA, Phase III projects would be pursued to infuse the technologies into flight projects.

Sub Topics:

Solid Oxide Fuel Cells and Electrolyzers Topic H8.02

Technologies are sought that improve the durability, efficiency, and reliability of solid oxide systems. Of particular interest are those technologies that address challenges common to both fuel cells fed by oxygen and methane and electrolyzers fed by carbon dioxide and/or water. Hydrocarbon fuels of interest include methane and fuels generated by processing lunar and Mars soils. Primary solid oxide components and systems of interest are:

- Solid oxide fuel cell, stack, materials and system development for operation on propellant grade direct methane in designs scalable to 1 to 3 kW at maturity. Strong preference for high power density configurations.
- Cell and stack development capable of Mars atmosphere electrolysis should consider feasibility at 0.4 to 0.8 kg/hr O₂; scalable to 2 to 3.5 kg/hr O₂ at maturity. CO₂ electrolysis or co-electrolysis designs must have demonstrated capability of withstanding 15 psid in Phase I with pathway to up to 50 psid in Phase II.

Proposed technologies should demonstrate the following characteristics:

- The developed systems are expected to operate as specified after at least 20 thermal cycles during Phase I

and greater than 70 thermal cycles for Phase II. The heat up rate must be stated in the proposal.

- The developed systems are expected to operate with less than five percent degradation after at least 500 hours of steady state operation on propellant-grade methane and oxygen. Operation for 2500 hours and less than five percent degradation is expected of a mature system.
- Fuel reforming must be water neutral. Integrated systems that minimize components and complexity are favored.
- Minimal cooling is available for power applications. Some cooling in the final application will be provided by means of conduction through the stack to a radiator exposed to space or other company proposed solution that minimizes resources required.
- Minimal power (heating plus electrolysis) required for CO₂ electrolysis applications.
- Demonstrate electrolysis of the following input gases: 100% CO₂, Mars atmosphere mixture (95.7% CO₂, 2.7% N₂, 1.6% Ar), 100% water vapor, and 0.7 to 1.6:1 CO₂:H₂O mass ratio. A final test using pure CO₂ of 500 hours (or stopping at 40% voltage degradation) is required. Description of technical path to achieve up to 11,000 hrs for human missions is requested.

Sub Topics:

Advanced Photovoltaic Systems Topic H8.03

Advanced photovoltaic (PV) power generation and enabling power system technologies are sought with improvements in power system performance (conversion efficiency, mass, stowed volume, etc.), mission operation capability, and reliability for PV power systems supporting NASA human exploration missions. Power levels may cover ranges of 25-250 kWe to MegaWatt-class systems. Component technologies and array concept designs are sought that can address all or parts of the following: improved efficiency (>30% cell conversion efficiency at Air Mass zero), cost (50% reduction compared to state-of-the-art (SOA) through modularization, automated manufacturing, and reduced material costs), improved reliability, reduced mass (50% reduction compared to SOA designs), reduced stowed volume (designs capable of accommodating 100kW power levels within a single launch), high array bus voltages (> 250 V), and long-lived, reliable operation within the expected space environment (i.e., high radiation environments, both high and low temperature and light intensity extremes, planetary surface dust conditions, electric propulsion plume impingement erosion, and minimal arcing/degradation due to interactions with the space plasma). The technologies being sought should enable or enhance the ability to provide low-cost, low mass, and higher efficiency solar power systems that support high power Solar Electric Propulsion (SEP), high radiation/extreme environments, and Mars surface NASA missions. Areas of particular emphasis include:

- Advanced PV blanket and component technology with designs that support very high power and high voltage (> 250 V) applications.
- Array structures and blankets optimized for Mars surface gravity and maximum wind loading conditions while still preserving the low mass, low stowed volume, high reliability, and possible retraction/redeployment capabilities.
- Array/blanket designs capable of operating in high dust environments.
- PV blanket, component technology, and arrays optimized for extreme environment conditions (high radiation, low/high temperature extremes, exposure to SEP plume environments, etc.).
- PV module/component technologies that emphasize low mass and cost reduction (via materials, fabrication, and reduced testing).
- Improvements to solar cell efficiency consistent with low cost, high volume fabrication techniques that are applicable to HEOMD missions.
- Automated/modular fabrication methods for PV panels/modules on flexible blankets (includes cell laydown, interconnects, shielding and high voltage operation mitigation techniques).

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

Sub Topics:

Advanced Next Generation Batteries Topic H8.04

Breakthrough battery cell technologies that far exceed the specific energy and energy density or temperature performance of state-of-the-art lithium-based cell technologies are required to achieve far-term energy storage goals for human and robotic missions to the moon, Near Earth Orbit, Venus, and Mars. NASA is seeking innovative, advanced electrochemical cell and battery technologies that can aggressively address requirements for these future missions. Proposed chemistries and components must meet performance goals while simultaneously delivering a high level of safety. Components and systems that can enable one of the following sets of cell-level

performance goals (simultaneously, within the same system) are sought for specific missions:

- Extravehicular Activities. 450 Wh/kg, 1000-1500 Wh/L, >100 full cycles, >5 year calendar life, up to C/5 rate capability, operation at 0 to 40° C, retention of at least 90% of room temperature capacity during operation at 0°C, and tolerant to electrical and mechanical abuse (i.e., abuse does not result in fire or thermal runaway).
- Human Lunar and Mars Landers and Rovers. 300-375 Wh/kg, 1000-1500 Wh/L, up to 2000 full cycles, >10 year calendar life, >C/2 rate capability, operation at -60 to 30°C, and retention of at least 80% of room temperature capacity during operation at -60° C.
- Mars Ascent Vehicle - Quiescent capability. >250-300 Wh/kg, 1000-1500 Wh/L, few cycles, >15 year shelf life after activation and very limited cycling, and C-rate capability. Extremely high reliability and very low irreversible capacity loss required after 15 year quiescent period. Calendar life and reliable operation after quiescent period are paramount.

Offerors may propose to develop a single or multiple components, or a full cell system. Phase I proposals shall include quantitative analysis, scientific evidence, and technical rationale that clearly demonstrates how the proposed component or components will meet or contribute to the cell performance goals by the end of a Phase II effort. If a single component(s) is proposed rather than full cells, the Offeror shall also include in their justification of the proposed technology the performance that other advanced cell components must achieve in order to meet the claimed cell-level goals. Additionally, Phase I proposals shall describe the technical path that will be followed to achieve the claimed goals. Where possible, laboratory scale prototype hardware should be proposed as deliverables to NASA in Phase I.

Phase I Deliverables - Laboratory scale prototype hardware.

Phase II Deliverables - Incremental hardware deliverables and breadboard demonstration.

Sub Topics:

Long Range Optical Telecommunications Topic H9.01

The Long Range Optical Communications subtopic seeks innovative technologies in free-space optical communications for increased data volume returns from space missions in multiple domains [1]:

- >100 gigabit/s cis-lunar (Earth or lunar orbit to ground).
- >10 gigabit/s Earth-sun L1 and L2.
- >1 gigabit/s per A.U.-squared deep space.
- >100 megabit/s planetary lander to orbiter.

Proposals are sought in the following specific areas (TRL3 Phase I to mature to TRL4 to 5 in Phase II):

- *Low-mass large apertures for high-EIRP laser transceivers [2]* - 30 to 100 cm diameter laser communications telescopes massing less than 65 kg/square-meter with wavefront errors less than 1/25th of a wavelength at 1550 nm and a cumulative wavefront error and transmission loss of <3dB in the far field that can survive direct sun-pointing. Operational range of -20° C to +50° C without active thermal control is desired.
- *High-gigabit/s laser transmitter and receiver optical-electronic subsystems* - space qualifiable 1550 nm laser transmitter and receiver optoelectronic modulator, detection, and Forward-Error-Correction assemblies for data rates from 1 gigabits/s to >200 gigabits/s with power efficiencies better than 10W per gigabit/s and mass efficiencies better than 100 g per gigabit/s. Radiation tolerance better than 100 Krad is required. Technologies for efficient waveform modulation, detection, and synchronization and on-board low-gap-to-capacity forward-error-correction decoding are of interest; also of interest are hybrid RF-optical technologies. Integrated photonic circuit solutions are strongly desired. Highly efficient (>20% DC-to-optical, including support electronics) and space qualifiable (including resilience to photo-darkening) multi-watt Erbium Doped Fiber Amplifier with high gain bandwidth (> 30nm, 0.5 dB flatness) concepts will also be considered. Detailed description of approaches to achieve the stated efficiency is a must.
- *Waveform signal processing technologies [3]* - **CCSDS White Book, "High Photon Efficiency Optical Communications -- Coding & Modulation," March 2015,** <http://www.nasa.gov/directorates/heo/scan/engineering/datastandards/index.html> [16] - 100 Mb/s and

higher hardware/firmware implementation of the coding and synchronization layer of the proposed Consultative Committee for Space Data Systems (CCSDS) high-photon-efficiency optical signaling waveform, including transmitter and receiver functions. Supported features are to include CCSDS Transfer Frame ingestion and slicing; attached frame sync markers; CRC; serially concatenated convolutional coding with accumulate pulse position modulation (SCPPM), including a constraint length 3 convolutional code of rates 1/3, 1/2, and 2/3, code interleaver, accumulator, and PPM of orders 4, 8, ..., 256; randomizer; 1 s channel interleaver; codeblock sync marker repeat/spreader, and guard slot insertion.

- *Large aperture ground receiver subsystem technologies [4]* - Demonstrate innovative subsystem technologies for >10 m diameter ground receiver capable of operating to within 3 degrees of solar limb with a better than 10 microradian spot size (excluding atmospheric seeing contribution). Desire demonstration of low-cost primary mirror segment fabrication to meet a cost goal of less than \$35K per square meter and low-cost techniques for segment alignment and control, including daytime operations. Also desired are cryogenic optical filters for operation at 40K with noise equivalent bandwidths of a few nm in the 1550 nm spectral region, transmission losses < 0.25 dB, clear aperture >35 mm, and acceptance angle >40 milliradians with out-of-band rejection of >65 dB from 0.4 to 5 microns.
- *Superconducting magnesium diboride (MgB₂) thin films for ground receiver detectors [5]* - 5 to 20 nm thick MgB₂ films with critical temperature T_c > 35 K and critical current density J_c > 5 MA / cm² at 20 K The preferred substrates are SiC, Sapphire or MgO. The substrate size should be at least 4 in². There is also strong interest in MgB₂ films deposited on buffered Si wafers. The MgB₂ films should be passivated with SiO₂ or Au.
- *Cryogenic read-out electronics for large format superconducting nanowire arrays [6]* - 64 to 1024 channel DC coupled amplifier arrays for mounting onto a 40K cryocooler stage with 50 to 110 Ohm input impedance, <0.5 dB noise figure, DC to >4 GHz bandwidth, >40 dB gain, <1 dB compression with -47 dBm input, < 5 ps additive jitter, and less than 20 mW per channel power dissipation; strongly desired is an integrated per-channel leading-edge detect discriminator with LVDS-compatible output signal levels. Also of great interest is development of an read-out integrated circuit for direct bump-bonding to superconducting nanowire arrays operating in the 1 to 3 K range, with <0.5 dB noise figure, DC to >4 GHz bandwidth, >20 dB gain, <1 dB compression with -47 dBm input, < 5 ps additive jitter, and less than 1 mW per channel power dissipation.
- *Beaconless pointing subsystems for operations beyond 3 A.U.* - Point 20 to 100 cm lasercomm transmitter aperture to an Earth-based receiver with a 1-sigma accuracy of better than 100 nanoradians with an assumed integrated spacecraft micro-vibration angular disturbance of 150 micro-radians (<0.1 Hz to ~500 Hz) without requiring a dedicated laser beacon transmission from Earth; lowest subsystem mass and power is a primary selection factor.
- *Low mass / low power / cold survivable optical transceivers for planetary lander to orbiter links [7]* - Bi-directional optical terminals with data rates from >100 megabit/second at a nominal link range of 1000 km, with an individual terminal mass <5 kg and operational power < 25W, including a pointing system for at least full hemisphere coverage. Terminals shall be capable of operationally surviving >500 cycles of unpowered temperature cycling from -40° C to +40° C and a 100 krad TID. Discussion of acquisition and tracking con-ops and requirements is a must.

Research must convincingly prove technical feasibility (proof-of-concept) during Phase I, ideally with hardware deliverables that can be tested to validate performance claims, with a clear path to demonstrating and delivering functional hardware meeting all objectives and specifications in Phase II.

References:

- [1] - (<http://ssed.gsfc.nasa.gov/IPM/PDF/1010.pdf> [17]).
- [2] - W. Farr, W, et al. "Overview and Design of the DOT Flight Laser Transceiver," IPN Progress Report 42-185, (2011).
- [3] - CCSDS White Book, "High Photon Efficiency Optical Communications -- Coding & Modulation," March 2015.
- [4] - Birnbaum, K., et al., "DOT Ground Laser Receiver: Overview and Major Trades," IPN Progress Report 42-182, (2010).
- [5] - Wolak, M. A. et al., IEEE Trans. Appl. Supercond. 25, 1-5 (2015).
- [6] - Dauler, E., et al., "Review of Superconducting Nanowire Single-Photon Detector System Design Options and Demonstrated Performance." Opt. Eng 53 (2014).

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- [7] - Biswas, A., et al., "Future Planetary Optical Access Links", 2011 International Conference on Space Optical Systems and Applications.

Sub Topics:

Advanced Space Communication Systems Topic H9.02

NASA's future systems require increased levels of adaptive, cognitive, and autonomous system technologies to improve mission communication capabilities for science and exploration. Goals of this capability are to improve communications efficiency, mitigate impairments (e.g., scintillation, interference), and reduce operations complexity and costs through intelligent and autonomous communications and data handling. These goals are further described in the TA05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems Roadmap, Sections 5.1, 5.2, 5.3 and 5.5.

Over the past 10 years software defined radio platforms and their applications have emerged and demonstrated the applicability of reconfigurable platforms and applications to space missions. This solicitation seeks advancements in cognitive and automation communication systems, networks, waveforms and components. While there are a number of acceptable definitions of cognitive systems/radio, for simplicity, a cognitive system should sense, detect, adapt, and learn from its environment to improve the communications capabilities and situation for the mission. Cognitive systems naturally lead to advanced multi-function RF platforms; platforms that serve more than one user or function and are reconfigurable, on-demand, either autonomously or by the user for arbitrary applications. NASA can leverage these systems, techniques, hardware, algorithms and waveforms for use in space applications to maximize science data return, enable substantial efficiencies, reduce operations costs, or adapt to unplanned scenarios. While much interest in cognitive radio in other domains focuses on dynamic spectrum access, this subtopic is primarily interested in much broader ways to apply cognition and automation. Areas of interest to develop and/or demonstrate are as follows:

- *System wide intelligence* – While much of the current research often describes negotiations and improvements between two radio nodes, the subtopic seeks solutions to understand system wide aspects and impacts of this new technology. Areas of interest include (but not limited to) -cognitive architectures considering mission spacecraft, relay satellites, other user spacecraft, and ground stations, system wide effects to decisions made by one or more communication/navigation elements, handling unexpected or undesired decisions, self-configuring networks, coordination among multiple spacecraft nodes in a multiple access scheme, cooperation and planning among networked space elements to efficiently and securely move data through the system, and automated link planning and scheduling to optimize data throughput and reduce operations costs. Capabilities may include interference mitigation, maximizing data throughput and efficiency, and intelligent network routing (best route) and disruptive tolerant networking over cognitive links. The focus here is on a cognitive understanding of, and adaptation to, temporally or spatially non-contiguous communications paths.
- *Advanced waveform development in the digital domain. Specifically* - The foundation has been laid through prior NASA investments in the area of generating the infrastructure for software-based algorithms. These investments led to the development and demonstration of the Space Telecommunication Radio System (STRS) architectural standard for software-defined radios. STRS based advanced backend platforms generate (for transmission) or process (from reception) the appropriate waveform at a common Intermediate Frequency (IF) for transmission to, or reception from, an appropriate RF front-end. In addition, the backend processor is reconfigurable, by the user, for a specific application at a given time (radar vs. short range communications link, etc.).
- *Flexible and adaptive hardware systems* - Signal processing platforms, wideband and multi-band adaptive front ends for RF (particularly at S-, X-, and Ka-bands) or optical communications, and other intelligent electronics that advance or enable flexible, cognitive, and intelligent operations. The development and demonstration of advanced RF Front-Ends that cover NASA RF bands of interest; specifically S-Band, X-Band and/or Ka-Band. These RF front-ends may support time-multiplexed waveforms such as radar or (digitized) half-duplex voice transmissions as well as frequency duplexed waveforms such as full-duplex two-way navigation and data communications. Specifically, these front-ends are expected to leverage state-of-the-art RF materials (e.g., GaN, SiC, CMOS, etc.), packaging (e.g., MIC, SMT, etc.), device (e.g., MMIC, MEMS, etc.) and component techniques to minimize mass, volume and energy resource usage while supporting multi-functionality
- *Autonomous Ka-band and/or optical communications antenna pointing* - Future mission spacecraft in low Earth orbit may need to access both shared relay satellites in geosynchronous orbit (GEO) and direct to ground stations via Ka-band (25.5-27.0 GHz) and/or optical (1550 nm) communications for high capacity

data return. To maximize the use of this capacity, user spacecraft will need to point autonomously and communicate on a coordinated, non-interfering basis along with other spacecraft using these same space- and ground-based assets. Included here are electronically steered antennas, especially at Ka-Band. Applications include large, high-performance electronically-steered antennas required for a dedicated communications relay spacecraft with multiple simultaneous connections, advanced multifunction antennas to support science missions that utilize a multifunction antenna to both communicate and conduct science, and small, lightweight antennas for communications only that provide moderate gain without the use of mechanical steering. Antennas that are reconfigurable in frequency, polarization, and radiation pattern that reduce the number of antennas needed to meet the communication requirements of NASA missions are desired.

For all technologies, Phase I will emphasize research aspects for technical feasibility, clear and achievable benefits (e.g., 2x-5x increase in throughput, 25-50% reduction in bandwidth, improved quality of service or efficiency, reduction in operations staff or costs) and show a path towards Phase II hardware/software development with delivery of hardware or software product for NASA. Proposals should demonstrate and explain how and where cognitive and automation technologies could be applied to NASA space systems and be discussed in the proposal.

Phase I Deliverables - Feasibility study and concept of operations of the research topic, including simulations and measurements, proving the proposed approach to develop a given product (TRL 3-4). Early development and delivery of the simulation and prototype software and platform(s) to NASA. Plan for further development and verification of specific capabilities or products to be performed at the end of Phase II.

Phase II Deliverables - Working engineering model of proposed product/platform or software delivery, along with documentation of development, capabilities, and measurements (showing specific improvement metrics). User's guide and other documents and tools as necessary for NASA to recreate, modify, and use the cognitive software capability or hardware component(s). Opportunities and plans should also be identified and summarized for potential commercialization or NASA infusion.

Software applications and platform/infrastructure deliverables for SDR platforms shall be compliant with the NASA standard for software defined radios, the Space Telecommunications Radio System (STRS), NASA-STD-4009 and NASA-HNBK-4009, found at: (<https://standards.nasa.gov/documents/detail/3315910> [18]).

Sub Topics:

Flight Dynamics and Navigation Systems Topic H9.03

NASA is investing in the advancement of software algorithm/stools, systems, and devices to enhance and extend its capabilities for providing position, attitude, and velocity estimates of its spacecraft as well as improve navigation, guidance and control functions to these same spacecraft. Efforts must demonstrate significant risk or cost reduction, significant performance benefit, or enabling capability.

Proposals can support mission engineering activities at any stage of development from the concept-phase/pre-formulation through operations and disposal. Applications in low Earth orbit, lunar, and deep space are in scope for this sub-topic. Proposals that could lead to the replacement of the Goddard Trajectory Determination System (GTDS), or leverage state-of-the-art capabilities already developed by NASA such as the General Mission Analysis Tool (<http://sourceforge.net/projects/gmat/> [19]), GPS-Inferred Positioning System and Orbit Analysis Simulation Software, (<http://gipsy.jpl.nasa.gov/orms/goa/> [20]), Optimal Trajectories by Implicit Simulation (<http://otis.grc.nasa.gov/> [21]) are especially encouraged. Proposers who contemplate licensing NASA technologies are highly encouraged to coordinate with the appropriate NASA technology transfer offices prior to submission of their proposals.

In particular, this solicitation is primarily focused on NASA's needs in the following focused areas:

Guidance and Control

- Advanced optimal control methodologies for chemical and electric space flight guidance and control systems.
- Numerical methods and solvers for robust targeting, and non-linear, constrained optimization problems.
- Applications of advanced dynamical theories to space mission design and analysis, in the context of unstable orbital trajectories in the vicinity of small bodies and libration points.
- Advanced guidance and control techniques that support autonomous, on-board applications.

Navigation

- Applications of cutting-edge estimation techniques to spaceflight navigation problems.
- Applications of estimation techniques that have an expanded state vector (beyond position, velocity, and/or attitude components) or that employ data fusion.
- Advanced autonomous navigation techniques including devices and systems that support significant advances in independence from Earth supervision while minimizing spacecraft burden by requiring low power and minimal mass and volume.
- Advanced time and frequency keeping and dissemination

Software

- Addition of novel guidance, navigation, and control improvements to existing NASA software that is either freely available via NASA Open Source Agreements, or that is licensed by the proposer.
- Interface improvements, tool modularization, APIs, workflow improvements, and cross platform interfaces for software that is either freely available via NASA Open Source Agreements, or that is licensed by the proposer that provide significant cost or performance benefits

Phase I research should be conducted to demonstrate technical feasibility, with preliminary software being delivered for NASA testing, as well as show a plan towards Phase II integration. For proposals that include hardware development, delivery of a prototype under the Phase I contract is preferred, but not necessary.

With the exception listed below for heritage software modifications, Phase II new technology development efforts shall deliver components at the TRL 5-6 level with mature algorithms and software components complete and preliminary integration and testing in an operational environment. For efforts that extend or improve existing NASA software tools, the TRL of the deliverable shall be consistent with the TRL of the heritage software. Note, for some existing software systems (see list above) this requires delivery at TRL 8. Final software, test plans, test results, and documentation shall be delivered to NASA.

Sub Topics:

Improved Test and Launch Operations via Interface Design Topic H10.01

This subtopic seeks to improve ground and surface processing in both the operational and test environments through improved interface design concepts. A substantial portion of pre-launch processing involves the integration of spacecraft assemblies to each other or to the ground/surface systems that supply the commodities, power or data. Each assembly requires an interface that connects it to the adjacent hardware which includes flight critical seals or connectors and other components. The impact of these interface-driven tasks are of particular concern for surface systems where the additional work must be accomplished by crew performing Extra-Vehicular Activities (EVAs) or by purpose-built robotic systems.

The interfaces between payloads, boosters and ground/surface support equipment have historically been drivers of numerous delays and unplanned work prior to launch. The developmental impact of interface design and requirements development includes extensive design labor and validation for any new integrated launch system. Finally, the historical trend of having unique interface types for different launch systems has hampered recent efforts to establish a multi-user capability for existing launch infrastructure.

Development and adoption of improved, standardized interfaces holds the potential of reducing the cost and complexity of future space systems and their related design and implementation, which can increase the funding available for flight hardware and drive down the cost of government and commercial access to space.

Standardization of interfaces used during testing or launch processing also provides eventual benefits to autonomous servicing, a key space technology for future missions. Future in-space and surface servicing of multiple spacecraft/user types such as satellites becomes more feasible if a common interface approach can be developed and widely adopted.

Technologies sought for interface design are grouped in the following two focus areas:

Physical Interfaces

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- Modular architectures of expandable surface systems that minimize the adverse impact of interface connections.
 - Interfaces suitable for modular, reliable, cryogenic propellant liquefaction architectures that enable incremental system approaches for increasing capacities as needed.
 - Dust-tolerant interface approaches that drive highly reliable and/or autonomous connections.
 - Development of earth based analog test hardware to test and validate these surface system interface concepts (module equipment interfaces and/or surface to vehicle interfaces).
 - Connector technologies including ports, disconnects or couplers that enable standardization across the industry for the transfer of cryogenic and storable propellants or other servicing fluids, power, and/or data for Governmental and Commercial launch providers and/or future surface system analog testing.
 - Interface concepts that simplify or standardize future Interface Requirements Documents (IRDs) or enable increased use of off-the-shelf hardware for future flight and exploration support systems.
 - Solutions that promote standardization of key payload to launch vehicle and subsystem interface standards to reduce the cost associated with analysis, design, configure, integration, and preparation of space systems for launch and reusability through standard servicing interfaces.
 - Novel concepts for adaptation of common interface architectures from relevant industries and the analysis and development required to adapt them to space and exploration architectures. Adaptation should include providing the relevant certification planning required for acceptance by government and industry.

Software/Data Interfaces

- Concepts for embedded intelligence within interfaces that include software attributes to enhance the usage of interface data for tasks such as self-testing, diagnostics, configuration verification and/or management of the interface.
- Concepts for the use of industry standards and/or open source software to reduce or eliminate the need for dedicated interfaces by more efficiently managing system configurations. Software addressable interfaces conducting fault isolation and recovery, and decrease of software integration costs.
- Interface concepts that simplify or standardize future Interface Requirements Documents (IRDs) or enable increased use of off-the-shelf hardware for future flight and exploration support systems.

For all above technologies, research should be conducted to demonstrate technical feasibility during Phase I and show a path toward Phase II demonstration, and delivering a demonstration package for NASA testing at the completion of the Phase II contract.

Phase I Deliverables - Research to identify and evaluate candidate technology applications, demonstrate the technical feasibility, and show a path towards a demonstration. Concept methodology should include the path for adaptation of the technology, infusion strategies (including risk trades), and business model. Identify improvements over the current state of the art for both operations and systems development and the feasibility of the approach in a multi-customer environment. Bench or lab-level demonstrations are desirable.

Phase II Deliverables - Emphasis should be placed on developing and demonstrating the technology under simulated operational conditions with analog earth-based systems including dynamic events such as commodity loading, disconnect or engine testing. The proposal shall outline a path showing how the technology could be developed into or applied to mission-worthy systems. The contract should deliver demonstration hardware for functional and environmental testing at the completion of the Phase II contract. The technology concept at the end of Phase II should be at a TRL of 5 or higher.

Sub Topics:

Advanced Propulsion Systems Ground Test Technology Topic H10.02

Rocket propulsion development is enabled by rigorous ground testing in order to mitigate the propulsion system risks that are inherent in spaceflight. This is true for virtually all propulsive devices of a space vehicle including liquid and solid rocket propulsion, chemical and non-chemical propulsion, boost stage and in-space propulsion and so forth. It involves a combination of component-level and engine-level testing to demonstrate the propulsion devices were designed to meet the specified requirements for a specified operational envelope and over robust margins and shown to be sufficiently reliable, prior to its first flight.

This topic area seeks to develop advanced ground test technology components and system level ground test

systems that enhance Chemical and Advanced Propulsion technology development and certification. The goal is to advance propulsion ground test technologies to enhance environment simulation, minimize test program time, cost and risk and meet existing environmental and safety regulations. It is focused on near-term products that augment and enhance proven, state-of-the-art propulsion test facilities.

In particular, technology needs includes producing large quantities of hot hydrogen, and develop robust materials, advanced instruments and monitoring systems capable of operating in extreme temperature and harsh environments.

This subtopic seeks innovative technologies in the following areas:

- Efficient generation of high temperature (>2500°R), high flowrate (<60 lb/sec) hydrogen.
- Devices for measurement of pressure, temperature, strain and radiation in a high temperature and/or harsh environment.
- Development of innovative rocket test facility components (e.g., valves, flowmeters, actuators, tanks, etc.) for ultra-high pressure (>8000 psi), high flow rate (>100 lbfm/sec) and cryogenic environments.
- Robust and reliable component designs which are oxygen compatible and can operate efficiently in high vibro-acoustic, environments.
- Advanced materials to resist high-temperature (<4400° F), hydrogen embrittlement and harsh environments.

- Tools using computational methods to accurately model and predict system performance are required that integrate simple interfaces with detailed design and/or analysis software. SSC is interested in improving capabilities and methods to accurately predict and model the transient fluid structure interaction between cryogenic fluids and immersed components to predict the dynamic loads, frequency response of facilities.
- Improved capabilities to predict and model the behavior of components (valves, check valves, chokes, etc.) during the facility design process are needed. This capability is required for modeling components in high pressure (to 12,000 psi), with flow rates up to several thousand lb/sec, in cryogenic environments and must address two-phase flows. Challenges include: accurate, efficient, thermodynamic state models; cavitation models for propellant tanks, valve flows, and run lines; reduction in solution time; improved stability; acoustic interactions; fluid-structure interactions in internal flows.
- Improved capability for monitoring environmental conditions for ground and launch facilities supporting test and launch operations. Instrumentation should provide a remote sensing capability to measure atmospheric data with respect to altitude from 300 meters to at least 10 km. The technology must have a vertical measurement resolution of 150 m or smaller and a full vertical profile multiple times an hour in both cloudy and clear environments.
- Improved capability for cryogenic leak and fire detection to support ground test or launch operations.
- Non-intrusive instrumentation for measuring rocket engine plume velocities including a volumetric assessment of plume extent, volume and turbulence.

For all above technologies, research should be conducted to demonstrate technical feasibility during Phase I and show a path towards Phase II hardware/software demonstration with delivery of a demonstration unit or software package for NASA testing at the completion of the Phase II contract.

Sub Topics:

Radiation Shielding Technologies - Transport Codes Topic H11.01

Advanced radiation shielding technologies are needed to protect humans from the hazards of space radiation during future NASA missions. All space radiation environments in which humans may travel in the foreseeable future are considered, including the Moon, Mars, asteroids, geosynchronous orbit (GEO), and low Earth orbit (LEO). All particulate radiations are considered, particularly galactic cosmic radiation (GCR), solar energetic particles (SEP), and secondary neutrons. For this 2016 solicitation, the special interest is in advanced space radiation transport codes. Mid-TRL (3 to 5) technologies of specific interest include, but are not limited to, the following:

- Computational tools that enable the evaluation of the transport of space radiation through highly complex vehicle architectures as represented in detailed computer-aided design (CAD) models are needed. A number of codes and computational packages currently exist that can be used to assess the transport of the diverse particle and energy spectra of the space environment through shielding materials. However,

using these transport codes on geometry represented by complex CAD models requires considerable human intervention. Computational tools that automate vehicle ray tracing for use with the NASA-developed HZETRN space radiation transport code are needed to enable vehicle dose mapping and a larger vehicle optimization capability.

- Tools that enable the use of Monte-Carlo transport codes with native CAD geometry could also make it possible to perform radiation analyses for space architectures using multiple transport codes.
- Phase I deliverables are alpha-tested computer codes.
- Phase II deliverables are beta-tested computer codes.

For additional information, please see the following link:

(http://www.nasa.gov/pdf/500436main_TA06-ID_rev6a_NRC_wTASR.pdf [22]).

Sub Topics:

Task Analysis Visualization and Data Management Tool Topic H12.01

Task analysis (TA) is a method within the Human-Centered Design process that represents tasks as sequences or concurring steps and actions that are necessary to accomplish goals. It is used to understand and document the sequence of tasks, steps, and the relationship among these in order to indicate how the user or users performing them. Furthermore, most major NASA programs, such as Orion, call for TA in the verification process. The output of the TA is a Master Task List (MTL) that feeds into design, models, and databases. Designers use the MTL to design systems, subsystems, and components to accommodate crew tasks. Operations personnel use the MTL for operations concepts and crew procedures development. This solicitation invites proposals intending to develop methods and technologies to manage and visualize TA information.

Although recognized as a critical function in design, task analysis is often erroneously overlooked until final design phases when hardware, system, and software designs are too costly to change. It is essential that task analysis be conducted as early in the design process as possible. Task analysis should be conducted iteratively and should be frequently evaluated throughout the design and development process to allow for proper verification of crew task and system design. Furthermore, task analysis should be performed to identify the "critical" tasks, i.e., those tasks that are necessary to successfully accomplish operations and mission objectives. Function allocation is also an important part of task analysis: deciding whether a particular function will be accomplished by the human or the system, or by some combination of humans and systems.

Task analyses for long-duration missions will result in a complex structure of tasks and sub-tasks. Master task lists can contain thousands of tasks that have complex temporal and sequential relations among them that need to be visualized. In order to use the results of a complex task analysis efficiently, there is a need for a robust visualization tool that helps with overviewing, sorting, and interpreting the results. Available commercial tools are not able to deal with the complexity of long-duration mission task analysis data due to the following limitations: cannot easily show simultaneous tasks and tasks performed by multiple operators, difficult to track changes, difficult to search for tasks, few/no summary options, and few/no file export options.

The tool should improve task design and system design by relating tasks and sequences of tasks in an efficient way, making the data more usable and ultimately improving overall design.

Phase I Deliverables - Conceptual prototype of a task analysis data management and visualization tool and final report detailing the conceptual prototype and software development plan including feature and display requirements.

Phase II Deliverables - Completed, usability-tested software tool along with the source code, user's guide, and final report on the development and testing of the tool.

Sub Topics:

Passive Vital Sign Monitoring Topic H12.02

Human exploration missions beyond low earth orbit (LEO) require physiologic monitoring of the crew. These highly mass, volume, and power constrained missions require significant leveraging of resources by all vehicle subsystems. To date, research and development resources involving physiologic monitoring have been allocated to crew worn devices to measure these physiologic parameters. NASA recognizes that there are numerous worn devices that provide monitoring, but all of these devices still require mass, volume, power, and crew time to operate. The exploration vehicle, however, will already provide a variety of technologies that could potentially be used to extrapolate human physiologic data in a more passive and continuous manner that does not require additional mass, volume, power, and crew time to operate. Examples of technology embedded within the vehicle include, but are not limited to, high quality video and audio, wireless networks, radio frequency identification, and

other electromagnetic (EM) sources/detectors.

NASA requires new technologies that will exploit vehicle infrastructure to passively and continuously monitor the crew's physiologic parameters. NASA is amenable to improving existing vehicle technologies to extract crew data, but also for incorporating novel and innovative technologies that could be added to the vehicle or the crew. Examples of technology developments can include, but are not limited to, heart and respiration rate detection via HD video, temperature detection via infrared camera, or circadian rhythm phase detection via automated urine analysis. Some of the parameters that would be desirable for monitoring include:

- Heart Rate.
- Oxygen Saturation Level.
- Respiration Rate.
- Blood Pressure (diastolic/systolic).
- Core and/or Skin Temperature.
- Urinary 6-sulfatoxymelatonin.

A list of anticipated medical conditions that would require monitoring can be found on the Exploration Medical Condition list (EMCL), which may be found on NASA's Human Research Wiki:

(<https://humanresearchwiki.jsc.nasa.gov/index.php?title=ExMC> [24]).

Phase I Deliverables - Conceptual prototype of a monitoring device/algorithm and final report detailing the conceptual prototype and hardware/software development plans.

Phase II Deliverables - Completed monitoring device/algorithm, and final report on the development, testing, and validation of the tool.

Sub Topics:

Novel Imaging Technologies for Space Medicine Topic H12.03

NASA is seeking novel medical imaging techniques in two areas: software-based ultrasound and portable x-ray.

Software-Based Ultrasound

Ultrasound has been, and will continue to be for the foreseeable future, NASA's workhorse modality for internal imaging in space. Ultrasound's smaller footprint, lower power consumption and lower emissions across the electromagnetic spectrum make it particularly well-suited for space medicine. Ultrasound also provides additional medically useful capabilities outside the realm of imaging, such as quantitative ultrasound diagnostic techniques, and therapeutic techniques that utilize the energy in the ultrasound signal itself. NASA's commitment to ultrasound has led to the development of the Flexible Ultrasound System (FUS), which is a software-based, state of the art clinical scanner specially adapted to support the development of novel research in ultrasound. The FUS may be thought of as an "ultrasound development platform". It features software-based beam forming, scanning and receiving on up to 192 channels, dual-probe operation, high power support, and full access to the radio frequency (RF) data. Developers using the FUS may implement their algorithms and techniques in an Application Programming Interface (API) that supports both Matlab and C++.

The ground-based demonstration of the FUS will begin in April of 2016 and will potentially last for several years. NASA requires novel ultrasound-based diagnostic and therapeutic techniques for diagnosing and/or treating conditions on the Exploration Medical Condition List (EMCL), which can be found on NASA's Human Research Wiki at – (<https://humanresearchwiki.jsc.nasa.gov/index.php?title=ExMC> [24]).

NASA is amenable to improving existing uses of ultrasound for both diagnostic and therapeutic purposes, but also for completely novel and innovative uses of ultrasound for diagnosis or treatment of any conditions on the EMCL. These novel techniques, which can include both hardware and software, should be developed with integration onto the FUS in mind, either by direct development on a system loaned to the developer by NASA or by porting the application from another system to the FUS at a later stage in the grant. Current examples of FUS integration include novel probe and algorithm development to quantify bone density and efforts to move/break up renal stones.

Portable X-Ray

Although ultrasound remains NASA's workhorse modality for internal imaging of body parts on spaceflight missions, there are gaps in ultrasound's ability to diagnose certain medical conditions that might arise during spaceflight, particularly to deep space destinations. Ultrasound is not as well suited to diagnosing dental conditions and certain musculoskeletal (MSK) injuries as traditional radiographic (x-ray) techniques. A set of limiting factors have precluded the use of x-ray devices on-orbit. These limitations include the relatively higher volumetric footprint, higher power requirements and higher electromagnetic (EM) emissions (particularly ionizing radiation, both in terms of dosage delivered to the crew and stray emissions) of x-ray devices and other imaging devices.

NASA needs new technology developments to overcome these limitations and ensure the diagnosis of dental and MSK conditions are more compatible with human spaceflight. NASA is amenable to improvements in existing x-ray devices and/or other novel and innovative imaging technologies. Example technology developments include, but are not limited to, those leading to more efficient x-ray sources, more sensitive detector technologies, improving image quality, reducing delivered EM dosage, and expanding the usefulness of handheld portable x-ray devices and other imaging devices to address dental and MSK conditions. A complete list of dental and MSK conditions can be found on the Exploration Medical Condition list (EMCL), which may be found on NASA's Human Research Wiki -

(<https://humanresearchwiki.jsc.nasa.gov/index.php?title=ExMC> [24]).

Proposals should address one of the two aforementioned technology areas.

The expected deliverables for Phase I for the software-based ultrasound are:

- Conceptual prototype of a novel device/algorithm.
- Final report detailing the conceptual prototype and hardware/software development plans.

The expected deliverables for Phase II are:

- Completed FUS device/algorithm.
- Integrated testing on FUS platform.
- Final report on the development, testing, and validation of the tool.

The expected deliverables for Phase I for the portable x-ray are:

- Conceptual prototype of an imaging device.
- Final report detailing the conceptual prototype and hardware/software development plans.

The expected deliverables for Phase II are:

- Completed imaging device.
- Final report on the development and testing of the tool.

Sub Topics:

NDE Simulation and Analysis Topic H13.01

Technologies sought under this SBIR include near real-time large scale nondestructive evaluation (NDE) and structural health monitoring (SHM) simulations and automated data reduction/analysis methods for large data sets. Simulation techniques will seek to expand NASA's use of physics based models to predict inspection coverage for complex aerospace components and structures. Analysis techniques should include optimized automated reduction of NDE/SHM data for enhanced interpretation appropriate for detection/characterization of critical flaws in space flight structures and components. Space flight structures will include light weight structural materials such as composites and thin metals. Future purposes will include application to long duration space vehicles, as well as validation of SHM systems.

Techniques sought include advanced material-energy interaction simulation in high-strength lightweight material

systems and include energy interaction with realistic damage types in complex 3D component geometries (such as bonded/built-up structures). Primary material systems can include metals but it is highly desirable to target composite structures. NDE/SHM techniques for simulation can include ultrasonic, Laser, Micro-wave, Terahertz, Infra-red, X-ray, X-ray Computed Tomography, Fiber Optic, backscatter X-Ray and eddy current. It is assumed that all systems will have high resolution high volume data. Modeling efforts should be physics based and account for changes in energy interaction due to material aging and induced damage such as micrometeoroid impact. Examples of damage states of interest include delamination, microcracking, porosity, fiber breakage. Techniques sought for data reduction/interpretation will yield automated and accurate results to improve quantitative data interpretation to reduce large amounts of NDE/SHM data into a meaningful characterization of the structure. Realistic computational methods for validating SHM systems are also desirable. It is advantageous to use co-processor configurations for simulation and data reduction. Co-Processor configurations can include graphics processing units (GPU), system on a chip (SOC), field-programmable gate array (FPGA) and Intel's Many Integrated Core (MIC) Architecture. Combined simulation and data reduction/interpretation techniques should demonstrate ability to guide the development of optimized NDE/SHM techniques, lead to improved inspection coverage predictions, and yield quantitative data interpretation for damage characterization.

Phase I Deliverables - Feasibility study, including demonstration simulations and data interpretation algorithms, proving the proposed approach to develop a given product (TRL 2-4). Plan for Phase II including proposed verification methods.

Phase II Deliverables - Software of proposed product, along with full report of development and test results, including verification methods (TRL 5-6). Opportunities and plans should also be identified and summarized for potential commercialization.

Sub Topics:

NDE Sensors Topic H13.02

Technologies sought under this SBIR program can be defined as advanced sensors, sensor systems, sensor techniques or software that enhance or expand NASA's current sensor capability. It is desirable but not necessary to target structural components of space flight hardware. Examples of space flight hardware will include light weight structural materials including composites and thin metals.

Technologies sought include modular, smart, advanced Nondestructive Evaluation (NDE) sensor systems and associated capture and analysis software. It is advantageous for techniques to include the development on quantum, meta- and nano sensor technologies for deployment. Technologies enabling the ability to perform inspections on large complex structures will be encouraged. Technologies should provide reliable assessments of the location and extent of damage. Methods are desired to perform inspections in areas with difficult access in pressurized habitable compartments and external environments for flight hardware. Many applications require the ability to see through assembled conductive and/or thermal insulating materials without contacting the surface. Techniques that can dynamically and accurately determine position and orientation of the NDE sensor are needed to automatically register NDE results to precise locations on the structure. Advanced processing and displays are needed to reduce the complexity of operations for astronaut crews who need to make important assessments quickly. NDE inspection sensors are needed for potential use on free-flying inspection platforms. Integration of wireless systems with NDE may be of significant utility. It is strongly encouraged to provide explanation of how proposed techniques and sensors will be applied to a complex structure. Examples of structural components include but are not limited to multi-wall pressure vessels, batteries, tile, thermal blankets, micrometeoroid shielding, International Space Station (ISS) Radiators or aerospace structural components.

Phase I Deliverables - Lab prototype, feasibility study or software package including applicable data or observation of a measurable phenomenon on which the prototype will be built. Inclusion of a proposed approach to develop a given methodology to Technology Readiness Level (TRL) of 2-4. All Phase I's will include minimum of short description for Phase II prototype. It will be highly favorable to include description of how the Phase II prototype or methodology will be applied to structures.

Phase II Deliverables - Working prototype or software of proposed product, along with full report of development and test results. Prototype or software of proposed product should be of Technology Readiness Level (TRL 5-6). Proposal should include plan of how to apply prototype or software on applicable structure or material system. Opportunities and plans should also be identified and summarized for potential commercialization.

Sub Topics:

International Space Station (ISS) Utilization Topic H14.01

NASA continues to invest in the near- and mid-term development of highly-desirable systems and technologies that

provide innovative ways to leverage existing ISS facilities for new scientific payloads and to provide on orbit analysis to enhance capabilities. Additionally, NASA is supporting commercial science, engineering, and technology to provide low earth orbit commercial opportunities utilizing the ISS. Utilization of the ISS is limited by available up-mass, down-mass, and crew time as well as by the capabilities of the interfaces and hardware already developed and in use. Innovative interfaces between existing hardware and systems, which are common to ground research, could facilitate both increased and faster payload development and subsequent utilization. Technologies that are portable and that can be matured rapidly for flight demonstration on the International Space Station are of particular interest.

Desired capabilities that will continue to enhance improvements to existing ISS research and support hardware, with the potential of reducing crew time needs, and those that promote commercial enterprise ventures include but are not limited to, the below examples:

- Providing additional on-orbit analytical tools. Development of instruments for on-orbit analysis of plants, cells, small mammals and model organisms including *Drosophila*, *C. elegans*, and yeast. Instruments to support studies of bone and muscle loss, multi-generational species studies and cell and plant tissue are desired. Providing flight qualified hardware that is similar to commonly used tools in biological and material science laboratories could allow for an increased capacity of on-orbit analysis thereby reducing the number of samples which must be returned to Earth.
- Instruments that can be used as infrared inspection tools for locating and diagnosing material defects, leaks of fluids and gases, and abnormal heating or electrical circuits. The technology should be suitable for hand-held portable use. Battery powered wireless operation is desirable. Specific issues to be addressed include: pitting from micro-meteoroid impacts, stress fractures, leaking of cooling gases and liquids and detection of abnormal hot spots in power electronics and circuit boards.
- Innovative technologies and flight projects that can enable significant terrestrial applications from microgravity development or in-space manufacturing and lead to private sector and/or government agency product development within a number of discipline areas, including biotechnology, medical applications, material sciences, electronics, and pharmaceuticals. This includes modifications to existing flight instruments as well as the development of novel flight hardware for deployment on the ISS.

For the above, research should be conducted to demonstrate technical feasibility and prototype hardware development during Phase I and show a path toward Phase II hardware and software demonstration and delivering an engineering development unit or software package for NASA testing at the completion of the Phase II contract that could be turned into a proof-of-concept system which can be demonstrated in flight.

Phase I Deliverables - Written report detailing evidence of demonstrated prototype technology in the laboratory or in a relevant environment and stating the future path toward hardware and software demonstration on orbit. Bench or lab-level demonstrations are desirable. The technology concept at the end of Phase I should be at a TRL of 3-6.

Phase II Deliverables - Emphasis should be placed on developing and demonstrating hardware and/or software prototype that can be demonstrated on orbit (TRL 8), or in some cases under simulated flight conditions. The proposal shall outline a path showing how the technology could be developed into space-worthy systems. The contract should deliver an engineering development unit for functional and environmental testing at the completion of the Phase II contract. The technology at the end of Phase II should be at a TRL of 6-7.

Sub Topics:
