



NASA SBIR 2015 Phase I Solicitation

Human Exploration and Operations

In-Situ Resource Utilization Topic H1

The purpose of In-Situ Resource Utilization (ISRU) is to harness and utilize resources (both natural and discarded material) at the site of exploration to create products and services which can enable new approaches for exploration and significantly reduce the mass, cost, and risk of near-term and long-term space exploration. The ability to make propellants, life support consumables, fuel cell reagents, and radiation shielding can provide significant benefits for sustained human activities beyond Earth very early in exploration architectures. 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. While the discipline of ISRU can encompass a large variety of different concept areas, resources, and products, the ISRU Topic will focus on technologies and capabilities associated with acquiring and processing regolith/soil resources for mission consumable production and construction.

Sub Topics:

H1.01 Regolith ISRU for Mission Consumable Production

Lead Center: JSC

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

In-Situ Resource Utilization (ISRU) involves collecting and converting local resources into products that can reduce mission mass, cost, and/or risk of human exploration. The primary destinations of interest for human exploration, the Moon, Mars and its moons, and Near Earth Asteroids, all contain regolith/soil that contain resources that can be harvested into products. The resources of primary interest are water and other components that can be released from the regolith/soil by heating, and oxygen found in the minerals to make consumables for life support, power, and propulsion system applications. State of the art (SOA) technologies for many ISRU processes either do not exist, are too complex, are too inefficient (mass, power, and/or volume), or are not designed to operate in the extraterrestrial environment in which the resource is found, especially the micro-gravity environment for asteroids. The subtopic seeks proposals for critical technologies associated with the design, fabrication, and testing of hardware associated with extracting and transferring regolith/soil materials from extraterrestrial bodies and processing the material to extract water/volatiles and oxygen. Technologies developed under this subtopic are applicable to feasibility testing on parabolic flights and the ISS, assessment and processing of material on the redirected asteroid to trans-lunar space, and robotic precursor missions to the lunar poles and surface of Phobos and Mars. Proposals should address one or more of the categories below.

Simulants for Ground Testing

1. Simulants for ordinary chondrites (LL, L, H) and carbonaceous chondrites (CI, CM) asteroids that replicate asteroid material characteristics such as physical (particle size/shape, particle size distribution, hardness), thermal, mineral/chemical, and volatile content for ground testing. Proposers must justify proposed simulant components and preparation based on documented research/publications.

Regolith/Soil Acquisition and Preparation

The first step in production of mission consumables from in situ resources is acquisition and preparation of the resource for processing. Proposals in this category should address one or more of the following:

2. Excavation, transfer, and preparation of hydrated and icy-soil/regolith on Mars.

3. Excavation, transfer, and preparation of asteroidal material from ordinary and carbonaceous chondrite asteroids.

4. Excavation, transfer, and preparation of lunar polar icy regolith.

Notes: Proposals must address both the physical/mineral properties of the regolith/soil and the environmental conditions of the resources location. For item 3 proposals must address options for anchoring or maintaining position at the site of excavation to overcome forces applied during excavation and transfer of asteroidal material. Concepts need to minimize the generation of material that can float off and create a hazard. The proposal must identify the potential mass, power, and operation life impact of the selected option. All acquisition and preparation proposals must identify and address any issues with measuring and maintaining constant/known material transfer rates, and the impact of continuous versus batch-mode processing of the material. Proposals can combine regolith/soil acquisition and preparation with processing if it allows for reduced mass, power, and/or complexity.

Soil/Regolith Processing for Mission Consumables

Once the soil/regolith has been acquired and prepared, it is ready for processing. Proposals in this category should address one or more of the following:

5. Water/volatile extraction and separation from carbonaceous chondrites asteroidal material. Identify potential contaminants for subsequent cleaning based on the method utilized for volatile extraction. Besides water, carbon-based gases are of significant interest for fuel and plastic production. Proposals should consider additional steps (higher temperatures, reactants, etc.) that may increase the extraction and collection of carbon-based gases. Proposers are also encouraged to examine the applicability of micro-gravity asteroidal processing techniques for crew/trash waste processing.

6. Water/volatile extraction and separation from lunar polar icy material. Identify potential contaminants for subsequent cleaning based on the method utilized for volatile extraction.

7. Water vapor and other volatile separation and collection from other gases/liquids. Separation techniques must address potential contaminants.

8. Regenerative dust separation from product and reactant gases.

9. Oxygen extraction from ordinary and carbonaceous chondrites asteroidal material. Regeneration of reactants used in oxygen extraction is required.

10. Metal extraction from ordinary and carbonaceous chondrites asteroidal material. Regeneration of reactants used in metal extraction is required.

Notes: Proposals must specify whether the process is performed in batches or by continuous processing with appropriate sealing techniques to minimize reactant/product losses identified. Proposers are encouraged to address more than one of the Soil/Regolith Processing needs above. Proposals can combine regolith/soil processing with acquisition and preparation if it allows for reduced mass, power, and/or complexity. Proposals addressing only item 7 or 8 need to identify the potential soil/regolith processing technique it is applicable for as well as minimum and maximum flow rates and/or product/reactant concentrations.

Further Requirements for Proposals

All proposals need to identify the SOA of applicable technologies and processes:

- *For Lunar polar-based ISRU* - Assume ice content in regolith is between 5 and 10% at temperatures below 100 K. Regolith excavation down to at least 1 meter below the surface is required for Phase II. Proposals must address material transfer, handling, and processing of polar material under temporary sunlight and continuous shadowed solar/thermal conditions.

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- *For Mars-based ISRU* - Assume hydrated soils between 3 and 15% (nominal 8%); icy soils containing 40% or more of ice. Soil excavation down to a minimum of 0.5 meters below the surface is required for Phase II. Proposals must recognize and address issues with perchlorate minerals in the Mars soil during processing and product separation. For hydrated soils, proposals must consider meeting time averaged excavation and processing rates of 3.5 to 7 kg/hr (8%) to 9 to 19 kg/hr (3%) soil to achieve time averaged water extraction and processing rates of 0.55 to 1.125 kg/hr. Proposals must consider and address operating life issues for surface applications that can last for up to 480 days of continuous operation.
 - *For Asteroid-based ISRU* - Technologies requested are subscale to allow for future testing on the reduced gravity assets and the ISS, but must be extensible to larger scale applications. For testing on the ISS, proposed hardware will need to process resource materials on the order of hundreds of grams to 5 kilograms within 1 to 5 hours to investigate gravity-dependent/independent phenomena. Proposed technologies must show extensibility to future ISRU missions to an asteroid which will require an increase in acquisition and processing by 1 to 2 orders of magnitude with material excavation/acquisition down to at least 3 meters. Proposals must address design and operation issues associated with performing material transfer, handling, and/or processing of solid material with gas, liquid, or molten reactants under micro-gravity and vacuum conditions. Regolith processing reactors must further address material transfer into the reactor before processing and removal from the reactor after processing while minimizing loss of reactants/products and minimizing contamination of external surfaces.

Space Transportation Topic H2

Achieving space flight remains a challenging enterprise. It is an undertaking of great complexity, requiring numerous technological and engineering disciplines and a high level of organizational skill. Human Exploration requires advances in operations, testing, and propulsion 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, 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 (including passenger transportation) supporting future orbital 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, for support 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 technologies that dramatically alter acquisition, reusability, reliability, and operability of space transportation systems.

Sub Topics:

H2.01 In-Space Chemical Propulsion

Lead Center: GRC

Participating Center(s): JSC, MSFC

The goal of this subtopic is to examine a range of key technology options associated with space engines that use methane as the propellant. Successful proposals are sought for focused investments on key technologies and design concepts that may transform the path for future exploration of Mars. In-space propulsion is defined as the development and demonstration of technologies for ascent, orbit transfer, pulsing attitude/reaction control, and descent engines. Key operational and performance parameters include:

- Reaction control thruster development in the 5 to 100 lbf thrust class with a target vacuum specific impulse of 325-sec. 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.
- Ascent/descent pressure-fed engines with 1,500 to 25,000 lbf thrust with a target vacuum specific impulse of 350 to 360-sec. The engine should be capable of throttling to 5:1 (20% power), and the chamber pressure should range from 200 to 650 psig.
- Ascent/descent pump-fed engine development is projected to range from 10,000 to 25,000 lbf thrust with a minimum vacuum specific impulse of 360-sec. The propulsion system should be capable of stable throttling

to 10:1 (10% power). The engine shall achieve 90% rated thrust within 0.5 second of the issuance of the 'Engine ON' command.

Specific technologies of interest for operation with liquid and gaseous methane are sought. Relevance of the technology to compatibility and applicability to challenges with methane must be identified. In addition, these engines should be compatible with the future use of in situ produced propellants such as oxygen and methane. For all proposed technologies, the proposer shall show in the proposal how the component would fit in a system cycle based on thermal capabilities and pressure budgets. Propulsion technologies of interest that support the performance parameters defined above include:

- New additive manufacturing techniques that can be demonstrated to allow for rapid manufacturing, surface finishes, structural integrity, and significant costs savings for complex combustion devices and turbomachinery components compared to the conventional manufacturing. Manufacturing methods must scale to a final flight component.
- Low-mass propellant injectors that provide stable and uniform combustion over a wide range of propellant inlet conditions.
- Combustion chamber designs using high temperature materials, coatings, and/or ablatives for combustion chambers, nozzles, and nozzle extensions.
- Regenerative cooled combustion chamber technologies which offer improved performance and adequate chamber life.
- 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 fatigue life impellers, zero net positive suction head (NPSH) inducers, low leakage seals, and long life in situ propellant fed bearings.

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.

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 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 released to stay within the current environmental regulations. The NTP primary test requirements can have multiple start-ups (>8)

with the longest single burn time ~50 minutes.

Specific engine technologies of interest to meet the proposed requirements include:

- High temperature (> 2600K), low burn-up composite, carbide, and/or ceramic-metallic (cermet) based nuclear fuels with improved coatings and/or claddings to maximize hydrogen propellant heating and to reduce fission product gas release and particulates into the engine's exhaust stream.
- Long life, lightweight, reliable turbopump modeling, designs and technologies including seals, bearing and fluid system components. Throttle ability is also considered. Zero net positive suction head (NPSH) hydrogen inducers have been demonstrated that can ingest 20-30% vapor by volume. The goal would be to develop inducers that can ingest 55% vapor by volume for up to 8 hours with less than 10 percent head fall off at the design point. Develop the capability to model (predict) turbopump cavitation dynamics. This includes first order rotating and alternating cavitation (1.1X –2X) and higher (6X-10X) order cavitation dynamics.
- High temperature and cryogenic radiation tolerant instrumentation and avionics for engine health monitoring. Non-invasive designs for measuring neutron flux (outside of reactor), chamber temperature, operating pressure, and liquid hydrogen propellant flow rates over wide range of temperatures are desired. Sensors need to operate for months/years instead of hours. Robonaut type inspections for prototype flight test considered.
- Concepts to cooldown 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 criticality control flexibility during burns beyond the reactor circumferential rotating control drums, and/or provide nuclear safety for ground processing, launch, and possible launch aborts.

Specific ground test technologies of interest to meet the proposed requirements include:

- Effluent scrubber 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%.
- Technologies providing a low power nuclear furnace to 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 technologies that can lead to high-power (100-kW to MW-class) 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, and at very high power levels enable piloted 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 system efficiencies exceeding 60% and 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.

Specific technologies of interest in addressing high power electric propulsion challenges include but are not limited to:

- Advanced concepts for high power plasma thruster systems that provide quantifiable benefits over state of the art high power electric propulsion systems. Proposals addressing advanced technology concepts should include a realistic and well-defined roadmap defining critical technology development milestones leading to an eventual flight system.
- Electric propulsion systems and components that enable the use of alternative space storable propellants, such as condensible or metal propellants and potential in-situ resource derived propellants.
- Advanced manufacturing methods for the fabrication of high power thruster components and associated systems; of particular interest is additive manufacturing for complex parts and components. 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.
- 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 (equal to or $>10^9$ pulses) operation.

In addressing technology requirements, proposers should identify candidate thruster systems and potential mission applications that would benefit from the proposed technology.

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.

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, transfer, and instrumentation to support NASA's exploration goals. This includes a wide range of applications, scales, and environments consistent with future NASA missions. Specifically, listed in order of NASA's current priority:

- Simple mass efficient techniques for vapor cooling of structural skirts (aluminum, stainless, or composites) on large upper stages containing liquid hydrogen and liquid methane (can include para-to-ortho hydrogen catalyst for hydrogen applications).
- Lightweight, multifunctional cryogenic insulation systems (including attachment methods) that can survive exposure to the free stream during the launch/ascent environment in addition to high performance (less than 0.5 W/m^2 with a warm boundary of 220 K) on orbit or $<5 \text{ W/m}^2$ on Mars surface.

- Advanced cryogenic spacecraft components including:
 - Valves (minimum ½” tube size) for low (< 50 psi, Cv > 5, goal of 100+) pressure liquid hydrogen with low internal (~ 1 sccm, goal of < 0.1 sccm) and external (~ 3 sccm, goal of < 0.1 sccm) leakage (> 500 cycles with a goal of 5,000 cycles).
 - Isolation valve/regulation (minimum ½”) for high pressure (>4500 psi) gaseous helium systems (< 70 K fluid, Cv > 2.1) with low internal (~ 1 sccm) and external (~ 3 sccm) leakage (> 500 cycles with a goal of 5,000 cycles).
 - Spherical all-composite 1-2 m diameter propellant tank for Mars application using LO₂/LCH₄; Pressure from 350-1000 psig; Temperature range from ambient to 77 K (LN₂); and Ghe permeability less than 1x10⁻⁴ sccs/m² (at 500 psi, 77 K).
- Micro-gravity cryogenic pressure control components for thermodynamic vent systems including:
 - Improved alternatives to state of the art spray bars for using fluid dynamics to collapse the ullage and thoroughly mix a propellant tank in micro-gravity.
 - Low voltage (28 VDC) two-phase flow tolerant mixing pumps of flow rates between 10 and 40 gpm.
 - Novel methods of packaging and manufacture to minimize feedthroughs to the tank and ease of installation into a tank.
- Innovative concepts for cryogenic fluid instrumentation including:
 - Fiberoptic and wireless concepts to enable accurate measurement (with minimal sensitivity to electromagnetic interference) of propellant pressures and temperatures in low-gravity storage tanks
 - Cryogenic pressure transducers (0 – 50 psia typical range, 1% full scale accuracy, 0.5 Hz response) at 20 K.
 - Low power (< 15 W goal) video camera systems for viewing fluid dynamics within a propellant tank (3 – 5 m diameter).
- Wicking materials or other novel methods/materials of liquid acquisition for use with liquid oxygen, liquid methane, and liquid hydrogen for low temperature heat pipes or tank expulsion.

Phase I proposals should at a minimum deliver proof of the concept including some sort of testing or physical demonstration (not just a paper study). Phase II proposals will be expected to provide component validation in a laboratory environment preferably with a hardware deliverable to NASA.

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 atmosphere revitalization, environmental monitoring and fire protection systems, crew accommodations, water recovery systems and thermal control. Technologies must be directed at long duration missions in microgravity, including Earth orbit and planetary transit. 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.

Sub Topics:

H3.01 Environmental Monitoring for Spacecraft Cabins

Lead Center: JPL

Participating Center(s): GRC, JSC, KSC

Measurement of Inorganic Species in Water

There is limited capability for water quality analysis onboard current spacecraft. Several hardware failures have occurred onboard ISS which demonstrate the need for measurement of inorganic contaminants. Monitoring capability is of interest for identification and quantification of inorganic species in potable water, thermal control system cooling water, and human wastewater. Examples of inorganic species of interest and their levels in potable water are specified in Spacecraft Water Exposure Guidelines (SWEGs), released as JSC 63414 (Last revised - November 2008). Target compounds identified in the SWEGs that will be needed for exploration missions include

ammonium, antimony, barium, cadmium, manganese, nickel, silver, and zinc. But there is also interest in measurement of other cations and anions including iron, copper, aluminum, chromium, calcium, magnesium, sodium, potassium, arsenic, lead, molybdenum, fluoride, bromide, boron, silicon, lithium, phosphates, sulfates, chloride, iodine, nitrate and nitrite. Detection limits should be below 0.5 mg/L where possible. The proposed analytical instrument should be compact, microgravity compatible, and have limited power and consumable requirements. Sample volumes should be minimized.

Particulate Monitor for Air

Instruments that measure indoor aerosols in spacecraft cabins to monitor air quality and for characterizing the background particle environment and major particle sources are desired. Real-time measurement instruments must be compact and low power, without volatile working fluids, intuitive for crew to operate, requiring minimal maintenance, and able to maintain calibration for years. A large measurement range is necessary in low gravity due to the absence of gravitational settling, and it is expected that more than one instrument, or a multi-sensor unit, will be required to cover the desired range from nanometer (ultrafine) to 50 microns in diameter. A major portion of aerosols on the International Space Station (ISS) are from lint and fibers, so instruments must not rely on spherical morphology for accurate measurements. High accuracy should be quantitatively demonstrated for the range of interest. Development of an instrument that covers a sub-range, as broad as possible, that optimizes the performance within that range and that can subsequently be easily expanded, or integrated with other instrumentation, to cover the full range and requirements will also be of interest. Ideally, the instrument would be portable, with a graphical user interface for crew to read directly and also with the ability to log data and offer standard data transfer interfaces for longer-term indoor air quality surveys.

Microbial Monitor

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, every attempt to monitor microbial communities on-board the ISS has relied on traditional, culture-based approaches. Such techniques are laborious (7 days), require a considerable amount of crew time (up to 5 hrs), sample return, and ground based analysis (1 month after sample return), and are fraught with difficulty, as different microbial species require various media or cultural conditions to grow. In current microbial quality verification protocols, which use a single medium and a single culture condition, many types of cells will go undetected.

Molecular detection of biological agents offers increased sensitivity and specificity, such that lower levels of contaminating material can be detected and unambiguous identification can be achieved. NASA is interested in an integrated molecular system that could combine all required steps such as:

- Sample collection/concentration/extraction.
- Amplification/enrichment.
- Detection.

The scope this solicitation is the first item, i.e., sample collection, concentration, and extraction. However, integration of any two of the above mentioned steps as a single module with a capability to develop the interface of the third step can also be proposed. Technologies that determine microbial content of the air and water environment of the crew habitat falls within acceptable limits and life support system is functioning properly and efficiently are solicited. Required technology characteristics include:

- 2 year shelf-life.
- Functionality in microgravity and low pressure environment (~8 psi).

Technologies that show improvements in miniaturization, reliability, life-time, self-calibration, and reduction of expendables are also of interest. The proposed integrated molecular microbial monitoring/detection system should be capable of measuring total microbial burden as well as identifying “problematic” microbial species on-board ISS (ISS MORD: SSP 50260; <http://emits.sso.esa.int/emits-doc/ESTEC/AO6216-SoW-RD9.pdf> [1]).

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 for NASA testing.

H3.02 Bioregenerative Technologies for Life Support

Lead Center: KSC

Participating Center(s): ARC, JSC

Food Production Technologies for Space Exploration

NASA is interested in food production and related food safety technologies for ISS, transit missions, and eventual surface missions (fractional gravity). Of special interest is the use of photosynthetic organisms such as plants to produce food, and contribute to cabin O₂ production and CO₂ removal. Food production technologies should address how light use efficiency will be improved to reduce energy costs, including advanced electric and solar lighting concepts. Electric light sources should achieve at least 1.5 μmol photosynthetically active radiation per Joule of electrical energy, and solar collection systems should achieve at least a 40% delivery efficiency of solar light. Innovative concepts for gravity independent watering and nutrient delivery techniques are also needed. Technical approaches could include selecting or adapting the plants for optimal performance in smaller growing volumes common to space. All systems should consider minimizing power, mass, consumables, and biologically produced waste, while maximizing reliability and efficiency. Consumables and waste products that allow their residual water to be recovered or are easily refurbished are desirable. System TRLs should be 2-4 for Phase I. Phase II projects that evolve from the call are expected to deliver a working prototype to NASA.

Biological Systems for Wastewater Treatment

NASA is interested in efficient biological or biochemical approaches to assist in purifying and recycling wastewater in confined spaces such as crewed spacecraft or space habitats. Of special interest are biological approaches and bioreactors for removing carbon, nitrogen and phosphorus, and reduction of biosolids. Specific technologies or approaches are sought for:

- Development of long term stable inocula.
- Inoculation and start-up of bioreactors in flight, including remote operations.

Systems should consider operating with low power, low consumables, small volumes, high reliability and rapid deployment, as well as addressing multi-phase flow issues for reduced gravity. Consumables that allow their residual water to be recovered or be easily refurbished are desirable. Proposed systems shall be capable of treating combined waste waters from hygiene activities (containing surfactants/dander/body oil), human urine (with minimal flush water and a bio compatible preservative), and humidity condensate (containing VOCs). Proposed systems should also be capable of maintaining viability during long periods of quiescent operations (90-365 days) when no human generate waste water is available. Proposed systems should use fewer consumables than the current ISS physico-chemical system. System TRLs should be 2-4 for Phase I. Phase II projects that evolve from the call are expected to deliver a working prototype to NASA.

H3.03 Spacecraft Cabin Atmosphere Quality and Thermal Management

Lead Center: MSFC

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

Advances in spacecraft atmospheric quality management are sought to address cabin ventilation and flow delivery to air scrubbing equipment, suspended particulate matter removal and disposal, and volatile trace chemical contaminant removal. Methods to separate particulate matter from both the cabin atmosphere and from Environmental Control and Life Support (ECLS) system process gas streams are sought. Interest in humidity control and separation processes within life support system processes are of interest. Specifics regarding areas of interest in spacecraft atmospheric quality management are the following.

Multifunctional Filtration Techniques

Techniques and methods are sought leading to compact, low power, autonomous, regenerable bulk particulate matter separation and collection techniques suitable for general cabin air purification. The particulate matter removal techniques and methods must accommodate high volumetric flow rates up to 11.3 m³/minute, yet possess pressure drop <125 Pa. Filtration performance equivalent to HEPA rating is desired. Configurations incorporating multi-stage filtration that separate and optimize regeneration and capturing efficiency functionalities may be considered. The particulate matter separation and collection technique must be suitable for seamless integration into a spacecraft cabin ventilation system from a volumetric perspective. The techniques and methods must safely store and enable easy disposal of collected particulate matter by the crew while minimizing exposure during the disposal operation.

Combination of the particulate matter separation and collection technique with techniques possessing high removal capacity for volatile chemical contaminants, with a focus on light polar organic compounds (e.g., ethanol and acetone) and linear and cyclic siloxanes, is of interest. The volatile chemical contaminant removal techniques must accommodate high volumetric flow rates up to 11.3 m³/minute and possess pressure drop <125 Pa. The technique must provide for a minimum 1 year service life and a goal of 3 years.

ECLS System Process Gas Filtration Techniques

Techniques and methods leading to compact, regenerable methods for removing particulate matter generated in ECLS system process equipment such as carbon formation reactors and methane plasma pyrolysis reactors. Filtration performance approaching HEPA rating is desired for ultrafine particulate matter with minimal pressure drop. The gas filter should be capable of operating for hours at high particle loading rates and then employ techniques and methods to restore its capacity back to nearly 100% of its original clean state through in-place and autonomous regeneration or self-cleaning operation. Compact storage of the particulate matter after it is collected is as important as the effective collection. The device must minimize crew exposure to accumulated particulate matter and enable easy particulate matter disposal.

Process Gas Phase Moisture Removal and Collection

Innovative technologies are sought to dehumidify a hot, humid airstream and remove and collect the product as condensate for further processing. The airstream pressure is between 0.2 and 1.0 atmospheres, its temperature is 150°C and it is saturated with water vapor. The dewpoint of the airstream must be reduced to 10°C and the condensed liquid that results must be completely removed. Cooling at ambient temperature and electrical power and are available. Both the electric power and liquid carryover must be minimized.

Future human spacecraft will require more sophisticated thermal control systems that can operate in severe environments ranging from full sun to deep space and can dissipate a wide range of heat loads. The systems must perform their function while using fewer of the limited spacecraft mass, volume and power resources. Advances are sought for microgravity thermal control in the following areas:

- Heat rejection systems and/or radiators that can operate at low fractions of their design heat load in the cold environments that are required for deep space missions. Room temperature thermal control systems are sought that are sized for full sun yet are able to maintain setpoint control and operate stably at 25% of their design heat load in a deep space (0 K) environment. Innovative components, working fluids, and systems may be needed to achieve this goal.
- Lightweight non-venting phase change heat exchangers are sought to ameliorate the environmental transients that would be seen in planetary (or lunar) orbit. Heat exchangers that have minimal structural mass and good thermal performance are sought. The goal is a ratio exceeding 2/3 phase change material mass and 1/3 structural mass.
- Two-phase heat transfer components and system architectures that will allow the acquisition, transport, and rejection of waste heat loads in the range of 100 kW to 10 megawatts are sought.
- Non-toxic working fluids are needed that are compatible with aluminum components and combine low operating temperature limits (<250K) and favorable thermophysical properties - e. g., viscosity and specific heat.

Technologies are expected to be raised from TRL2 to TRL 3/4 during Phase I. Minimum deliverables at the end of Phase I are analysis/test reports, but delivery of development hardware for further testing is desirable. In addition,

the necessity and usefulness of moving on to a Phase II should be demonstrated. Technologies would be expected to be matured from TRL 3/4 to TRL 5 during a potential Phase II effort. Expected deliverables for a Phase II effort are analysis/test reports and prototypic hardware.

Extra-Vehicular Activity and Crew Survival Systems Technology 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 space suit pressure garment systems (PGS); the portable life support system (PLSS); the power, avionics and software (PAS) systems including 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, with improved comfort, productivity, less fatigue, and lower injury risks. Reductions in commodity and life-limited part consumption rates and the size/weight/power of worn systems are needed. Primary goals for crew survival systems include development of technologies enhancing crew survival in the post-landing environment, significant mass reduction of hardware, and development of space-qualified survival hardware technologies designed to operate after exposure to space vacuum and thermal effects. Launch, Entry, and Abort (LEA) crew survival equipment development is a critical need tied to any future manned Design Reference Mission (DRM), as well as providing benefit to both Orion/MPCV and Commercial Crew Program engineering efforts. All proposed Phase I research must lead to specific Phase II experimental development that could be integrated into a functional EVA system.

Sub Topics:

H4.01 Crew Survival Systems for Launch, Entry, Abort

Lead Center: JSC

This subtopic seeks technology innovation supporting the launch, entry, and abort (LEA) crew survival equipment needs for future human exploration beyond low-earth orbit. Primary goals include development of technologies enhancing crew survival in the launch, entry, and abort phases of flight as well as the post-landing environment, significant mass reduction of hardware, and development of space-qualified survival hardware technologies designed to operate after exposure to space vacuum and thermal effects. LEA crew survival equipment development is a critical need tied to any future manned Design Reference Mission (DRM) laid out by the agency, as well as providing benefit to both Orion/MPCV and Commercial Crew Program engineering efforts. Many candidate technologies will have direct application to Orion's EM-2 mission and follow on manned spaceflight activities.

Systems and technologies relating to enhancement of post-landing survival and rescue following manned exploration spacecraft launch, entry, and abort (LEA) events are sought in the following areas:

- *Lightweight Survival Life Raft Materials, Construction Methods, and Related Technologies* - Programmatic need exists for a low mass, self-inflating life raft under 30 lbm. Technologies should be directed to enable crew survivability in the post landing off-shore ocean environment meeting SOLAS and/or FAA standards and Orion/MPCV Design Specification for Natural Environments (DSNE) sea state definitions while meeting a 30 lbm mass constraint. Of particular interest is significant mass reduction in raft inflation systems, innovative construction techniques and techniques / methods for enhanced operability by long-duration spaceflight de-conditioned crew members. The current space equivalent baseline is an FAA six person raft. Currently this type of raft does not exist without 'breaking' the 30 lbm mass requirement or sacrificing survivability attributes. Efforts should focus upon novel lighter weight materials and constructions methods, as well as inflation systems. Another area of concern from the medical community is raft ops and ingress by deconditioned crew members experiencing neurovestibular effects of long-duration spaceflight.
- *Suit-Integrated Global Coverage Personal Locating Technologies* - Current commercially-available Personal Locating Beacons (PLBs) are not optimized for use in the manned spaceflight thermal and vacuum environment or integration into a survival suit cover layer. Innovative technologies/efforts should be directed towards novel flexible patch antenna development, robust beacon packaging technologies, analytical

methodology for integrated beacon operational analysis, and beacon triggering (RF, saltwater, etc.) technologies. Additionally, there is interest in prototype electronics board development for use with future satellite-based GPS/Doppler locating systems such as the NASA-led Distress Alerting Satellite System (DASS). This technology development subheading also includes development of high-reflectivity materials in the visible, IR, and radar wavelengths.

- *Occupant Protection Materials, Analytical Tools, and Technologies* - Products and materials leading to enhanced occupant protection in the capsule landing loads environment. Innovative technologies and efforts should be directed towards acceleration, vibration, and impact attenuation systems designed to mitigate dynamic flight event impacts on the crew member. Of potential interest are materials and products to protect crew members from head and neck injuries during landing load shocks. Additionally, technologies such as innovative restraint mechanisms preventing crew member flail and flail-related injuries during dynamic flight events are of potential interest. When considering impact attenuation material properties, attention should be paid to preventing crew member exposure to rate changes of acceleration greater than 500 g/s. Material space-rating requirements should be taken into account in relation to the manned spaceflight thermal / vacuum environment. Within this subtopic, analytical methods should be directed to prevention of extremity flail, head, and neck injuries during linear, vibrational, and angular acceleration events.
- *In-Suit Waste Management Technologies* - Development of technologies allowing for long-duration waste management for use by a pressurized suited crew member. In the event of cabin depressurization or other contingency, crew members may need to take refuge in LEA pressure garments for a long-duration (144-hour) return trajectory back to Earth. Technology development should be tailored to a 144-hour suited contingency, meeting the NASA Human Systems Integration Requirement (HSIR) inside an LEA suit pressurized to 4.3 PSID referenced to the ambient environment. Waste management technologies should address fecal and urine waste containment and human physiological responses / countermeasures to long duration waste management in a pressurized survival suit environment from one to six days. Advanced technologies and materials should ideally provide for urine collection of up to 1L per day per crew member, for a total of 6 days. Additionally, mitigation and/or elimination of urine-generated ammonia inside the pressure garment volume is a candidate area of interest. Fecal collection rates should be targeted for 75 grams of fecal mass and 75 mL fecal volume per crew member per day for a total of 6 days duration.

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.

H4.02 EVA Space Suit Pressure Garment Systems

Lead Center: JSC

Space suit pressure garments technology developments are focused on providing enabling technologies for long-duration missions inclusive of extensive extra-vehicular activity (EVA). To that end, priority technologies address mass reductions, durability and reliability. Mass reduction for exploration pressure garments is driven, in addition to launch mass considerations, by the human factor of on-back weight for a planetary walking suit configuration following a long-duration micro-gravity transit, which may reduce astronaut load bearing capability. Driving reference missions such as a 1.5-year Mars surface stay include on the order of 700 hours of EVA. Therefore, long-duration exploration missions require, in some cases orders of magnitude, increases in suit durability or new approaches to providing long duration mission EVA capability or logistics. The following technology areas address mass reduction, increased durability, or both.

Multi-function Materials

The pressure garment must perform functions such as: gas retention and structural integrity including fall cases;

mobility to perform science and surface asset set-up and maintenance; and environmental protection from thermal extremes, micrometeoroids and secondary impacts, dust, and tears. The combination of performance of two or more of these functions in single pressure garment material layer contributes to mass reduction. For example, a composite structure that provides gas retention, structural integrity, and thermal protection/regulation would be beneficial. Another example would be a fabric that mitigates the effects of dust and is thermal protection in a single layer is sought.

Self-diagnosing and Self-healing Materials

Fabric wear due to repetitive joint cycling, dust and UV radiation exposure, and handling is anticipated. To improve safety and decrease crew time investment in the EVA system, materials that can indicate wear or self-heal are valuable. Current materials with these capabilities are heavy, stiff, or require prohibitive power quantities. Ideally, self-diagnosing and self-healing capabilities would be combined in with a material that also performs one of the functions described in the 'Multi-function materials' section

Titanium Bearings

This topic addresses both mass reduction and increasing durability. The emphasis on mass reduction is countered by the need for increased mobility, which tends to increase mass due to the addition of low torques bearings in joint mobility systems. Titanium bearings are being incorporated to decrease the mass of joint mobility systems. However, refinement of titanium bearings to meet durability requirements is required based on 2014 bearing in-configuration oxygen compatibility testing, which passed for flammability, but indicated cycle wear issues. To address titanium bearing wear, coatings, treatments, lubricants, ball material, and space ball materials are all considerations to be investigated. Titanium bearings that can withstand 8 psi suit pressure plug loads in addition to suit manloads over tens of thousands of cycles are required for exploration pressure garments.

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.

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, a significant risk for the development of spacesuit avionics is the non-availability certain ancillary electronic devices that are rated for spaceflight. 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 no particular order of priority, key innovations sought include:

- Wireless Communication:
 - 802.11n baseband processor that supports channel bonding and possibly multiple RF channels.
 - Low-power (<5W), low-rate (500-1000kbps) baseband software-defined radio that is, at the very least, capable of supporting the existing Space-to-Space Communications System (SSCS) wireless suit interface.
 - Dual-band WLAN-class RF front-end module capable of supporting the SSCS (410 to 420 MHz) and a channel-bonded 802.11n system (40MHz of bandwidth) operating at the 2.4GHz ISM band. Consideration will also be given to devices capable of supporting the 802.11n system operating in the 900MHz region. Consideration for supporting multiple antennas for the 802.11n system will be given, but this is not required.
- Human-Machine Interface (HMI) for Informatics:
 - Input device technologies that provide mouse-like functionality or a minimum of directional control to navigate display menu system. In general devices need to minimize hand use. Technologies that require hand use must be limited to operation with a single gloved EVA hand. Devices must minimize SWAP and computing power needed for final implementation. Solutions must be reliable and robust enough for vacuum space environments.
- 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.
- Audio:
 - Simultaneously sampled, deep bit-width, low rate Analog to Digital Converter (ADC) circuits and/or Pulse Density Modulator (PDM) circuits. Requirements are for devices with dynamic range greater than 90 dB (threshold) and as much as 110 dB (goal) with sampling rates > 24 kS/s (threshold) and as high as 48 kS/s (goal). Requirements exist for 8 channel devices (threshold) simultaneously sampled (< 1 ps jitter) with a goal of 16 channels. Devices should support a Least Significant Bit (in Pulse Code Modulation) of 1 micro-Volt or less with a noise floor of 10 micro-Volts or less.
 - Highly linear, high Signal to Noise Ratio (SNR) Micro Electro Mechanical System (MEMS) microphones with PDM output. Microphones should exhibit < 1% THD at 105 dB SPL (threshold) and 115 dB SPL (goal). Microphones should have frequency response of +/-10 dB from 80 Hz to 12 kHz and SNR > 50 dB (threshold) and > 60 dB (goal).
 - High dynamic range, audio frequency Digital to Analog Converters (DACs). Converters should provide >100 dB spur free dynamic range (TBR).
 - High efficiency, low power (< 1 W output), audio frequency power amplifiers.
 - High efficiency, audio frequency pre amplifiers with adjustable gain (0 to 30 dB).
 - High speed (> 100 Mb/s) serial communications transceivers suitable for protocols such as Ethernet, Low Voltage Differential Signal (LVDS) and Rocket-IO.

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 Spacecraft Materials and Structures Topic H5

The SBIR topic area of Lightweight Spacecraft Materials and Structures 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 advanced materials have been identified as a critical need since the reduction of structural mass translates directly to additional up and down mass capability that would facilitate additional logistics capacity and increased science return for all 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:

- 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 multifunctional materials and structures, deployable structures, and extreme environment structures. 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 Deployable Structures

Lead Center: LaRC

Participating Center(s): GRC, JSC

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

- Large deployable solar arrays for 50+ kW solar electric propulsion (SEP) missions.
- Lightweight deployable hatches for manned inflatable structures.

Design solutions must minimize mass and launch volume while meeting other mission requirements including deployed strength, stiffness, and durability.

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

- Novel design, packaging, deployment, and in-space manufacturing or assembly concepts.
- Lightweight, compact components including booms, ribs, 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 Arrays

NASA is currently developing solar array systems for solar electric propulsion in the 30-50 kW power range for near-term missions such as the Asteroid Redirect Mission (ARM). This subtopic seeks structures and materials innovations for the next generation of lightweight solar arrays beyond 50 kW. NASA has a vital interest in developing much larger arrays over the next 20 years with up to 1 MW of power (4000 m² total deployed area) for SEP-powered exploration missions. Scaling up solar array size by over an order-of-magnitude will require game changing innovations. In particular, novel flexible-substrate designs are needed that minimize structural mass and packaging volume while maximizing deployment reliability, deployed stiffness, deployed strength, and longevity.

Nominal solar array requirements for large-scale SEP applications are:

- Specific power > 120 W/kg at beginning of life (BOL).
- Packaging efficiency > 40 kW/m³ BOL.
- Deployment reliability > 0.999.
- Deployed stiffness > 0.1 Hz.
- Deployed strength > 0.1 g (all directions).
- Lifetime > 5 yrs.

Variations of NASA's in-house large solar array concept referred to as the Compact Telescoping Array (CTA) could be used for design, analysis, and hardware studies. Improved packaging, joints, deployment methods, etc. to enable CTA-type solar arrays up to 4000 m² in size (1 MW) with up to 250 W/kg and 60 kW/m³ BOL are of special interest. The CTA is described in Reference 1.

Capability #2: Deployable Hatches

NASA is also seeking concepts for lightweight, deployable hatch systems for manned inflatable structures that require ingress/egress across a pressure differential. Designs should be efficient and tight-sealing and use softgoods materials in whole or in part. "Softgoods" refers to advanced high-strength fabrics or woven materials. Applications of this technology include barometric chambers, airlocks and habitats, and large-scale space hangars for on-orbit assembly. The pressure vessel geometry could require hatches that conform to flat, singly-curved, or doubly-curved surfaces. Concepts will be evaluated on mass efficiency, minimal packaging volume for launch, operational reliability and simplicity, and strategy for integration into a soft-goods structure. Proposals should detail a concept of operations including packaged and deployed geometry, deployment approach, and operation of sealing/unsealing the hatch. Reference 2 provides additional information on deployable soft space structures.

Nominal hatch requirements are:

- 40-inch diameter clear opening for ingress/egress.
- Designed for a differential pressure of 15.2 psi.
- Hatch can be sealed and verified even when parent vessel is at vacuum.
- The hatch can be easily operated by a suited astronaut.

For both capabilities, contractors should prove the feasibility of proposed innovations using suitable analyses and tests in Phase I. In Phase II, significant hardware 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.

References:

- Mikulas, M. M. et al., "Telescoping Solar Array Concept for Achieving High Packaging Efficiency," To be presented at the AIAA Spacecraft Structures Conference, January 2015.
- Bell L., "Deployable Soft Space Structures: Concepts and Application Requirements," 50th AIAA Structures, Dynamics and Materials Conference, Paper 2009-2168, May 2009.

H5.02 Extreme Temperature Structures

Lead Center: MSFC

Participating Center(s): LaRC

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 systems and manufacturing processes which enable the capability to store and transfer cryogenic propellants (liquid oxygen & liquid hydrogen) to orbit. Operating temperature ranges for these fluids are -183°C to -253°C. Specific areas include:
 - Composite systems to be used in the construction of storage vessels or ductwork for cryogenic propellants. 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 composite structures. Concepts must address seal systems for both composite to composite and composite to metal applications. Techniques must consider scale up and manufacturability factors.
- *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 1500°C to 3000°C, while maintaining structural integrity. Significant reductions in vehicle weight can be achieved with the application of hot structures, which do not require parasitic thermal protection systems. This area seeks innovative technologies in one or more of the following:
 - Light-weight, low-cost, composite material systems that include continuous fibers.
 - Significant improvements of in-plane and thru the thickness mechanical properties, compared to current high temperature laminated composites.
 - Decreased processing time and increased consistency for high temperature materials.
 - Improvement in potential reusability for multiple missions.
 - Low conductivity, low thermal expansion, high impact resistance.

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> [2])

H5.03 Multifunctional Materials and Structures

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/501625main_TA12-ID_rev6_NRC-wTASR.pdf [3]), 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), inflatable, protective (radiation and micrometeoroids and orbital debris), sensing, healing, in-situ inspectable (e.g., IVHM), actuating, integral cooling/heating, and power generating (thermal-electric, photovoltaic ...), 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 FY15, this SBIR subtopic seeks innovative structures and materials technologies and capabilities for three principle areas:
 - Integration of acoustic metamaterial concepts into the primary structure to reduce interior acoustic and vibration environments. Specifically, innovations are solicited which maintain the load bearing capability of the primary structure while simultaneously reducing interior noise and vibration levels below 400 Hz. Successful innovations are anticipated to enable the design of lighter and cheaper spacecraft and launch vehicle structures, as well as lower costs associated with ruggedizing and qualifying spacecraft and launch vehicle secondary structures.
 - Sensory materials incorporated into a primary structure to provide health monitoring data, and low-mass/wireless methods of transmitting localized structural responses to diagnostic models for material and structural state. Manufacturing technologies capable of producing structural components with embedded capability for sensing strain, damage initiation and propagation, and temperature are of particular interest. Ideally, the sensing technology should also augment the load carrying capability or some other structural design requirement. Technologies should enable weight reduction with similar or better structural performance when compared to traditional approaches.
 - Thin film conformal layers on structures or integrated in structures with different functional capabilities. Examples include conformal solar cells, conformal antennas, conformal energy storage, and conformal energy harvesting. The conformal layer should provide additional functionality to the structure without adversely affecting the load bearing capability. The conformal functional layer offers the potential for significant weight reduction and reduced complexity for spacecraft, rovers,

and habitats. For example, conformal photovoltaic layer on spacecraft, rover, or habitat can eliminate the need for separate solar array panels."

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.

Sub Topics:

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

Lead Center: JSC

Participating Center(s): ARC, KSC

The objective of this subtopic is to create human-robotic technologies (hardware and software) to improve the 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, in orbit, and interplanetary), and with a range of time-delay and communications bandwidth.

Proposals are sought that address the following three subtopics:

- *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, and infrastructure-free localization.
- *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, and novel manipulation methods.
- *Human-system interaction (HSI)* - 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, ground data system tools, command planning and sequencing, real-time visualization/notification, and software for situational awareness.

Entry, Descent, and Landing Technologies 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 modeling, testing, monitoring, and inspection of ablative thermal protection materials 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. 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. Inspection of thermal protection material/aeroshell interfaces is critical to assure quality and is extremely difficult for porous, low density composites.

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, Sensors and NDE Methods

Lead Center: ARC

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

The technologies described below support the goal of developing advancements in instrumentation systems, inspection techniques, 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.

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:

- 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.
- Non Destructive Evaluation (NDE) tools for evaluation of bondline and in-depth integrity for light- weight

rigid and/or flexible ablative materials. Non Destructive Evaluation (NDE) tools are sought to verify design requirements are met during manufacturing and assembly of the heat shield, e.g., verifying that anisotropic materials have been installed in their proper orientation, and that the bondline as well as the TPS materials have the proper integrity and are free of voids or defects. Void and/or defect detection requirements will depend upon the materials being inspected. Typical internal void volume detection requirements are on the order of 6 mm on a side (6x6x6), and bondline defect detection requirements are on the order of 25.4 mm by 25.4 mm by the thickness of the adhesive.

- 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:

- *Sensors* - Sensor system design, including electronics, with specified measurement performance, mass, power, and volume. Proposed test approach for Phase II, which 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.
- *NDE* - Detection technique/process and equipment design, to meet the specified requirements. Validation test plan, to be executed on relevant materials in Phase II.
- *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:

- *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.
- *NDE* - Working engineering model of the detection system with the proposed performance characteristics. Full report of development, architecture, and measurement performance, including data from completed test proposed in Phase I (TRL 4-5).
- *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.

The range of diagnostics to be considered is not restricted. Examples of diagnostics of interest include those that characterize high enthalpy flows (e.g., temperature, velocity, electron number density, pyrolysis/ablation byproducts) or characterization of test articles (recession, thermal emission, etc.). Proposals for adapting existing techniques to unique aspects of the facility (e.g., free flight in ballistic range, or short duration in shock tubes) are of interest, as well as the development of new techniques. Proposers are encouraged to contact operators and users of individual facilities to understand their specific challenges and requirements, and for details of interfacing into the existing systems.

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 Systems 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.
- Nuclear fission systems to power electric spacecraft and/or surface space power systems.
- Photovoltaic technology to power electric spacecraft.

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.

Technologies to enable space-based nuclear fission systems are sought for three power classes:

- Kilowatt-class to support robotic missions as precursors to human exploration.
- 10 kWe-class power conversion devices and 400-500K radiators to support large surface power and 100 kWe-class electric propulsion vehicles.
- 100 kWe-class power conversion devices, >500K radiators, and high temperature fuels, materials, and heat transport to support MW-class electric vehicles.

Photovoltaic (PV) technologies are sought to provide lower-cost power systems with particular emphasis on high power arrays to support solar electric propulsion spacecraft on deep space missions.

Sub Topics:

H8.01 Space Nuclear Power Systems

Lead Center: GRC

Participating Center(s): JPL, JSC, MSFC

NASA is developing fission power system technology for future space exploration applications using a stepwise approach. Initial small fission systems are envisioned in the 1 to 10 kWe range that utilize cast uranium-metal fuel and heat pipe cooling coupled to static or dynamic power conversion. Follow-on systems could produce 10s or 100s of kilowatts utilizing a pin-type uranium fueled reactor with pumped liquid metal cooling, dynamic power conversion, and high temperature radiators. The anticipated design life for these systems is 8 to 15 years with no maintenance. Candidate mission applications include power sources for robotic precursors, human outposts on the moon or Mars, and nuclear electric propulsion (NEP) vehicles. NASA is planning a variety of nuclear and non-nuclear system ground tests to validate technologies required to transfer reactor heat, convert the heat into electricity, reject waste heat, process the electrical output, and demonstrate overall system performance.

The primary goals for the early systems are low cost, high reliability, and long life. Proposals are solicited that could help supplement or augment the planned NASA system testing. Specific areas for development include:

- 800-1000 K heat transport technology for reactor cooling (liquid metal heat pipes, liquid metal pumps).
- 1-10 kWe-class power conversion technology (thermoelectric, Stirling, Brayton).
- 400-500 K heat rejection technology for waste heat removal (water heat pipes, composite radiators, water pumps).

The early systems are expected to provide the foundation for later systems in the multi-hundred kilowatt or megawatt range that utilize higher operating temperatures, alternative materials, and advanced components to improve system performance. Specific areas for development include:

- 100 kWe-class power conversion technologies.
- Waste heat rejection technologies for 500 K and above.
- High temperature reactor fuels, structural materials and heat transport technologies.

H8.02 Solid Oxide Fuel Cells and Electrolyzers

Lead Center: GRC

Participating Center(s): 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 hydrocarbon fuels, 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 cell, stack, materials and system development for operation on 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 as specified after at least 500 hours of steady state operation on propellant-grade methane and oxygen with 2500 hours expected of a mature system. System should startup dry but after reaching operating conditions an amount of water/H₂ consistent with what can be obtained from anode recycle can be used. Amounts must be justified in the proposal.
- Minimal cooling required for power applications. 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.
- 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 for improvements in capability and reliability of PV power generation for space exploration missions. Power levels for PV applications may reach 100s of kWe. System and component technologies are sought that can deliver efficiency, cost, reliability, mass and volume improvements under various operating conditions, in extreme environments, and over wide temperature ranges.

PV technologies must enable or enhance the ability to provide low-cost, low mass and higher efficiency for power systems with particular emphasis on high power arrays to support solar electric propulsion missions. Areas of particular emphasis include:

- Advanced PV blanket and component technology/ designs that support very high power and high voltage (> 200 V) applications.
- PV power generation (cell, interconnect, and small self-deployable arrays) for CubeSat/ small satellite applications.
- PV module/ component technologies that emphasize low mass and cost reduction (in materials, fabrication and testing).
- Improvements to solar cell efficiency that are consistent with low cost, high volume fabrication techniques
- Automated/ modular fabrication methods for PV panels/ modules on flexible blankets (includes cell laydown, interconnects, shielding and high voltage operation mitigation techniques).
- Integrated PV system including cells, blanket, array, inverters, interconnect technologies, storage, structures, etc. with a balance-of-components while matching specifications of various systems.
- Simulated PV capability that take optimizes system components, ensures compatibility of modules/inverters, and takes temperature extremes and unique aspects of the space environment into account including radiation tolerance.

Research 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 demonstration unit for functional and environmental testing at the completion of the Phase II contract.

Space Communications and Navigation (SCaN) 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.

Today our communication and navigation capabilities, using Radio Frequency technology, can support our spacecraft to the fringes of the solar system and beyond. As we move into the future, we are challenged to increase current data rates - 300 Mbps in LEO to about 6 Mbps at Mars - to support the anticipated numerous missions for space science, earth science and exploration of the universe. Technologies such as optical systems, RF systems including ground based Earth stations, surface networks, cognitive and adaptive systems and networks, access links, reprogrammable communications systems, advanced antenna technology, innovative, relevant research in the areas of positioning, navigation, and timing (PNT) and communications in support of launch services are very important to the future of exploration and science activities of NASA.

This year, three major technology areas are being solicited:

- Long Range Optical Telecommunications, seeks innovative technologies for significant improvement in long range (> 0.1 AU) optical telecommunications providing increased data throughput in both directions, and lower spacecraft mass and power, in support of human and robotic space missions.
- Intelligent Communications Systems, seeks advancements of cognitive system capabilities to sense, detect, adapt, and learn from the environment to improve communication and/or navigation capabilities for NASA missions. And
- Flight Dynamics and Navigation Technology for the development of software tools, ground facilities, system concepts and on-board devices to enhance capabilities for providing spacecraft position, attitude, and velocity and for advancements that enable independence from earth supervision. For spacecraft systems, emphasis is placed on size, weight and power improvements to reduce the user spacecraft burden or provide greater capability within NASA's networks. Innovative solutions centered on operational issues are needed in all of the aforementioned areas. All technologies developed under this topic area to be aligned with the Architecture Definition Document and technical direction as established by the NASA SCA Office.

For more details: <https://www.spacecomm.nasa.gov/spacecomm/> [4]

Sub Topics:

H9.01 Long Range Optical Telecommunications

Lead Center: JPL

Participating Center(s): GRC, GSFC

This subtopic seeks innovative technologies for long range (> 0.1 AU) optical telecommunications supporting the needs of space missions where human and robotic explorers will visit distant bodies within the solar system and beyond. Multi-use technologies that will also benefit high rate optical communications in cis-lunar and Earth-Sun Lagrange point domains are of particular interest. Goals are increased data-rate capability in both directions and significant reductions of telecommunications system mass, power-consumption, and volume at the spacecraft.

Proposals are sought in the following areas (TRL3 Phase I, and TRL4-5 Phase II):

- *Spacecraft Disturbance Isolation Platforms and Related Technologies* - Compact, low mass, space-qualifiable, vibration isolation and spacecraft disturbance rejection assemblies with included re-usable launch lock that require less than 5 W of average power and mass less than 3 kg that will attenuate an integrated spacecraft micro-vibration angular disturbance of 150 micro-radians (with a spectrum of $10E-6 \text{ rad}^2/\text{Hz}$ below 0.1 Hz, with a 20 dB/decade roll-off), plus an assumed translational disturbance resulting from an offset of 2 m between the payload and the center of rotation of the spacecraft, to less than 0.15 micro-radians (1-sigma), for payloads massing between 3 and 25 kg. Proposed solutions may use control inputs from ground-beacon-based pointing sensor with noise of 150 nrad/sqrt (Hz). Also desired are

innovative low-noise, low mass, low power, DC-kHz bandwidth inertial, angular, position, or rate sensors to assist platform stabilization, including beaconless pointing.

- *PPM Space Laser Transmitters* - Space-qualifiable, 1520 to 1630 nm laser transmitter for pulse-position modulated (PPM) with >25% DC-to-optical (wall-plug) efficiency. Transmitter must support laser pulse widths from 0.2 ns (or lower) to 16 ns (or greater) for PPM orders from 16 slots per symbol (6.25% average duty cycle) to 256 slots per symbol plus 64 slots of inter-symbol guard time (0.31% average duty cycle). Other desired parameters include: <35 ps pulse rise and fall times and jitter; <25% pulse-to-pulse energy variation (at a given pulse width); single spatial mode output with near transform limited spectral width, single polarization with at least 20 dB polarization extinction ratio; amplitude extinction ratio greater than 48dB, average output power of 10 to 100W; massing less than 500 g/W. Laser transmitter to feature slot-serial PPM data input at CML, LVDS, or AC-coupled PCEL levels and an RS-422 or LVDS levels control port. All power consumed by control electronics will be considered as part of DC-to-optical efficiency. Also of interest for the laser transmitter is robust and compact packaging with >100krad radiation tolerant electronics inherent in the design. Detailed description of approaches to achieve the stated efficiency is a must. Also of interest is a space-qualifiable high power fiber switch for implementing redundant space laser transmitters.
- *PPM Ground Laser Transmitters* - >2000W average power PPM laser transmitters for nested modulation forward links to support simultaneous data rates of ~10 b/s (outer code) and at least 10 Mb/s (inner code) with an outer rate inter-symbol guard time of 50%. Operational wavelength in either 1030 - 1080 nm or 1480 - 1570 nm bands. Other desired parameters include: spectral line width of 0.5 nm or less; amplitude extinction ratio greater than 35 dB; output M-squared of 1.2 or less; projected MTTF of at least 20,000 hours; high wall-plug AC-to-optical power efficiency.
- *Photon Counting Near-infrared Detectors Arrays for Ground Receivers* - Close packed (not lens-coupled) kilo-pixel arrays sensitive to 1520 to 1630 nm wavelength range with single photon detection efficiencies greater than 90%, single photon detection jitters less than 40 ps FWHM, total active diameter greater than 500 microns, 1 dB saturation rates of at least 10 mega-photons (detected) per pixel, false count rates (intrinsic dark rate plus after-pulsing rate) of less than 1 MHz/square-mm. Also desired are cryogenic read-out integrated circuits with an operating temperature of 40K capable of time-tagging electronic pulses from 64 high-bandwidth readout channels to an accuracy of 100 ps or better and a maximum count rate of 10 MHz per channel. The approach should demonstrate scalability to >1000 readout channels. Also of interest are: sub-Kelvin cryogenic systems which can support >1000 channels of high-bandwidth (2 GHz or higher) readout signals with a low-temperature hold time of 24 hours, and preferably can be tilted from vertical to near-horizontal during operations; cryogenic interconnects and vacuum feedthroughs for high-density cabling solutions capable of supporting kilochannel readouts from a 1 K detector focal plane stage to room temperature.
- *Photon Counting PPM Digital Ground Receivers* - Digital receiver and decoder assemblies for processing photon counting detector array outputs of PPM encoded data. Receiver to support PPM orders from 2 to 256, data rates to at least 1 Gb/s, and PPM slot widths down to 200 ps. Receiver shall support SCPPM or other demonstrated low-gap-to-capacity (< 1 dB) forward error correction code for PPM. Receiver shall provide signal and background photon flux estimates at kHz rates to support 2-axis control of a fine pointing mirror in a ground receiver telescope.
- *Photon Counting Near-infrared Detectors Arrays for Flight Receivers* - 128x128 or larger array with integrated read-out integrated circuit and thermo-electric cooling for the 1030 to 1080 nm or 1520 to 1650 nm wavelength range with single photon detection efficiencies greater than 40% and 1dB saturation loss rates of at least 2 mega-photons/pixel and dark count rates of <10 kHz/pixel. ROIC to provide time-stamping of each photon arrival with a precision of 500 ps or better, and an interface bus bandwidth of 125 MHz or less. Radiation doses of at least 5 Krad (unshielded) shall result in less than 10% drop in single photon detection efficiency and less than 2X increase in dark count rate.
- *Advanced Flight Opto-electronics* - Ultra-small, low-mass, low-cost, low-power, modular transceivers, transponders, amplifiers, and components for 1520 to 1630 nm optical links at GHz modulation bandwidths, incorporating integrated photonic circuits and other components such as commercially-available ASICs to provide forward-error-correction and other digital signal processing as required.
- *Ground-based Telescope Assembly* - All-weather ground station telescope/photon-bucket technologies for implementing effective receive areas of > 100 square meters at a projected production cost of < \$300K per square meter. Operations wavelength is monochromatic at a wavelength in the range of 1000-1600nm. Key requirements: a maximum image spot size of <20 microradian (static error); capable of operation while pointing to within 3° of the solar limb; and field-of-view of >50 micro-radian. Telescope shall be positioned with a two-axis gimbal capable of <50 micro-radian pointing accuracy, with dynamic error <10 micro-radian RMS while tracking after tip-tilt correction.

Research should be conducted to convincingly prove technical feasibility (proof-of-concept) during Phase I, ideally through hardware development, with clear pathways to demonstrating and delivering functional hardware meeting all objectives and specifications, in Phase II.

References:

- (<http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/42091/1/11-1338.pdf> [5])
- (http://ipnpr.jpl.nasa.gov/progress_report/42-183/183A.pdf [6])
- (http://ipnpr.jpl.nasa.gov/progress_report/42-185/185D.pdf [7])
- (http://ipnpr.jpl.nasa.gov/progress_report/42-182/182C.pdf [8])

H9.02 Intelligent Communication Systems

Lead Center: GRC

Participating Center(s): JPL

NASA seeks novel approaches to improve mission communication and navigation capabilities for science and exploration through advancements in cognitive systems and automation. Over the past 10 years software defined radios and their applications have emerged and demonstrated the potential and applicability of reconfigurable platforms and applications to space missions. The SCaN Testbed launched in 2012 demonstrated software defined radio applications capable of sensing and reacting to environment conditions. Building on this foundation, cognition and automation have the potential to improve system performance, increase data volume return, improve data transmission efficiency, and reduce user spacecraft burden to improve science return from NASA missions. Understanding how and where to apply cognitive and automation technologies is critical and should be discussed in the proposal.

This solicitation seeks advancements in cognitive and automation systems and components as applied to communication and navigation capabilities. 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 or navigation capabilities for the mission. The goal is to improve the state of the user spacecraft system to maximize science data return, enable substantial efficiencies, or adapt to unplanned scenarios. While much interest in cognitive radio entails dynamic spectrum access, this subtopic is also interested in other ways to apply cognition and automation. Areas of interest to develop and/or demonstrate are as follows:

- *Cognitive engine (algorithm) and component development* - to demonstrate new capability in sensing and adapting to the radio/mission environment. Technologies may include changes in physical (PHY) layer data rate, modulation, and coding, medium access control (MAC) layers for new protocols, and cognitive engines to negotiate changes between nodes and throughout the network, learning opportunities and techniques, and networking and application layers (and across layers) to adjust to signal conditions, efficiently using links for different data types (e.g., telemetry v. video), adaptive and intelligent routing, etc.
- *System wide distributed intelligence of cognitive and intelligent applications* - 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) system wide effects (e.g., protocols) to decisions made by one or more communication/navigation elements, how to handle unexpected or undesired decisions, how changing data rate, modulation, or frequency between nodes effects data distribution through relay satellites, and throughout space and ground network and multiple access techniques that optimize connectivity and throughput while minimizing onboard data storage and interference.
- *Flexible and adaptive hardware systems* - (e.g., signal processing platforms, adaptive front ends for RF or optical communications, and other intelligent electronics) which directly implements or demonstrates cognitive or intelligent applications as an alternative to more general software-based intelligent systems. Systems should highlight advancements to provide needed capability while minimizing on-board resources and cost.
- *Autonomous Ka-band and/or optical communications antenna pointing on mission spacecraft within intelligent multiple access systems* - 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 with both the relays and ground terminals on a coordinated, non-interfering basis along with other spacecraft using these same space- and ground-based assets. Areas of interest include (but are not limited to): autonomous navigation and pointing techniques with sufficient precision to minimize pointing loss; techniques to coordinate multiple autonomous activities and adaptive or cognitive radio systems that can continuously maximize data return via both multiple beam GEO relays and direct to ground links.

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) and show a path towards Phase II hardware/software demonstration with delivery of a demonstration unit or software product for NASA testing at the completion of the Phase II contract.

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). Delivery of the simulation or demonstration software and/or platform(s) to NASA. Plan for verification of specific measurements or capabilities to be performed at the end of Phase II.

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

Depending on the status at the time, there may be opportunity to port software (cognitive engines and applications) to the SCan Testbed software defined radio ground and/or flight system on International Space Station (ISS) for demonstration and/or test in the actual space environment. At a minimum, the SCan Testbed ground system radio testbed will provide an ideal cognitive application test environment, as user spacecraft, relay satellites, and control centers are all emulated in hardware. Software applications and infrastructure should consider 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> [9]).

H9.03 Flight Dynamics and Navigation Technology

Lead Center: GSFC

Participating Center(s): GRC

NASA is investing in the development of software tools, systems and devices to enhance 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. Interest includes software tools, ground facilities as well as system concepts and on-board devices to support organic capabilities for its deep-space missions. Products developed under this sub-topic can be in support of any mission phase from design and development through operation and disposal. Proposals can be for either near-Earth or interplanetary missions. Specific application areas that will be considered under this subtopic are:

- Software that fuses and analyzes spacecraft sensor data and other spacecraft tracking data available at ground/mission operations centers (i.e., facility software). Proposals for algorithms and software for flight dynamics GNC technologies can support mission engineering activities at any stage of development from the concept-phase/pre-formulation through operations and disposal. 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/> [10]), GPS-Inferred Positioning System and Orbit Analysis Simulation Software, (<http://gipsy.jpl.nasa.gov/orms/goa/> [11]), Optimal Trajectories by Implicit Simulation (<http://otis.grc.nasa.gov/> [12]) 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:
 - Applications of optimal control theory to high and low thrust space flight guidance and control

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- systems.
- Numerical methods and solvers for robust targeting, and non-linear, constrained optimization.
 - 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.
 - 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 combine measurements from multiple sensor suites in a highly-coupled manner to improve upon the overall system accuracy.
 - 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 celestial navigation techniques including devices and systems, especially those that support of deep-space, planetary missions. System concepts should support significant advances of independence from Earth supervision including the ability to operate effectively in the absence of Earth-based transmissions or transmissions from planetary relay spacecraft with those that operate in the complete absence of human intervention or Earth-based transmissions are preferred. Proposed solutions should meet objectives while minimizing spacecraft burden by requiring low power and minimal mass and volume. User spacecraft impact is of significant importance and proposed solutions include assessments of mass, power, thermal impact on targeted mission spacecraft as well as identifying any requirements placed on the user spacecraft by the proposed design. Of particular interest are concepts that support pointing of high rate optical communications terminals to earth terminals that do not rely on the use of optical uplinks or beacons for achieving proper pointing of the communication beam. However, concepts which are capable of supporting planetary missions of any type are of interest. Proposals that include re-purposing/cross-purposing of advanced sensors contemplated for future deep-space missions such as x-ray telescopes are preferred. In addition to advances in positioning, attitude estimation, orbit determination, guidance, navigation and control particular interest in the area of deep-space celestial navigation lies in the following focus topics:
 - Time and frequency keeping and dissemination.
 - Advanced methods and sensors for optical/IR detection of star fields (i.e., star cameras).
 - Advanced methods and sensors detecting RF and x-ray pulsars.
 - Methods to process celestial observations to perform Orbit Determination (OD) and precision attitude estimation.

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 Cryogenic Purge Gas Recovery and Reclamation

Lead Center: SSC

Participating Center(s): GRC, KSC

Helium is becoming a major issue for NASA and the country. Helium is used as a purge gas in cryogenic piping systems to reduce the concentration of hydrogen below the flammable threshold at test and launch complexes. Most of the Nation's helium comes from the National Helium Reserve operated by the Bureau of Land Management (BLM). The statutory authority for BLM to operate is expiring and responsibility is being transferred to the commercial sector. Helium is a non-renewable gas that is in limited supply. There are already helium shortages and prices are going up.

Fuel cell technology has demonstrated the ability to output high quality helium from a hydrogen/helium gas mixture. The helium/hydrogen gas mixture was collected, helium extracted and recovered. The recovered helium meets the stringent purity requirements for reuse. Proposals are sought that improve upon the demonstrated technology or develop new alternative cryogenic gas separation technology.

This subtopic has the potential to substantially reduce the costs of NASA's test and launch operations. Additional development is needed to increase the efficiency of the recovery process, capture large amounts of mixed gases, and provide real-time solid state sensor technologies for characterizing constituent gases. Helium is the highest value cryogenic gas, but other cryogenic gases could be conserved also.

Specific areas of interest includes the following technologies:

- Enhanced membrane technologies including Proton Exchange Membrane (PEM) fuel cells that increase the efficiency, recovery production rate or life span of fuel cell based separation technologies.
- Development of alternative cryogenic gas separation technologies.
- Technologies for the rapid capture and storage of high volumes of mixed cryogenic gases.
- Development of zero trapped gas system technologies to improve purge effectiveness.
- Development of real-time, solid state sensor technologies for monitoring the current state of the system concentration levels and helium/nitrogen purge process effectively (e.g., hydrogen, oxygen, water vapor content, etc.).

Examples of this type of technology:

- (<http://www.sustainableinnov.com/products/h2renew/> [13])
- (<http://www.extrel.com/> [14])

Radiation Protection Topic H11

The SBIR Topic area of Radiation Protection focuses on the development and testing of mitigation concepts to protect astronaut crews from the harmful effects of space radiation, both in low Earth orbit (LEO) and while conducting long duration missions beyond LEO. 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. Advances in radiation shielding systems technologies are needed to protect humans from all threats of space radiation. All particulate radiations are considered, including electrons, protons, neutrons, alpha particles, light ions, and heavy ions. This topic is particularly interested in mid-TRL (technology readiness level) technologies. Lightweight radiation shielding materials are needed to shield humans in aerospace transportation vehicles, large space structures, space stations, orbiters, landers, rovers, habitats, and spacesuits. The materials emphasis should be on non-parasitic radiation shielding materials, or multifunctional materials, where two of the functions are structural and radiation shielding. Non-materials solutions, such as utilizing food, water, trash, and treated waste already on board as radiation shielding are also sought. 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. Laboratory and spaceflight data are needed to validate the accuracy of radiation transport codes, as well as to validate the effectiveness of multifunctional radiation shielding materials and subsystems. Also of interest are comprehensive radiation shielding databases and design tools to enable designers to incorporate and optimize radiation shielding into space systems during the initial design phases. Research under this topic should be conducted to demonstrate technical feasibility during Phase I and show a path forward to Phase II hardware demonstration. When possible, deliver a demonstration unit for functional and radiation testing at the completion of the Phase II contract.

Sub Topics:

H11.01 Radiation Shielding Technologies

Lead Center: LaRC

Participating Center(s): MSFC

Advances in radiation shielding technologies are needed to protect humans from the hazards of space radiation during NASA missions. All space radiation environments in which humans may travel in the foreseeable future are considered, including low Earth orbit (LEO), geosynchronous orbit (GEO), Moon, Mars, and the Asteroids. All particulate radiations are considered, including electrons, protons, neutrons, alpha particles, and light to heavy ions. Mid-TRL (3 to 5) technologies of specific interest include, but are not limited to, the following:

- Lightweight innovative radiation shielding materials are needed to shield humans in aerospace transportation vehicles, large space structures such as space stations, orbiters, landers, rovers, habitats, and spacesuits. The materials emphasis should be on non-parasitic radiation shielding materials, or multifunctional materials, where two of the functions are structural and radiation shielding. Materials of interest include, but are not limited to, polymers, polymer matrix composites, nanomaterials, and regolith derived materials. The objective is to replace primary, secondary, and interior structures, including equipment and components, with radiation protective materials. There is particular interest in the development of high hydrogen content materials and materials systems to replace traditional materials (particularly metals). Note that the goal is not necessarily mass reduction. The goal is replacing mass with mass that not only meets structural requirements, but also is more effective for radiation protection. Decreased mass is a bonus. High hydrogen materials can include polymer matrix composites, where the polymer and/or fibers are high in hydrogen content. Phase I deliverables are materials coupons. Phase II deliverables are materials panels or standard materials test specimens, along with relevant materials test data.
- Processing of regolith derived materials for radiation shielding structures is also of interest. The regolith can be combined with polymer matrix materials to increase the hydrogen content. Phase I deliverables are materials coupons. Phase II deliverables are materials panels or standard materials test specimens, along with relevant materials test data.
- Non-materials solutions are also of interest. Examples are utilizing food, water, supplies, trash, and treated waste already onboard as radiation shielding. This involves developing and utilizing storage containers for food, supplies, and treated waste as multipurpose radiation shielding. This includes developing multipurpose containers for biomaterials to contain treated waste safely without adversely affecting crew (smell/leakage/handling/transfer). Other options include developing water walls for crew quarters and vehicle walls to be used for storing drinking water, potable water, and treated waste, as well as repurposing the trash and treated waste into protective shielding. Phase I deliverables are detailed conceptual designs.

Phase II deliverables are initial prototypes.

- NASA is also interested in out-of-the-box credible solutions for radiation shielding. Phase I deliverables are detailed conceptual designs. Phase II deliverables are initial prototypes.
- Advanced computer codes for rapid computing that can handle complex geometries and large collections of data are needed to model and predict the transport of radiation through space vehicles and structures. These are needed to support optimization studies and analyses for vehicle design and mission planning. Phase I deliverables are alpha tested computer codes. Phase II deliverables are beta tested computer codes.
- Experimental laboratory and spaceflight data are needed to validate the accuracy of radiation transport codes and analysis tools. Phase I deliverables are draft data compilations or databases. Phase II deliverables are formal, publishable, and archival data compilations or databases.

For additional information, please see the following link:

- (http://www.nasa.gov/pdf/500436main_TA06-ID_rev6a_NRC_wTASR.pdf [15])

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 early lunar missions of extended duration. The Human Research Roadmap (<http://humanresearchroadmap.nasa.gov> [16]) 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 & Performance.
- Exploration Medical Capability.
- Space Human Factors and Habitability.
- Space Radiation and ISS Medical Projects.

Each of the HRP Elements address a subset of the risks, with ISS Medical Projects responsible for the implementation of the research on various space and ground analog platforms. With the exception of Space Radiation, HRP subtopics are aligned with the Elements and solicit technologies identified in their respective research plans.

Sub Topics:

H12.01 Measurements of Net Ocular Blood Flow

Lead Center: GRC

Participating Center(s): JSC

The goal of this SBIR call is the development of rapid and accurate hardware to characterize the net blood flow to and from the eye. Due to limits on instrumentation, most of the literature on ocular blood flow to date has

emphasized measurements that only partially characterize the net flow, such as minimum and maximum velocity in a single retinal arterial vessel or choroidal thickness in the vicinity of the fovea. However, there is significant spatial and interindividual variation in these ocular structures, for example, in choroidal and retinal thickness and in arterial and venous branching structures. Consequently, there are likely to be new insights to be gained from examining the choroid and retina from a bulk perspective. Recent advances in high-quality imaging, such as those based on wide-field Optical Coherence Tomography or high-resolution angiography, have allowed increased depth of penetration at high resolution for unparalleled accuracy in choroidal and retinal measurements that extend well beyond the posterior pole of the eye. The ready availability of computational resources renders it straightforward to capture and analyze the entire time history of ocular hemodynamics.

This SBIR solicits novel hardware that can quantify net ocular blood flow in the retina. Measurements of interest include the temporal history of the following:

- Maps of choroidal and retinal thickness, which include near- and far-field contributions.
- Net volume of the choroid and retina.
- Net volumetric blood flow to and from the choroid and retina.
- Pressures and net luminal areas at the entrance and exit of the choroid and retina.

Measurements must be presented in physical units, such as blood flow in milliliters per minute. The measurement system must also process the raw data, either in a real-time or post-processing mode. Data analysis capabilities should include the calculation of the overall time-averaged mean values, as well as the mean waveform over a cardiac cycle. It would be of significant interest if comparable measurements were made simultaneously of intraocular pressure, reference arterial pressure (systemic, brachial and/or ophthalmic artery), fundus pulsation amplitude, and/or heart rate.

Phase I Deliverables - Concept of hardware capable of producing some or all of the above measurements.

Phase II Deliverables - Prototype hardware and data from a pilot study.

H12.02 Unobtrusive Workload Measurement

Lead Center: JSC

Participating Center(s): ARC

Task design and associated hardware and software impose cognitive and physical demands on an operator and thus, drive the workload associated with a task. This solicitation is looking for technologies and methods to measure, assess, and predict astronaut workload unobtrusively, and to extend these technologies to measuring and predicting astronaut workload during long duration operations. Unobtrusive measures would be ones that do not require operators to specifically interact with a technology or provide inputs, and would not interrupt an operator's work.

Astronauts on long-duration missions will potentially have long periods of low workload and short bursts of high workload combined with reduced workload capacity that needs to be taken into account for system and mission design. Both high task demand and reduced workload capacity at any phase of a flight may lead to performance errors, which could potentially compromise mission objectives, and consequently the mission.

Astronauts, mission planners, and system designers require the capability to assess and predict when astronauts will be at a reduced capacity resulting from either work underload or from work overload. An unobtrusive workload tool could be used during development to ensure a system produces acceptable workload, or in real-time, to drive schedule modifications or to adapt interfaces based on the current workload the astronaut is experiencing. Unobtrusive objective measures such as video, voice, thermal infrared imaging or eye tracking methods may be more appropriate when measuring long duration workload, so long as the technology's credibility is ensured.

Phase I of this SBIR is to complete a review of the current state of the art in automatically, unobtrusively measuring and tracking workload and informing astronaut of such workload levels in scenarios that are applicable to long duration missions. This Phase I effort will identify suitable unobtrusive measurement technologies and the parameters that need to be included in a candidate workload algorithm and subsequently generate the algorithm.

NASA has already supported the development of wrist and arm-worn devices, therefore any unobtrusive wearables proposed should consider alternative concepts and/or new implementations of existing wearable technologies. Phase II of this SBIR is to take the current state of the art and recommendations from the Phase I effort to develop an unobtrusive workload measurement tool prototype, and test and validate the tool.

H12.03 Technology for Monitoring Muscle Protein Synthesis and Breakdown in Spaceflight

Lead Center: JSC

Post flight decrements in skeletal muscle size and function are well documented, however, the true time course of muscle adaptations during long duration spaceflight have thus far been unaddressed. This information is of importance because it can help to identify:

- When the most critical stages of adaptation to space are occurring.
- Whether changes are occurring at a constant rate or if they begin to plateau, and if so when.
- Targeted muscle countermeasures to mitigate true muscle loss.

Muscle protein synthesis and breakdown are typically measured via invasive biopsy which will not be feasible during space flight missions. Current terrestrial assays for protein synthesis involve use of stable isotopes to measure incorporation of amino acids into muscle and are determined in muscle biopsy samples. Markers for protein degradation (e.g., MuRF1, Atrogen-1) in muscle biopsy samples are often determined by real time PCR (mRNA expression) or Western blot analysis (protein expression), though these results are primarily qualitative. This subtopic seeks novel, non- or minimally-invasive technologies to measure muscle protein turnover for use in subsequent research studies. The most important measurement would be a synthesis: breakdown ratio indicative of the state of muscle balance (formation, breakdown or stability) as opposed to exact protein synthetic rates. However, absolute protein synthesis and breakdown rates are highly desirable.

This Subtopic addresses the following Human Research Program requirements:

- Risk of Impaired Performance Due to Reduced Muscle Mass, Strength and Endurance
- Gap M24. Characterize the time course of changes in muscle protein turnover, muscle mass and function during long duration space flight.

The technology developed should accurately be able to quantify protein synthesis, breakdown and total turnover.

A successful proposal will include the technologies being considered and detailed test plan for evaluating them during Phase I. A vision for miniaturizing the device and operating the device in microgravity is required.

Phase I Deliverables - Test results and plan for developing a low volume, low mass, easy-to-operate prototype. The expected TRL resulting from the Phase I effort should be 4.

Phase II Deliverables - Prototype in year 1 with minimal human testing in year 2 to demonstrate efficacy.

Non-Destructive Evaluation 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 3-D 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 Advanced NDE Modeling 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 3-D 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. It is assumed that all systems will have high resolution high volume data. Modeling efforts should be physics based and account for variations between material aging characteristics 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 Many Integrated Core (MIC) Architectures. 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, outlining the proposed approach to develop a given product (TRL 2-4), and describing any models and algorithms developed/utilized. Plan for Phase II including proposed verification methods.

Phase II Deliverables - Software of proposed product, report including detailed description of algorithms and models, 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): 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 measurable phenomena 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 and Development of Improved Exploration Technologies and Increased ISS Utilization Topic H14

The Human Exploration and Operations Mission Directorate (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. This new deep space exploration era starts with increasingly challenging test missions in cis-lunar space, including flights to the Lagrange points, followed by human missions to near-Earth asteroids (NEAs), Earth's moon, the moons of Mars, and Mars itself as part of a sustained journey of exploration in the inner solar system. HEOMD was formed in 2011 by combining the Space Operations Mission Directorate (SOMD) and the Exploration Systems Mission Directorate (ESMD) to optimize the elements, systems, and technologies of the precursor Directorates to the maximum extent possible. HEOMD accomplishes its mission through the following goals:

- Development and use of launch systems and in-space transport capabilities permitting exploration of various regions of space.
- Development of space habitats that permit the processing and operation of physical and life science

experiments in the space environment.

- Development of means to return data and explorers to Earth from these in-space operations.

HEOMD encapsulates several key technology areas, including Space Transportation, Space Communications and Navigation, Human Research and Health Maintenance, Radiation Protection, Life Support and Habitation, High Efficiency Space Power Systems, and Ground Processing/ISS Utilization. These areas of focus, along with enabling technologies and capabilities, will continue to evolve synergistically as the directorate guides their development and enhancement to meet future needs. In addition, operational capacity will continue to grow by including these enhancements as other NASA programs develop new mission capabilities and requirements. To generate new capabilities and contribute to the knowledge required for humans to explore in-space destinations, HEOMD is responsible for:

- 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.
- Increasing investments in Human Operations and research to prepare for long-duration missions in deep space.
- Enabling U.S. commercial human spaceflight capabilities.
- Developing communication and navigation technologies.
- Maximizing ISS utilization.

HEOMD looks forward to incorporating SBIR-developed technologies into current and future systems to contribute to the expansion of humanity across the solar system while providing continued cost effective space access and operations for its customers, with a high standard of safety, reliability, and affordability.

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. 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 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.
- Development of instruments and software for reconstructing 3-D tomographic images that provides a non-intrusive measurement of the spatial phase distribution in gas-liquid flows. Instruments must be capable of a high temporal acquisition (200 Hz or greater) with resolution between phase boundaries within the

measured region on the order of 2-3 millimeters or better. The fluids are typically air-water systems. Providing flight qualified hardware with these capabilities will allow for real-time measurements of phase distribution for a number of life support and biology technologies such as reactor beds, separators, and plant habitats.

- Devices that provide rapid or snap freezing of samples are sought due to their capability to provide for the preservation of samples that support a broad range of space research in the plant, microbiology, cell biology and animal biology subject areas.
- Increased use of the Light Microscopy Module (LMM). Several additions to the module continue to be solicited, such as: laser tweezers, dynamic light scattering, stage stabilization (or sample position encoding) for reconstructing better 3-D confocal images.
- 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 handheld portable use. Battery powered wireless operation is desirable. Specific issues to be addressed include: pitting from micrometeoroid impacts, stress fractures, leaking of cooling gases and liquids and detection of abnormal hot spots in power electronics and circuit boards.

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.

H14.02 International Space Station (ISS) Demonstration of Improved Exploration Technologies

Lead Center: JSC

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. Successful submissions will describe requisite testing on ISS. Proposals that do not require testing at the ISS should respond to other subtopic solicitations in appropriate technical areas. If submitted to this subtopic they will be considered non-responsive.

NASA encourages submissions that increase the Technology Readiness Level of space exploration and pioneering technologies in areas that include but are not limited to the following:

- Ambient temperature catalyst replacement for the ISS Water Processing Assembly.
- High pressure oxygen generation applicable to both ISS and future human space flight vehicles, demonstrated on ISS.

For all proposed technologies, research should at a minimum 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 flight unit or software package for ISS testing.

Phase I Deliverables - Research to identify and evaluate candidate technologies applications to demonstrate the technical feasibility and show a path towards a hardware/software demonstration. 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 prototypes that can be demonstrated on orbit (TRL 8). The contract should deliver 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.

Proposals should be generated to assume costs that are limited to the deliverables and the ISS Program, if chosen for flight, would provide safety, upmass and other integration costs.

Potential NASA Customers include:

- International Space Station Program (http://www.nasa.gov/mission_pages/station/main/index.html [17]).
- Orion Multipurpose Crew Vehicle (<http://www.nasa.gov/exploration/systems/mpcv/index.html> [18]).

H14.03 Recycling/Reclamation of 3-D Printer Plastic Including Transformation of Launch Package Solutions into 3-D Printed Parts

Lead Center: MSFC

Participating Center(s): ARC, JSC, KSC

The National Aeronautics and Space Administration (NASA) has a long-term strategy to fabricate components and equipment on-demand for crew exploration missions. The greater the distance from Earth and the longer the mission duration, the more difficult resupply becomes; thus requiring a significant change from the current space travel supply chain model. The ISS is an ideal platform to begin testing and transitioning from the current model for resupply and repair to one that is more suitable for exploration missions. 3-D Printing, more formally known as Additive Manufacturing, is the method of building parts/objects/tools layer-by-layer. 3-D Printers on-board ISS will use extrusion-based additive manufacturing, which involves building an object out of plastic deposited by a wire-feed via an extruder head. While this process does provide on-demand capability for printing parts, to truly develop a self-sustaining, closed-loop on-orbit manufacturing process that will result in meaningfully less mass to launch and enabling space exploration, a means of recycling/reclaiming readily available materials will ultimately be required.

NASA seeks launch packing solutions that can be composed of materials suitable for recyclable processing into 1.75mm filament and subsequently 3-D printed parts. This capability will significantly decrease current waste and substantially increase sustainability. The solution may be obtained using a variety of approaches, such as:

- Converting commonly used 3-D printing feedstocks into packing solutions, including but not limited foam or bags.
- Transforming traditional packing materials into 3-D Printing feedstock.
- Developing a technology that utilizes a novel approach to identify compatible materials for both packing solutions and 3-D Printing. For example, this could include such materials as netting, fabrics, structures, containers, etc.

Examples of traditional packing materials currently used for ISS, as well as commonly used feedstocks and types of 3-D Printed parts are provided below. These are intended to serve as examples rather than requirements. The proposal does not have to be limited to these materials:

- Foams currently used on ISS:
 - Plastazote (LD24FR & LD45FR).
 - Polyethylene.
 - Polyurethane.
 - PVDF.
 - PTFE film (for bubble wrap).
- Bagging materials currently used on ISS:
 - Pink Poly (not pink and white).
 - Llumaloy (good for ESD compatibility).

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- Tedlar (particularly for containment).
 - Kynar (positive flammability ratings).
 - Common Feedstock Materials:
 - ABS.
 - PTFE.
 - PEAK.
 - Ultem.
 - Examples of 3-D Printed Parts:
 - Common hand tools.
 - Handles, containers.
 - Clips.
 - Personal items such as grooming tools.
 - 'Seat track' strips.
 - Corresponding studs.

Phase I Deliverable is a Technical Feasibility Study and should provide:

- Demonstration of a close-looped system that provides launch packing solutions that can be recycled into 1.75mm filament for creating 3-D Printed parts without requiring any additional mass other than the shared packing/printing materials and process. The 3-D Printed part(s) must be able to be printed using 1.75mm filament feedstock via a Fused Deposition Melting (FDM) process.
- A materials assessment, which addresses such things as materials composition, flammability, toxicity, off-gassing, etc.
- Technology Readiness Level (TRL) rating from 2-5.
- A Systems Engineering and Proposed Design path for developing an ISS locker-sized hardware demonstration for functional testing at the completion of the Phase II contract.

The ultimate objective is to evolve this technology into a Phase II SBIR ISS Technology Demonstration payload.

H14.04 Optical Components, Sensors, and Systems for ISS Utilization

Lead Center: LaRC

The International Space Station (ISS) is an on-orbit research platform that provides a superior environment for human health and exploration, technology testing for enabling future exploration, research in basic life and physical science, and earth and space science as enunciated in the NASA Authorization ACT of 2010. This subtopic would focus on the utilization of ISS as a foremost test bed for test, operation, and validation of the functionality of advanced optical components, sensors and systems for enabling future exploration. The goal of this subtopic research is to satisfy the mission of the International Space Station (ISS) Program by advancing science and technology research and there by significantly contributing to expand human knowledge, inspire and educate the next generation, foster the commercial development of space and demonstrate capabilities to enable future exploration missions beyond low Earth orbit (LEO) as discussed in the International Space Station (ISS) Researcher's Guide is published by the NASA ISS Program Science Office. Under this subtopic, innovative research topics compatible to ISS test environment would address HEOMD core issues related to radiation protection, deep space habitat elements and analog missions.

This subtopic would take advantage of revolutionary and rapid advances that are taking place in optics, materials and processing disciplines. Development of sensors and systems using innovative sources, detectors, materials, components and configurations for accomplishing new and/or improved performance, increased reliability and ruggedness, reduction in size, weight and power consumption (SWaP), and cost would advance HEOMD missions.

Topics of interest include but not limited to optical materials, optical components such high temperature and broadband windows and elements, active and passive sensing architectures, smart sensors and sensor suites including multifunctional aspects, monolithic or hybrid high operating temperature detectors and focal plane arrays, ISS compatible miniature remote sensing systems for characterization of hard targets, terrain mapping, deep space

imaging (3-D and hyper spectral) sensors and systems, and precision, navigation, and timing systems.

Regolith ISRU for Mission Consumable Production Topic H1.01

In-Situ Resource Utilization (ISRU) involves collecting and converting local resources into products that can reduce mission mass, cost, and/or risk of human exploration. The primary destinations of interest for human exploration, the Moon, Mars and its moons, and Near Earth Asteroids, all contain regolith/soil that contain resources that can be harvested into products. The resources of primary interest are water and other components that can be released from the regolith/soil by heating, and oxygen found in the minerals to make consumables for life support, power, and propulsion system applications. State of the art (SOA) technologies for many ISRU processes either do not exist, are too complex, are too inefficient (mass, power, and/or volume), or are not designed to operate in the extraterrestrial environment in which the resource is found, especially the micro-gravity environment for asteroids. The subtopic seeks proposals for critical technologies associated with the design, fabrication, and testing of hardware associated with extracting and transferring regolith/soil materials from extraterrestrial bodies and processing the material to extract water/volatiles and oxygen. Technologies developed under this subtopic are applicable to feasibility testing on parabolic flights and the ISS, assessment and processing of material on the redirected asteroid to trans-lunar space, and robotic precursor missions to the lunar poles and surface of Phobos and Mars. Proposals should address one or more of the categories below.

Simulants for Ground Testing

1. Simulants for ordinary chondrites (LL, L, H) and carbonaceous chondrites (CI, CM) asteroids that replicate asteroid material characteristics such as physical (particle size/shape, particle size distribution, hardness), thermal, mineral/chemical, and volatile content for ground testing. Proposers must justify proposed simulant components and preparation based on documented research/publications.

Regolith/Soil Acquisition and Preparation

The first step in production of mission consumables from in situ resources is acquisition and preparation of the resource for processing. Proposals in this category should address one or more of the following:

2. Excavation, transfer, and preparation of hydrated and icy-soil/regolith on Mars.
3. Excavation, transfer, and preparation of asteroidal material from ordinary and carbonaceous chondrite asteroids.
4. Excavation, transfer, and preparation of lunar polar icy regolith.

Notes: Proposals must address both the physical/mineral properties of the regolith/soil and the environmental conditions of the resources location. For item 3 proposals must address options for anchoring or maintaining position at the site of excavation to overcome forces applied during excavation and transfer of asteroidal material. Concepts need to minimize the generation of material that can float off and create a hazard. The proposal must identify the potential mass, power, and operation life impact of the selected option. All acquisition and preparation proposals must identify and address any issues with measuring and maintaining constant/known material transfer rates, and the impact of continuous versus batch-mode processing of the material. Proposals can combine regolith/soil acquisition and preparation with processing if it allows for reduced mass, power, and/or complexity.

Soil/Regolith Processing for Mission Consumables

Once the soil/regolith has been acquired and prepared, it is ready for processing. Proposals in this category should address one or more of the following:

5. Water/volatile extraction and separation from carbonaceous chondrites asteroidal material. Identify potential contaminants for subsequent cleaning based on the method utilized for volatile extraction. Besides water, carbon-based gases are of significant interest for fuel and plastic production. Proposals should consider additional steps (higher temperatures, reactants, etc.) that may increase the extraction and collection of carbon-based gases. Proposers are also encouraged to examine the applicability of micro-gravity asteroidal processing techniques for crew/trash waste processing.

6. Water/volatile extraction and separation from lunar polar icy material. Identify potential contaminants for subsequent cleaning based on the method utilized for volatile extraction.

7. Water vapor and other volatile separation and collection from other gases/liquids. Separation techniques must address potential contaminants.

8. Regenerative dust separation from product and reactant gases.

9. Oxygen extraction from ordinary and carbonaceous chondrites asteroidal material. Regeneration of reactants used in oxygen extraction is required.

10. Metal extraction from ordinary and carbonaceous chondrites asteroidal material. Regeneration of reactants used in metal extraction is required.

Notes: Proposals must specify whether the process is performed in batches or by continuous processing with appropriate sealing techniques to minimize reactant/product losses identified. Proposers are encouraged to address more than one of the Soil/Regolith Processing needs above. Proposals can combine regolith/soil processing with acquisition and preparation if it allows for reduced mass, power, and/or complexity. Proposals addressing only item 7 or 8 need to identify the potential soil/regolith processing technique it is applicable for as well as minimum and maximum flow rates and/or product/reactant concentrations.

Further Requirements for Proposals

All proposals need to identify the SOA of applicable technologies and processes:

- *For Lunar polar-based ISRU* - Assume ice content in regolith is between 5 and 10% at temperatures below 100 K. Regolith excavation down to at least 1 meter below the surface is required for Phase II. Proposals must address material transfer, handling, and processing of polar material under temporary sunlight and continuous shadowed solar/thermal conditions.
- *For Mars-based ISRU* - Assume hydrated soils between 3 and 15% (nominal 8%); icy soils containing 40% or more of ice. Soil excavation down to a minimum of 0.5 meters below the surface is required for Phase II. Proposals must recognize and address issues with perchlorate minerals in the Mars soil during processing and product separation. For hydrated soils, proposals must consider meeting time averaged excavation and processing rates of 3.5 to 7 kg/hr (8%) to 9 to 19 kg/hr (3%) soil to achieve time averaged water extraction and processing rates of 0.55 to 1.125 kg/hr. Proposals must consider and address operating life issues for surface applications that can last for up to 480 days of continuous operation.
- *For Asteroid-based ISRU* - Technologies requested are subscale to allow for future testing on the reduced gravity assets and the ISS, but must be extensible to larger scale applications. For testing on the ISS, proposed hardware will need to process resource materials on the order of hundreds of grams to 5 kilograms within 1 to 5 hours to investigate gravity-dependent/independent phenomena. Proposed technologies must show extensibility to future ISRU missions to an asteroid which will require an increase in acquisition and processing by 1 to 2 orders of magnitude with material excavation/acquisition down to at least 3 meters. Proposals must address design and operation issues associated with performing material transfer, handling, and/or processing of solid material with gas, liquid, or molten reactants under micro-gravity and vacuum conditions. Regolith processing reactors must further address material transfer into the reactor before processing and removal from the reactor after processing while minimizing loss of reactants/products and minimizing contamination of external surfaces.

Sub Topics:

In-Space Chemical Propulsion Topic H2.01

The goal of this subtopic is to examine a range of key technology options associated with space engines that use methane as the propellant. Successful proposals are sought for focused investments on key technologies and design concepts that may transform the path for future exploration of Mars. In-space propulsion is defined as the development and demonstration of technologies for ascent, orbit transfer, pulsing attitude/reaction control, and descent engines. Key operational and performance parameters include:

- Reaction control thruster development in the 5 to 100 lbf thrust class with a target vacuum specific impulse

of 325-sec. 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.

- Ascent/descent pressure-fed engines with 1,500 to 25,000 lbf thrust with a target vacuum specific impulse of 350 to 360-sec. The engine should be capable of throttling to 5:1 (20% power), and the chamber pressure should range from 200 to 650 psig.
- Ascent/descent pump-fed engine development is projected to range from 10,000 to 25,000 lbf thrust with a minimum vacuum specific impulse of 360-sec. The propulsion system should be capable of stable throttling to 10:1 (10% power). The engine shall achieve 90% rated thrust within 0.5 second of the issuance of the 'Engine ON' command.

Specific technologies of interest for operation with liquid and gaseous methane are sought. Relevance of the technology to compatibility and applicability to challenges with methane must be identified. In addition, these engines should be compatible with the future use of in situ produced propellants such as oxygen and methane. For all proposed technologies, the proposer shall show in the proposal how the component would fit in a system cycle based on thermal capabilities and pressure budgets. Propulsion technologies of interest that support the performance parameters defined above include:

- New additive manufacturing techniques that can be demonstrated to allow for rapid manufacturing, surface finishes, structural integrity, and significant costs savings for complex combustion devices and turbomachinery components compared to the conventional manufacturing. Manufacturing methods must scale to a final flight component.
- Low-mass propellant injectors that provide stable and uniform combustion over a wide range of propellant inlet conditions.
- Combustion chamber designs using high temperature materials, coatings, and/or ablatives for combustion chambers, nozzles, and nozzle extensions.
- Regenerative cooled combustion chamber technologies which offer improved performance and adequate chamber life.
- 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 fatigue life impellers, zero net positive suction head (NPSH) inducers, low leakage seals, and long life in situ propellant fed bearings.

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.

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 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 released to stay within the current environmental regulations. The NTP primary test requirements can have multiple start-ups (>8) with the longest single burn time ~50 minutes.

Specific engine technologies of interest to meet the proposed requirements include:

- High temperature (> 2600K), low burn-up composite, carbide, and/or ceramic-metallic (cermet) based nuclear fuels with improved coatings and/or claddings to maximize hydrogen propellant heating and to reduce fission product gas release and particulates into the engine's exhaust stream.
- Long life, lightweight, reliable turbopump modeling, designs and technologies including seals, bearing and fluid system components. Throttle ability is also considered. Zero net positive suction head (NPSH) hydrogen inducers have been demonstrated that can ingest 20-30% vapor by volume. The goal would be to develop inducers that can ingest 55% vapor by volume for up to 8 hours with less than 10 percent head fall off at the design point. Develop the capability to model (predict) turbopump cavitation dynamics. This includes first order rotating and alternating cavitation (1.1X –2X) and higher (6X-10X) order cavitation dynamics.
- High temperature and cryogenic radiation tolerant instrumentation and avionics for engine health monitoring. Non-invasive designs for measuring neutron flux (outside of reactor), chamber temperature, operating pressure, and liquid hydrogen propellant flow rates over wide range of temperatures are desired. Sensors need to operate for months/years instead of hours. Robonaut type inspections for prototype flight test considered.
- Concepts to cooldown 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 criticality control flexibility during burns beyond the reactor circumferential rotating control drums, and/or provide nuclear safety for ground processing, launch, and possible launch aborts.

Specific ground test technologies of interest to meet the proposed requirements include:

- Effluent scrubber 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%.
- Technologies providing a low power nuclear furnace to 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 technologies that can lead to high-power (100-kW to MW-class) 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, and at very

high power levels enable piloted 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 system efficiencies exceeding 60% and 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.

Specific technologies of interest in addressing high power electric propulsion challenges include but are not limited to:

- Advanced concepts for high power plasma thruster systems that provide quantifiable benefits over state of the art high power electric propulsion systems. Proposals addressing advanced technology concepts should include a realistic and well-defined roadmap defining critical technology development milestones leading to an eventual flight system.
- Electric propulsion systems and components that enable the use of alternative space storable propellants, such as condensible or metal propellants and potential in-situ resource derived propellants.
- Advanced manufacturing methods for the fabrication of high power thruster components and associated systems; of particular interest is additive manufacturing for complex parts and components. 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.
- 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 (equal to or $>10^9$ pulses) operation.

In addressing technology requirements, proposers should identify candidate thruster systems and potential mission applications that would benefit from the proposed technology.

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.

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, transfer, and instrumentation to support NASA's exploration goals. This includes a wide range of applications, scales, and environments consistent with future NASA missions. Specifically, listed in order of NASA's current priority:

- Simple mass efficient techniques for vapor cooling of structural skirts (aluminum, stainless, or composites) on large upper stages containing liquid hydrogen and liquid methane (can include para-to-ortho hydrogen catalyst for hydrogen applications).
- Lightweight, multifunctional cryogenic insulation systems (including attachment methods) that can survive exposure to the free stream during the launch/ascent environment in addition to high performance (less than 0.5 W/m^2 with a warm boundary of 220 K) on orbit or $<5 \text{ W/m}^2$ on Mars surface.
- Advanced cryogenic spacecraft components including:
 - Valves (minimum $\frac{1}{2}$ " tube size) for low (< 50 psi, $C_v > 5$, goal of 100+) pressure liquid hydrogen with low internal (~ 1 sccm, goal of < 0.1 sccm) and external (~ 3 sccm, goal of < 0.1 sccm) leakage (> 500 cycles with a goal of 5,000 cycles).
 - Isolation valve/regulation (minimum $\frac{1}{2}$ "") for high pressure (>4500 psi) gaseous helium systems (< 70 K fluid, $C_v > 2.1$) with low internal (~ 1 sccm) and external (~ 3 sccm) leakage (> 500 cycles with

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- a goal of 5,000 cycles).
 - Spherical all-composite 1-2 m diameter propellant tank for Mars application using LO₂/LCH₄; Pressure from 350-1000 psig; Temperature range from ambient to 77 K (LN₂); and Ghe permeability less than 1x10⁻⁴ sccs/m² (at 500 psi, 77 K).
 - Micro-gravity cryogenic pressure control components for thermodynamic vent systems including:
 - Improved alternatives to state of the art spray bars for using fluid dynamics to collapse the ullage and thoroughly mix a propellant tank in micro-gravity.
 - Low voltage (28 VDC) two-phase flow tolerant mixing pumps of flow rates between 10 and 40 gpm.
 - Novel methods of packaging and manufacture to minimize feedthroughs to the tank and ease of installation into a tank.
 - Innovative concepts for cryogenic fluid instrumentation including:
 - Fiberoptic and wireless concepts to enable accurate measurement (with minimal sensitivity to electromagnetic interference) of propellant pressures and temperatures in low-gravity storage tanks
 - Cryogenic pressure transducers (0 – 50 psia typical range, 1% full scale accuracy, 0.5 Hz response) at 20 K.
 - Low power (< 15 W goal) video camera systems for viewing fluid dynamics within a propellant tank (3 – 5 m diameter).
 - Wicking materials or other novel methods/materials of liquid acquisition for use with liquid oxygen, liquid methane, and liquid hydrogen for low temperature heat pipes or tank expulsion.

Phase I proposals should at a minimum deliver proof of the concept including some sort of testing or physical demonstration (not just a paper study). Phase II proposals will be expected to provide component validation in a laboratory environment preferably with a hardware deliverable to NASA.

Sub Topics:

Environmental Monitoring for Spacecraft Cabins Topic H3.01

Measurement of Inorganic Species in Water

There is limited capability for water quality analysis onboard current spacecraft. Several hardware failures have occurred onboard ISS which demonstrate the need for measurement of inorganic contaminants. Monitoring capability is of interest for identification and quantification of inorganic species in potable water, thermal control system cooling water, and human wastewater. Examples of inorganic species of interest and their levels in potable water are specified in Spacecraft Water Exposure Guidelines (SWEGs), released as JSC 63414 (Last revised - November 2008). Target compounds identified in the SWEGs that will be needed for exploration missions include ammonium, antimony, barium, cadmium, manganese, nickel, silver, and zinc. But there is also interest in measurement of other cations and anions including iron, copper, aluminum, chromium, calcium, magnesium, sodium, potassium, arsenic, lead, molybdenum, fluoride, bromide, boron, silicon, lithium, phosphates, sulfates, chloride, iodine, nitrate and nitrite. Detection limits should be below 0.5 mg/L where possible. The proposed analytical instrument should be compact, microgravity compatible, and have limited power and consumable requirements. Sample volumes should be minimized.

Particulate Monitor for Air

Instruments that measure indoor aerosols in spacecraft cabins to monitor air quality and for characterizing the background particle environment and major particle sources are desired. Real-time measurement instruments must be compact and low power, without volatile working fluids, intuitive for crew to operate, requiring minimal maintenance, and able to maintain calibration for years. A large measurement range is necessary in low gravity due to the absence of gravitational settling, and it is expected that more than one instrument, or a multi-sensor unit, will be required to cover the desired range from nanometer (ultrafine) to 50 microns in diameter. A major portion of aerosols on the International Space Station (ISS) are from lint and fibers, so instruments must not rely on spherical morphology for accurate measurements. High accuracy should be quantitatively demonstrated for the range of interest. Development of an instrument that covers a sub-range, as broad as possible, that optimizes the performance within that range and that can subsequently be easily expanded, or integrated with other instrumentation, to cover the full range and requirements will also be of interest. Ideally, the instrument would be portable, with a graphical user interface for crew to read directly and also with the ability to log data and offer standard data transfer interfaces for longer-term indoor air quality surveys.

Microbial Monitor

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, every attempt to monitor microbial communities on-board the ISS has relied on traditional, culture-based approaches. Such techniques are laborious (7 days), require a considerable amount of crew time (up to 5 hrs), sample return, and ground based analysis (1 month after sample return), and are fraught with difficulty, as different microbial species require various media or cultural conditions to grow. In current microbial quality verification protocols, which use a single medium and a single culture condition, many types of cells will go undetected.

Molecular detection of biological agents offers increased sensitivity and specificity, such that lower levels of contaminating material can be detected and unambiguous identification can be achieved. NASA is interested in an integrated molecular system that could combine all required steps such as:

- Sample collection/concentration/extraction.
- Amplification/enrichment.
- Detection.

The scope this solicitation is the first item, i.e., sample collection, concentration, and extraction. However, integration of any two of the above mentioned steps as a single module with a capability to develop the interface of the third step can also be proposed. Technologies that determine microbial content of the air and water environment of the crew habitat falls within acceptable limits and life support system is functioning properly and efficiently are solicited. Required technology characteristics include:

- 2 year shelf-life.
- Functionality in microgravity and low pressure environment (~8 psi).

Technologies that show improvements in miniaturization, reliability, life-time, self-calibration, and reduction of expendables are also of interest. The proposed integrated molecular microbial monitoring/detection system should be capable of measuring total microbial burden as well as identifying “problematic” microbial species on-board ISS (ISS MORD: SSP 50260; <http://emits.sso.esa.int/emits-doc/ESTEC/AO6216-SoW-RD9.pdf> [1]).

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 for NASA testing.

Sub Topics:

Bioregenerative Technologies for Life Support Topic H3.02

Food Production Technologies for Space Exploration

NASA is interested in food production and related food safety technologies for ISS, transit missions, and eventual surface missions (fractional gravity). Of special interest is the use of photosynthetic organisms such as plants to produce food, and contribute to cabin O₂ production and CO₂ removal. Food production technologies should address how light use efficiency will be improved to reduce energy costs, including advanced electric and solar lighting concepts. Electric light sources should achieve at least 1.5 μmol photosynthetically active radiation per Joule of electrical energy, and solar collection systems should achieve at least a 40% delivery efficiency of solar light. Innovative concepts for gravity independent watering and nutrient delivery techniques are also needed. Technical approaches could include selecting or adapting the plants for optimal performance in smaller growing volumes common to space. All systems should consider minimizing power, mass, consumables, and biologically produced waste, while maximizing reliability and efficiency. Consumables and waste products that allow their residual water to be recovered or are easily refurbished are desirable. System TRLs should be 2-4 for Phase I. Phase II projects that evolve from the call are expected to deliver a working prototype to NASA.

Biological Systems for Wastewater Treatment

NASA is interested in efficient biological or biochemical approaches to assist in purifying and recycling wastewater in confined spaces such as crewed spacecraft or space habitats. Of special interest are biological approaches and bioreactors for removing carbon, nitrogen and phosphorus, and reduction of biosolids. Specific technologies or approaches are sought for:

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- Development of long term stable inocula.
 - Inoculation and start-up of bioreactors in flight, including remote operations.

Systems should consider operating with low power, low consumables, small volumes, high reliability and rapid deployment, as well as addressing multi-phase flow issues for reduced gravity. Consumables that allow their residual water to be recovered or be easily refurbished are desirable. Proposed systems shall be capable of treating combined waste waters from hygiene activities (containing surfactants/dander/body oil), human urine (with minimal flush water and a bio compatible preservative), and humidity condensate (containing VOCs). Proposed systems should also be capable of maintaining viability during long periods of quiescent operations (90-365 days) when no human generate waste water is available. Proposed systems should use fewer consumables than the current ISS physico-chemical system. System TRLs should be 2-4 for Phase I. Phase II projects that evolve from the call are expected to deliver a working prototype to NASA.

Sub Topics:

Spacecraft Cabin Atmosphere Quality and Thermal Management Topic H3.03

Advances in spacecraft atmospheric quality management are sought to address cabin ventilation and flow delivery to air scrubbing equipment, suspended particulate matter removal and disposal, and volatile trace chemical contaminant removal. Methods to separate particulate matter from both the cabin atmosphere and from Environmental Control and Life Support (ECLS) system process gas streams are sought. Interest in humidity control and separation processes within life support system processes are of interest. Specifics regarding areas of interest in spacecraft atmospheric quality management are the following.

Multifunctional Filtration Techniques

Techniques and methods are sought leading to compact, low power, autonomous, regenerable bulk particulate matter separation and collection techniques suitable for general cabin air purification. The particulate matter removal techniques and methods must accommodate high volumetric flow rates up to 11.3 m³/minute, yet possess pressure drop <125 Pa. Filtration performance equivalent to HEPA rating is desired. Configurations incorporating multi-stage filtration that separate and optimize regeneration and capturing efficiency functionalities may be considered. The particulate matter separation and collection technique must be suitable for seamless integration into a spacecraft cabin ventilation system from a volumetric perspective. The techniques and methods must safely store and enable easy disposal of collected particulate matter by the crew while minimizing exposure during the disposal operation.

Combination of the particulate matter separation and collection technique with techniques possessing high removal capacity for volatile chemical contaminants, with a focus on light polar organic compounds (e.g., ethanol and acetone) and linear and cyclic siloxanes, is of interest. The volatile chemical contaminant removal techniques must accommodate high volumetric flow rates up to 11.3 m³/minute and possess pressure drop <125 Pa. The technique must provide for a minimum 1 year service life and a goal of 3 years.

ECLS System Process Gas Filtration Techniques

Techniques and methods leading to compact, regenerable methods for removing particulate matter generated in ECLS system process equipment such as carbon formation reactors and methane plasma pyrolysis reactors. Filtration performance approaching HEPA rating is desired for ultrafine particulate matter with minimal pressure drop. The gas filter should be capable of operating for hours at high particle loading rates and then employ techniques and methods to restore its capacity back to nearly 100% of its original clean state through in-place and autonomous regeneration or self-cleaning operation. Compact storage of the particulate matter after it is collected is as important as the effective collection. The device must minimize crew exposure to accumulated particulate matter and enable easy particulate matter disposal.

Process Gas Phase Moisture Removal and Collection

Innovative technologies are sought to dehumidify a hot, humid airstream and remove and collect the product as condensate for further processing. The airstream pressure is between 0.2 and 1.0 atmospheres, its temperature is 150°C and it is saturated with water vapor. The dewpoint of the airstream must be reduced to 10°C and the condensed liquid that results must be completely removed. Cooling at ambient temperature and electrical power and are available. Both the electric power and liquid carryover must be minimized.

Future human spacecraft will require more sophisticated thermal control systems that can operate in severe

environments ranging from full sun to deep space and can dissipate a wide range of heat loads. The systems must perform their function while using fewer of the limited spacecraft mass, volume and power resources. Advances are sought for microgravity thermal control in the following areas:

- Heat rejection systems and/or radiators that can operate at low fractions of their design heat load in the cold environments that are required for deep space missions. Room temperature thermal control systems are sought that are sized for full sun yet are able to maintain setpoint control and operate stably at 25% of their design heat load in a deep space (0 K) environment. Innovative components, working fluids, and systems may be needed to achieve this goal.
- Lightweight non-venting phase change heat exchangers are sought to ameliorate the environmental transients that would be seen in planetary (or lunar) orbit. Heat exchangers that have minimal structural mass and good thermal performance are sought. The goal is a ratio exceeding 2/3 phase change material mass and 1/3 structural mass.
- Two-phase heat transfer components and system architectures that will allow the acquisition, transport, and rejection of waste heat loads in the range of 100 kW to 10 megawatts are sought.
- Non-toxic working fluids are needed that are compatible with aluminum components and combine low operating temperature limits (<250K) and favorable thermophysical properties - e. g., viscosity and specific heat.

Technologies are expected to be raised from TRL2 to TRL 3/4 during Phase I. Minimum deliverables at the end of Phase I are analysis/test reports, but delivery of development hardware for further testing is desirable. In addition, the necessity and usefulness of moving on to a Phase II should be demonstrated. Technologies would be expected to be matured from TRL 3/4 to TRL 5 during a potential Phase II effort. Expected deliverables for a Phase II effort are analysis/test reports and prototypic hardware.

Sub Topics:

Crew Survival Systems for Launch, Entry, Abort Topic H4.01

This subtopic seeks technology innovation supporting the launch, entry, and abort (LEA) crew survival equipment needs for future human exploration beyond low-earth orbit. Primary goals include development of technologies enhancing crew survival in the launch, entry, and abort phases of flight as well as the post-landing environment, significant mass reduction of hardware, and development of space-qualified survival hardware technologies designed to operate after exposure to space vacuum and thermal effects. LEA crew survival equipment development is a critical need tied to any future manned Design Reference Mission (DRM) laid out by the agency, as well as providing benefit to both Orion/MPCV and Commercial Crew Program engineering efforts. Many candidate technologies will have direct application to Orion's EM-2 mission and follow on manned spaceflight activities.

Systems and technologies relating to enhancement of post-landing survival and rescue following manned exploration spacecraft launch, entry, and abort (LEA) events are sought in the following areas:

- *Lightweight Survival Life Raft Materials, Construction Methods, and Related Technologies* - Programmatic need exists for a low mass, self-inflating life raft under 30 lbm. Technologies should be directed to enable crew survivability in the post landing off-shore ocean environment meeting SOLAS and/or FAA standards and Orion/MPCV Design Specification for Natural Environments (DSNE) sea state definitions while meeting a 30 lbm mass constraint. Of particular interest is significant mass reduction in raft inflation systems, innovative construction techniques and techniques / methods for enhanced operability by long-duration spaceflight de-conditioned crew members. The current space equivalent baseline is an FAA six person raft. Currently this type of raft does not exist without 'breaking' the 30 lbm mass requirement or sacrificing survivability attributes. Efforts should focus upon novel lighter weight materials and constructions methods, as well as inflation systems. Another area of concern from the medical community is raft ops and ingress by deconditioned crew members experiencing neurovestibular effects of long-duration spaceflight.
- *Suit-Integrated Global Coverage Personal Locating Technologies* - Current commercially-available Personal Locating Beacons (PLBs) are not optimized for use in the manned spaceflight thermal and vacuum environment or integration into a survival suit cover layer. Innovative technologies/efforts should be directed towards novel flexible patch antenna development, robust beacon packaging technologies, analytical methodology for integrated beacon operational analysis, and beacon triggering (RF, saltwater, etc.)

technologies. Additionally, there is interest in prototype electronics board development for use with future satellite-based GPS/Doppler locating systems such as the NASA-led Distress Alerting Satellite System (DASS). This technology development subheading also includes development of high-reflectivity materials in the visible, IR, and radar wavelengths.

- *Occupant Protection Materials, Analytical Tools, and Technologies* - Products and materials leading to enhanced occupant protection in the capsule landing loads environment. Innovative technologies and efforts should be directed towards acceleration, vibration, and impact attenuation systems designed to mitigate dynamic flight event impacts on the crew member. Of potential interest are materials and products to protect crew members from head and neck injuries during landing load shocks. Additionally, technologies such as innovative restraint mechanisms preventing crew member flail and flail-related injuries during dynamic flight events are of potential interest. When considering impact attenuation material properties, attention should be paid to preventing crew member exposure to rate changes of acceleration greater than 500 g/s. Material space-rating requirements should be taken into account in relation to the manned spaceflight thermal / vacuum environment. Within this subtopic, analytical methods should be directed to prevention of extremity flail, head, and neck injuries during linear, vibrational, and angular acceleration events.
- *In-Suit Waste Management Technologies* - Development of technologies allowing for long-duration waste management for use by a pressurized suited crew member. In the event of cabin depressurization or other contingency, crew members may need to take refuge in LEA pressure garments for a long-duration (144-hour) return trajectory back to Earth. Technology development should be tailored to a 144-hour suited contingency, meeting the NASA Human Systems Integration Requirement (HSIR) inside an LEA suit pressurized to 4.3 PSID referenced to the ambient environment. Waste management technologies should address fecal and urine waste containment and human physiological responses / countermeasures to long duration waste management in a pressurized survival suit environment from one to six days. Advanced technologies and materials should ideally provide for urine collection of up to 1L per day per crew member, for a total of 6 days. Additionally, mitigation and/or elimination of urine-generated ammonia inside the pressure garment volume is a candidate area of interest. Fecal collection rates should be targeted for 75 grams of fecal mass and 75 mL fecal volume per crew member per day for a total of 6 days duration.

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:

EVA Space Suit Pressure Garment Systems Topic H4.02

Space suit pressure garments technology developments are focused on providing enabling technologies for long-duration missions inclusive of extensive extra-vehicular activity (EVA). To that end, priority technologies address mass reductions, durability and reliability. Mass reduction for exploration pressure garments is driven, in addition to launch mass considerations, by the human factor of on-back weight for a planetary walking suit configuration following a long-duration micro-gravity transit, which may reduce astronaut load bearing capability. Driving reference missions such as a 1.5-year Mars surface stay include on the order of 700 hours of EVA. Therefore, long-duration exploration missions require, in some cases orders of magnitude, increases in suit durability or new approaches to providing long duration mission EVA capability or logistics. The following technology areas address mass reduction, increased durability, or both.

Multi-function Materials

The pressure garment must perform functions such as: gas retention and structural integrity including fall cases; mobility to perform science and surface asset set-up and maintenance; and environmental protection from thermal extremes, micrometeoroids and secondary impacts, dust, and tears. The combination of performance of two or more of these functions in single pressure garment material layer contributes to mass reduction. For example, a composite structure that provides gas retention, structural integrity, and thermal protection/regulation would be beneficial. Another example would be a fabric that mitigates the effects of dust and is thermal protection in a single

layer is sought.

Self-diagnosing and Self-healing Materials

Fabric wear due to repetitive joint cycling, dust and UV radiation exposure, and handling is anticipated. To improve safety and decrease crew time investment in the EVA system, materials that can indicate wear or self-heal are valuable. Current materials with these capabilities are heavy, stiff, or require prohibitive power quantities. Ideally, self-diagnosing and self-healing capabilities would be combined in with a material that also performs one of the functions described in the 'Multi-function materials' section

Titanium Bearings

This topic addresses both mass reduction and increasing durability. The emphasis on mass reduction is countered by the need for increased mobility, which tends to increase mass due to the addition of low torques bearings in joint mobility systems. Titanium bearings are being incorporated to decrease the mass of joint mobility systems. However, refinement of titanium bearings to meet durability requirements is required based on 2014 bearing in-configuration oxygen compatibility testing, which passed for flammability, but indicated cycle wear issues. To address titanium bearing wear, coatings, treatments, lubricants, ball material, and space ball materials are all considerations to be investigated. Titanium bearings that can withstand 8 psi suit pressure plug loads in addition to suit manloads over tens of thousands of cycles are required for exploration pressure garments.

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:

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, a significant risk for the development of spacesuit avionics is the non-availability certain ancillary electronic devices that are rated for spaceflight. 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 no particular order of priority, key innovations sought include:

- Wireless Communication:
 - 802.11n baseband processor that supports channel bonding and possibly multiple RF channels.
 - Low-power (<5W), low-rate (500-1000kbps) baseband software-defined radio that is, at the very least, capable of supporting the existing Space-to-Space Communications System (SSCS) wireless suit interface.
 - Dual-band WLAN-class RF front-end module capable of supporting the SSCS (410 to 420 MHz) and a channel-bonded 802.11n system (40MHz of bandwidth) operating at the 2.4GHz ISM band. Consideration will also be given to devices capable of supporting the 802.11n system operating in the 900MHz region. Consideration for supporting multiple antennas for the 802.11n system will be given, but this is not required.
- Human-Machine Interface (HMI) for Informatics:
 - Input device technologies that provide mouse-like functionality or a minimum of directional control to navigate display menu system. In general devices need to minimize hand use. Technologies that require hand use must be limited to operation with a single gloved EVA hand. Devices must minimize SWAP and computing power needed for final implementation. Solutions must be reliable and robust enough for vacuum space environments.
- 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.
- Audio:
 - Simultaneously sampled, deep bit-width, low rate Analog to Digital Converter (ADC) circuits and/or Pulse Density Modulator (PDM) circuits. Requirements are for devices with dynamic range greater than 90 dB (threshold) and as much as 110 dB (goal) with sampling rates > 24 kS/s (threshold) and as high as 48 kS/s (goal). Requirements exist for 8 channel devices (threshold) simultaneously sampled (< 1 ps jitter) with a goal of 16 channels. Devices should support a Least Significant Bit (in Pulse Code Modulation) of 1 micro-Volt or less with a noise floor of 10 micro-Volts or less.
 - Highly linear, high Signal to Noise Ratio (SNR) Micro Electro Mechanical System (MEMS) microphones with PDM output. Microphones should exhibit < 1% THD at 105 dB SPL (threshold) and 115 dB SPL (goal). Microphones should have frequency response of +/-10 dB from 80 Hz to 12 kHz and SNR > 50 dB (threshold) and > 60 dB (goal).
 - High dynamic range, audio frequency Digital to Analog Converters (DACs). Converters should provide >100 dB spur free dynamic range (TBR).
 - High efficiency, low power (< 1 W output), audio frequency power amplifiers.
 - High efficiency, audio frequency pre amplifiers with adjustable gain (0 to 30 dB).
 - High speed (> 100 Mb/s) serial communications transceivers suitable for protocols such as Ethernet, Low Voltage Differential Signal (LVDS) and Rocket-IO.

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:

Deployable Structures Topic H5.01

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

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- Large deployable solar arrays for 50+ kW solar electric propulsion (SEP) missions.
 - Lightweight deployable hatches for manned inflatable structures.

Design solutions must minimize mass and launch volume while meeting other mission requirements including deployed strength, stiffness, and durability.

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

- Novel design, packaging, deployment, and in-space manufacturing or assembly concepts.
- Lightweight, compact components including booms, ribs, 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 Arrays

NASA is currently developing solar array systems for solar electric propulsion in the 30-50 kW power range for near-term missions such as the Asteroid Redirect Mission (ARM). This subtopic seeks structures and materials innovations for the next generation of lightweight solar arrays beyond 50 kW. NASA has a vital interest in developing much larger arrays over the next 20 years with up to 1 MW of power (4000 m² total deployed area) for SEP-powered exploration missions. Scaling up solar array size by over an order-of-magnitude will require game changing innovations. In particular, novel flexible-substrate designs are needed that minimize structural mass and packaging volume while maximizing deployment reliability, deployed stiffness, deployed strength, and longevity.

Nominal solar array requirements for large-scale SEP applications are:

- Specific power > 120 W/kg at beginning of life (BOL).
- Packaging efficiency > 40 kW/m³ BOL.
- Deployment reliability > 0.999.
- Deployed stiffness > 0.1 Hz.
- Deployed strength > 0.1 g (all directions).
- Lifetime > 5 yrs.

Variations of NASA's in-house large solar array concept referred to as the Compact Telescoping Array (CTA) could be used for design, analysis, and hardware studies. Improved packaging, joints, deployment methods, etc. to enable CTA-type solar arrays up to 4000 m² in size (1 MW) with up to 250 W/kg and 60 kW/m³ BOL are of special interest. The CTA is described in Reference 1.

Capability #2: Deployable Hatches

NASA is also seeking concepts for lightweight, deployable hatch systems for manned inflatable structures that require ingress/egress across a pressure differential. Designs should be efficient and tight-sealing and use softgoods materials in whole or in part. "Softgoods" refers to advanced high-strength fabrics or woven materials. Applications of this technology include barometric chambers, airlocks and habitats, and large-scale space hangars for on-orbit assembly. The pressure vessel geometry could require hatches that conform to flat, singly-curved, or doubly-curved surfaces. Concepts will be evaluated on mass efficiency, minimal packaging volume for launch, operational reliability and simplicity, and strategy for integration into a soft-goods structure. Proposals should detail a concept of operations including packaged and deployed geometry, deployment approach, and operation of sealing/unsealing the hatch. Reference 2 provides additional information on deployable soft space structures.

Nominal hatch requirements are:

- 40-inch diameter clear opening for ingress/egress.
- Designed for a differential pressure of 15.2 psi.

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- Hatch can be sealed and verified even when parent vessel is at vacuum.
 - The hatch can be easily operated by a suited astronaut.

For both capabilities, contractors should prove the feasibility of proposed innovations using suitable analyses and tests in Phase I. In Phase II, significant hardware 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.

References:

- Mikulas, M. M. et al., "Telescoping Solar Array Concept for Achieving High Packaging Efficiency," To be presented at the AIAA Spacecraft Structures Conference, January 2015.
- Bell L., "Deployable Soft Space Structures: Concepts and Application Requirements," 50th AIAA Structures, Dynamics and Materials Conference, Paper 2009-2168, May 2009.

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 systems and manufacturing processes which enable the capability to store and transfer cryogenic propellants (liquid oxygen & liquid hydrogen) to orbit. Operating temperature ranges for these fluids are -183°C to -253°C. Specific areas include:
 - Composite systems to be used in the construction of storage vessels or ductwork for cryogenic propellants. 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 composite structures. Concepts must address seal systems for both composite to composite and composite to metal applications. Techniques must consider scale up and manufacturability factors.
- *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 1500°C to 3000°C, while maintaining structural integrity. Significant reductions in vehicle weight can be achieved with the application of hot structures, which do not require parasitic thermal protection systems. This area seeks innovative technologies in one or more of the following:
 - Light-weight, low-cost, composite material systems that include continuous fibers.
 - Significant improvements of in-plane and thru the thickness mechanical properties, compared to current high temperature laminated composites.
 - Decreased processing time and increased consistency for high temperature materials.
 - Improvement in potential reusability for multiple missions.
 - Low conductivity, low thermal expansion, high impact resistance.

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> [2])

Sub Topics:

Multifunctional Materials and Structures 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/501625main_TA12-ID_rev6_NRC-wTASR.pdf [3]), 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), inflatable, protective (radiation and micrometeoroids and orbital debris), sensing, healing, in-situ inspectable (e.g., IVHM), actuating, integral cooling/heating, and power generating (thermal-electric, photovoltaic ...), 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 FY15, this SBIR subtopic seeks innovative structures and materials technologies and capabilities for three principle areas:
 - Integration of acoustic metamaterial concepts into the primary structure to reduce interior acoustic and vibration environments. Specifically, innovations are solicited which maintain the load bearing capability of the primary structure while simultaneously reducing interior noise and vibration levels below 400 Hz. Successful innovations are anticipated to enable the design of lighter and cheaper spacecraft and launch vehicle structures, as well as lower costs associated with ruggedizing and qualifying spacecraft and launch vehicle secondary structures.
 - Sensory materials incorporated into a primary structure to provide health monitoring data, and low-mass/wireless methods of transmitting localized structural responses to diagnostic models for material and structural state. Manufacturing technologies capable of producing structural components with embedded capability for sensing strain, damage initiation and propagation, and temperature are of particular interest. Ideally, the sensing technology should also augment the load carrying capability or some other structural design requirement. Technologies should enable weight reduction with similar or better structural performance when compared to traditional approaches.
 - Thin film conformal layers on structures or integrated in structures with different functional capabilities. Examples include conformal solar cells, conformal antennas, conformal energy storage, and conformal energy harvesting. The conformal layer should provide additional functionality to the structure without adversely affecting the load bearing capability. The conformal functional layer offers the potential for significant weight reduction and reduced complexity for spacecraft, rovers, and habitats. For example, conformal photovoltaic layer on spacecraft, rover, or habitat can eliminate the need for separate solar array panels."

Sub Topics:

Human Robotic Systems - Mobility Subsystem, Manipulation Subsystem, and Human System Interaction Topic

H6.01

The objective of this subtopic is to create human-robotic technologies (hardware and software) to improve the 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, in orbit, and interplanetary), and with a range of time-delay and communications bandwidth.

Proposals are sought that address the following three subtopics:

- *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, and infrastructure-free localization.
- *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, and novel manipulation methods.
- *Human-system interaction (HSI)* - 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, ground data system tools, command planning and sequencing, real-time visualization/notification, and software for situational awareness.

Sub Topics:

Ablative Thermal Protection Systems Technologies, Sensors and NDE Methods Topic H7.01

The technologies described below support the goal of developing advancements in instrumentation systems, inspection techniques, 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.

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:

- 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.

- Non Destructive Evaluation (NDE) tools for evaluation of bondline and in-depth integrity for light-weight rigid and/or flexible ablative materials. Non Destructive Evaluation (NDE) tools are sought to verify design requirements are met during manufacturing and assembly of the heat shield, e.g., verifying that anisotropic materials have been installed in their proper orientation, and that the bondline as well as the TPS materials have the proper integrity and are free of voids or defects. Void and/or defect detection requirements will depend upon the materials being inspected. Typical internal void volume detection requirements are on the order of 6 mm on a side (6x6x6), and bondline defect detection requirements are on the order of 25.4 mm by 25.4 mm by the thickness of the adhesive.
- 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:

- *Sensors* - Sensor system design, including electronics, with specified measurement performance, mass, power, and volume. Proposed test approach for Phase II, which 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.
- *NDE* - Detection technique/process and equipment design, to meet the specified requirements. Validation test plan, to be executed on relevant materials in Phase II.
- *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:

- *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.
- *NDE* - Working engineering model of the detection system with the proposed performance characteristics. Full report of development, architecture, and measurement performance, including data from completed test proposed in Phase I (TRL 4-5).
- *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.

The range of diagnostics to be considered is not restricted. Examples of diagnostics of interest include those that characterize high enthalpy flows (e.g., temperature, velocity, electron number density, pyrolysis/ablation byproducts) or characterization of test articles (recession, thermal emission, etc.). Proposals for adapting existing techniques to unique aspects of the facility (e.g., free flight in ballistic range, or short duration in shock tubes) are of interest, as well as the development of new techniques. Proposers are encouraged to contact operators and users of individual facilities to understand their specific challenges and requirements, and for details of interfacing into the existing systems.

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:

Space Nuclear Power Systems Topic H8.01

NASA is developing fission power system technology for future space exploration applications using a stepwise approach. Initial small fission systems are envisioned in the 1 to 10 kWe range that utilize cast uranium-metal fuel and heat pipe cooling coupled to static or dynamic power conversion. Follow-on systems could produce 10s or 100s of kilowatts utilizing a pin-type uranium fueled reactor with pumped liquid metal cooling, dynamic power conversion, and high temperature radiators. The anticipated design life for these systems is 8 to 15 years with no maintenance. Candidate mission applications include power sources for robotic precursors, human outposts on the moon or Mars, and nuclear electric propulsion (NEP) vehicles. NASA is planning a variety of nuclear and non-nuclear system ground tests to validate technologies required to transfer reactor heat, convert the heat into electricity, reject waste heat, process the electrical output, and demonstrate overall system performance.

The primary goals for the early systems are low cost, high reliability, and long life. Proposals are solicited that could help supplement or augment the planned NASA system testing. Specific areas for development include:

- 800-1000 K heat transport technology for reactor cooling (liquid metal heat pipes, liquid metal pumps).
- 1-10 kWe-class power conversion technology (thermoelectric, Stirling, Brayton).
- 400-500 K heat rejection technology for waste heat removal (water heat pipes, composite radiators, water pumps).

The early systems are expected to provide the foundation for later systems in the multi-hundred kilowatt or megawatt range that utilize higher operating temperatures, alternative materials, and advanced components to improve system performance. Specific areas for development include:

- 100 kWe-class power conversion technologies.
- Waste heat rejection technologies for 500 K and above.
- High temperature reactor fuels, structural materials and heat transport technologies.

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 hydrocarbon fuels, 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 cell, stack, materials and system development for operation on 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 as specified after at least 500 hours of steady state operation on propellant-grade methane and oxygen with 2500 hours expected of a mature system. System should startup dry but after reaching operating conditions an amount of water/H₂ consistent with what can be obtained from anode recycle can be used. Amounts must be justified in the proposal.
- Minimal cooling required for power applications. 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.
- 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 for improvements in capability and reliability of PV power generation for space exploration missions. Power levels for PV applications may reach 100s of kW. System and component technologies are sought that can deliver efficiency, cost, reliability, mass and volume improvements under various operating conditions, in extreme environments, and over wide temperature ranges.

PV technologies must enable or enhance the ability to provide low-cost, low mass and higher efficiency for power systems with particular emphasis on high power arrays to support solar electric propulsion missions. Areas of particular emphasis include:

- Advanced PV blanket and component technology/ designs that support very high power and high voltage (> 200 V) applications.
- PV power generation (cell, interconnect, and small self-deployable arrays) for CubeSat/ small satellite applications.
- PV module/ component technologies that emphasize low mass and cost reduction (in materials, fabrication and testing).
- Improvements to solar cell efficiency that are consistent with low cost, high volume fabrication techniques
- Automated/ modular fabrication methods for PV panels/ modules on flexible blankets (includes cell laydown, interconnects, shielding and high voltage operation mitigation techniques).
- Integrated PV system including cells, blanket, array, inverters, interconnect technologies, storage, structures, etc. with a balance-of-components while matching specifications of various systems.
- Simulated PV capability that take optimizes system components, ensures compatibility of modules/inverters, and takes temperature extremes and unique aspects of the space environment into account including radiation tolerance.

Research 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 demonstration unit for functional and environmental testing at the completion of the Phase II contract.

Sub Topics:

Long Range Optical Telecommunications Topic H9.01

This subtopic seeks innovative technologies for long range (> 0.1 AU) optical telecommunications supporting the needs of space missions where human and robotic explorers will visit distant bodies within the solar system and beyond. Multi-use technologies that will also benefit high rate optical communications in cis-lunar and Earth-Sun Lagrange point domains are of particular interest. Goals are increased data-rate capability in both directions and

significant reductions of telecommunications system mass, power-consumption, and volume at the spacecraft.

Proposals are sought in the following areas (TRL3 Phase I, and TRL4-5 Phase II):

- *Spacecraft Disturbance Isolation Platforms and Related Technologies* - Compact, low mass, space-qualifiable, vibration isolation and spacecraft disturbance rejection assemblies with included re-usable launch lock that require less than 5 W of average power and mass less than 3 kg that will attenuate an integrated spacecraft micro-vibration angular disturbance of 150 micro-radians (with a spectrum of $10E-6 \text{ rad}^2/\text{Hz}$ below 0.1 Hz, with a 20 dB/decade roll-off), plus an assumed translational disturbance resulting from an offset of 2 m between the payload and the center of rotation of the spacecraft, to less than 0.15 micro-radians (1-sigma), for payloads massing between 3 and 25 kg. Proposed solutions may use control inputs from ground-beacon-based pointing sensor with noise of 150 nrad/sqrt (Hz). Also desired are innovative low-noise, low mass, low power, DC-kHz bandwidth inertial, angular, position, or rate sensors to assist platform stabilization, including beaconless pointing.
- *PPM Space Laser Transmitters* - Space-qualifiable, 1520 to 1630 nm laser transmitter for pulse-position modulated (PPM) with >25% DC-to-optical (wall-plug) efficiency. Transmitter must support laser pulse widths from 0.2 ns (or lower) to 16 ns (or greater) for PPM orders from 16 slots per symbol (6.25% average duty cycle) to 256 slots per symbol plus 64 slots of inter-symbol guard time (0.31% average duty cycle). Other desired parameters include: <35 ps pulse rise and fall times and jitter; <25% pulse-to-pulse energy variation (at a given pulse width); single spatial mode output with near transform limited spectral width, single polarization with at least 20 dB polarization extinction ratio; amplitude extinction ratio greater than 48dB, average output power of 10 to 100W; massing less than 500 g/W. Laser transmitter to feature slot-serial PPM data input at CML, LVDS, or AC-coupled PCEL levels and an RS-422 or LVDS levels control port. All power consumed by control electronics will be considered as part of DC-to-optical efficiency. Also of interest for the laser transmitter is robust and compact packaging with >100krad radiation tolerant electronics inherent in the design. Detailed description of approaches to achieve the stated efficiency is a must. Also of interest is a space-qualifiable high power fiber switch for implementing redundant space laser transmitters.
- *PPM Ground Laser Transmitters* - >2000W average power PPM laser transmitters for nested modulation forward links to support simultaneous data rates of ~10 b/s (outer code) and at least 10 Mb/s (inner code) with an outer rate inter-symbol guard time of 50%. Operational wavelength in either 1030 - 1080 nm or 1480 - 1570 nm bands. Other desired parameters include: spectral line width of 0.5 nm or less; amplitude extinction ratio greater than 35 dB; output M-squared of 1.2 or less; projected MTTF of at least 20,000 hours; high wall-plug AC-to-optical power efficiency.
- *Photon Counting Near-infrared Detectors Arrays for Ground Receivers* - Close packed (not lens-coupled) kilo-pixel arrays sensitive to 1520 to 1630 nm wavelength range with single photon detection efficiencies greater than 90%, single photon detection jitters less than 40 ps FWHM, total active diameter greater than 500 microns, 1 dB saturation rates of at least 10 mega-photons (detected) per pixel, false count rates (intrinsic dark rate plus after-pulsing rate) of less than 1 MHz/square-mm. Also desired are cryogenic read-out integrated circuits with an operating temperature of 40K capable of time-tagging electronic pulses from 64 high-bandwidth readout channels to an accuracy of 100 ps or better and a maximum count rate of 10 MHz per channel. The approach should demonstrate scalability to >1000 readout channels. Also of interest are: sub-Kelvin cryogenic systems which can support >1000 channels of high-bandwidth (2 GHz or higher) readout signals with a low-temperature hold time of 24 hours, and preferably can be tilted from vertical to near-horizontal during operations; cryogenic interconnects and vacuum feedthroughs for high-density cabling solutions capable of supporting kilochannel readouts from a 1 K detector focal plane stage to room temperature.
- *Photon Counting PPM Digital Ground Receivers* - Digital receiver and decoder assemblies for processing photon counting detector array outputs of PPM encoded data. Receiver to support PPM orders from 2 to 256, data rates to at least 1 Gb/s, and PPM slot widths down to 200 ps. Receiver shall support SCPPM or other demonstrated low-gap-to-capacity (< 1 dB) forward error correction code for PPM. Receiver shall provide signal and background photon flux estimates at kHz rates to support 2-axis control of a fine pointing mirror in a ground receiver telescope.
- *Photon Counting Near-infrared Detectors Arrays for Flight Receivers* - 128x128 or larger array with integrated read-out integrated circuit and thermo-electric cooling for the 1030 to 1080 nm or 1520 to 1650 nm wavelength range with single photon detection efficiencies greater than 40% and 1dB saturation loss rates of at least 2 mega-photons/pixel and dark count rates of <10 kHz/pixel. ROIC to provide time-stamping of each photon arrival with a precision of 500 ps or better, and an interface bus bandwidth of 125

MHz or less. Radiation doses of at least 5 Krad (unshielded) shall result in less than 10% drop in single photon detection efficiency and less than 2X increase in dark count rate.

- *Advanced Flight Opto-electronics* - Ultra-small, low-mass, low-cost, low-power, modular transceivers, transponders, amplifiers, and components for 1520 to 1630 nm optical links at GHz modulation bandwidths, incorporating integrated photonic circuits and other components such as commercially-available ASICs to provide forward-error-correction and other digital signal processing as required.
- *Ground-based Telescope Assembly* - All-weather ground station telescope/photon-bucket technologies for implementing effective receive areas of > 100 square meters at a projected production cost of < \$300K per square meter. Operations wavelength is monochromatic at a wavelength in the range of 1000-1600nm. Key requirements: a maximum image spot size of <20 microradian (static error); capable of operation while pointing to within 3° of the solar limb; and field-of-view of >50 micro-radian. Telescope shall be positioned with a two-axis gimbal capable of <50 micro-radian pointing accuracy, with dynamic error <10 micro-radian RMS while tracking after tip-tilt correction.

Research should be conducted to convincingly prove technical feasibility (proof-of-concept) during Phase I, ideally through hardware development, with clear pathways to demonstrating and delivering functional hardware meeting all objectives and specifications, in Phase II.

References:

- (<http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/42091/1/11-1338.pdf> [5])
- (http://ipnpr.jpl.nasa.gov/progress_report/42-183/183A.pdf [6])
- (http://ipnpr.jpl.nasa.gov/progress_report/42-185/185D.pdf [7])
- (http://ipnpr.jpl.nasa.gov/progress_report/42-182/182C.pdf [8])

Sub Topics:

Intelligent Communication Systems Topic H9.02

NASA seeks novel approaches to improve mission communication and navigation capabilities for science and exploration through advancements in cognitive systems and automation. Over the past 10 years software defined radios and their applications have emerged and demonstrated the potential and applicability of reconfigurable platforms and applications to space missions. The SCaN Testbed launched in 2012 demonstrated software defined radio applications capable of sensing and reacting to environment conditions. Building on this foundation, cognition and automation have the potential to improve system performance, increase data volume return, improve data transmission efficiency, and reduce user spacecraft burden to improve science return from NASA missions. Understanding how and where to apply cognitive and automation technologies is critical and should be discussed in the proposal.

This solicitation seeks advancements in cognitive and automation systems and components as applied to communication and navigation capabilities. 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 or navigation capabilities for the mission. The goal is to improve the state of the user spacecraft system to maximize science data return, enable substantial efficiencies, or adapt to unplanned scenarios. While much interest in cognitive radio entails dynamic spectrum access, this subtopic is also interested in other ways to apply cognition and automation. Areas of interest to develop and/or demonstrate are as follows:

- *Cognitive engine (algorithm) and component development* - to demonstrate new capability in sensing and adapting to the radio/mission environment. Technologies may include changes in physical (PHY) layer data rate, modulation, and coding, medium access control (MAC) layers for new protocols, and cognitive engines to negotiate changes between nodes and throughout the network, learning opportunities and techniques, and networking and application layers (and across layers) to adjust to signal conditions, efficiently using links for different data types (e.g., telemetry v. video), adaptive and intelligent routing, etc.
- *System wide distributed intelligence of cognitive and intelligent applications* - 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) system wide effects (e.g., protocols) to decisions made by one or more communication/navigation elements, how to handle unexpected or undesired decisions, how changing data rate, modulation, or frequency between nodes effects data distribution through relay satellites, and

throughout space and ground network and multiple access techniques that optimize connectivity and throughput while minimizing onboard data storage and interference.

- *Flexible and adaptive hardware systems* - (e.g., signal processing platforms, adaptive front ends for RF or optical communications, and other intelligent electronics) which directly implements or demonstrates cognitive or intelligent applications as an alternative to more general software-based intelligent systems. Systems should highlight advancements to provide needed capability while minimizing on-board resources and cost.
- *Autonomous Ka-band and/or optical communications antenna pointing on mission spacecraft within intelligent multiple access systems* - 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 with both the relays and ground terminals on a coordinated, non-interfering basis along with other spacecraft using these same space- and ground-based assets. Areas of interest include (but are not limited to): autonomous navigation and pointing techniques with sufficient precision to minimize pointing loss; techniques to coordinate multiple autonomous activities and adaptive or cognitive radio systems that can continuously maximize data return via both multiple beam GEO relays and direct to ground links.

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) and show a path towards Phase II hardware/software demonstration with delivery of a demonstration unit or software product for NASA testing at the completion of the Phase II contract.

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). Delivery of the simulation or demonstration software and/or platform(s) to NASA. Plan for verification of specific measurements or capabilities to be performed at the end of Phase II.

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

Depending on the status at the time, there may be opportunity to port software (cognitive engines and applications) to the SCaN Testbed software defined radio ground and/or flight system on International Space Station (ISS) for demonstration and/or test in the actual space environment. At a minimum, the SCaN Testbed ground system radio testbed will provide an ideal cognitive application test environment, as user spacecraft, relay satellites, and control centers are all emulated in hardware. Software applications and infrastructure should consider 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> [9]).

Sub Topics:

Flight Dynamics and Navigation Technology Topic H9.03

NASA is investing in the development of software tools, systems and devices to enhance 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. Interest includes software tools, ground facilities as well as system concepts and on-board devices to support organic capabilities for its deep-space missions. Products developed under this sub-topic can be in support of any mission phase from design and development through operation and disposal. Proposals can be for either near-Earth or interplanetary missions. Specific application areas that will be considered under this subtopic are:

- Software that fuses and analyzes spacecraft sensor data and other spacecraft tracking data available at ground/mission operations centers (i.e., facility software). Proposals for algorithms and software for flight dynamics GNC technologies can support mission engineering activities at any stage of development from the concept-phase/pre-formulation through operations and disposal. 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/> [10]), GPS-Inferred Positioning System and Orbit Analysis Simulation Software, (<http://gipsy.jpl.nasa.gov/orms/goa/> [11]), Optimal Trajectories by Implicit Simulation

(<http://otis.grc.nasa.gov/> [12]) 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:

- Applications of optimal control theory to high and low thrust space flight guidance and control systems.
 - Numerical methods and solvers for robust targeting, and non-linear, constrained optimization.
 - 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.
 - 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 combine measurements from multiple sensor suites in a highly-coupled manner to improve upon the overall system accuracy.
 - 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 celestial navigation techniques including devices and systems, especially those that support of deep-space, planetary missions. System concepts should support significant advances of independence from Earth supervision including the ability to operate effectively in the absence of Earth-based transmissions or transmissions from planetary relay spacecraft with those that operate in the complete absence of human intervention or Earth-based transmissions are preferred. Proposed solutions should meet objectives while minimizing spacecraft burden by requiring low power and minimal mass and volume. User spacecraft impact is of significant importance and proposed solutions include assessments of mass, power, thermal impact on targeted mission spacecraft as well as identifying any requirements placed on the user spacecraft by the proposed design. Of particular interest are concepts that support pointing of high rate optical communications terminals to earth terminals that do not rely on the use of optical uplinks or beacons for achieving proper pointing of the communication beam. However, concepts which are capable of supporting planetary missions of any type are of interest. Proposals that include re-purposing/cross-purposing of advanced sensors contemplated for future deep-space missions such as x-ray telescopes are preferred. In addition to advances in positioning, attitude estimation, orbit determination, guidance, navigation and control particular interest in the area of deep-space celestial navigation lies in the following focus topics:
 - Time and frequency keeping and dissemination.
 - Advanced methods and sensors for optical/IR detection of star fields (i.e., star cameras).
 - Advanced methods and sensors detecting RF and x-ray pulsars.
 - Methods to process celestial observations to perform Orbit Determination (OD) and precision attitude estimation.

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:

Cryogenic Purge Gas Recovery and Reclamation Topic H10.01

Helium is becoming a major issue for NASA and the country. Helium is used as a purge gas in cryogenic piping systems to reduce the concentration of hydrogen below the flammable threshold at test and launch complexes. Most of the Nation's helium comes from the National Helium Reserve operated by the Bureau of Land Management (BLM). The statutory authority for BLM to operate is expiring and responsibility is being transferred to the commercial sector. Helium is a non-renewable gas that is in limited supply. There are already helium shortages and prices are going up.

Fuel cell technology has demonstrated the ability to output high quality helium from a hydrogen/helium gas mixture. The helium/hydrogen gas mixture was collected, helium extracted and recovered. The recovered helium meets the stringent purity requirements for reuse. Proposals are sought that improve upon the demonstrated technology or develop new alternative cryogenic gas separation technology.

This subtopic has the potential to substantially reduce the costs of NASA's test and launch operations. Additional development is needed to increase the efficiency of the recovery process, capture large amounts of mixed gases, and provide real-time solid state sensor technologies for characterizing constituent gases. Helium is the highest value cryogenic gas, but other cryogenic gases could be conserved also.

Specific areas of interest includes the following technologies:

- Enhanced membrane technologies including Proton Exchange Membrane (PEM) fuel cells that increase the efficiency, recovery production rate or life span of fuel cell based separation technologies.
- Development of alternative cryogenic gas separation technologies.
- Technologies for the rapid capture and storage of high volumes of mixed cryogenic gases.
- Development of zero trapped gas system technologies to improve purge effectiveness.
- Development of real-time, solid state sensor technologies for monitoring the current state of the system concentration levels and helium/nitrogen purge process effectively (e.g., hydrogen, oxygen, water vapor content, etc.).

Examples of this type of technology:

- (<http://www.sustainableinnov.com/products/h2renew/> [13])
- (<http://www.extrel.com/> [14])

Sub Topics:

Radiation Shielding Technologies Topic H11.01

Advances in radiation shielding technologies are needed to protect humans from the hazards of space radiation during NASA missions. All space radiation environments in which humans may travel in the foreseeable future are considered, including low Earth orbit (LEO), geosynchronous orbit (GEO), Moon, Mars, and the Asteroids. All particulate radiations are considered, including electrons, protons, neutrons, alpha particles, and light to heavy ions. Mid-TRL (3 to 5) technologies of specific interest include, but are not limited to, the following:

- Lightweight innovative radiation shielding materials are needed to shield humans in aerospace transportation vehicles, large space structures such as space stations, orbiters, landers, rovers, habitats, and spacesuits. The materials emphasis should be on non-parasitic radiation shielding materials, or multifunctional materials, where two of the functions are structural and radiation shielding. Materials of interest include, but are not limited to, polymers, polymer matrix composites, nanomaterials, and regolith derived materials. The objective is to replace primary, secondary, and interior structures, including equipment and components, with radiation protective materials. There is particular interest in the development of high hydrogen content materials and materials systems to replace traditional materials (particularly metals). Note that the goal is not necessarily mass reduction. The goal is replacing mass with mass that not only meets structural requirements, but also is more effective for radiation protection. Decreased mass is a bonus. High hydrogen materials can include polymer matrix composites, where the polymer and/or fibers are high in hydrogen content. Phase I deliverables are materials coupons. Phase II deliverables are materials panels or standard materials test specimens, along with relevant materials test data.
- Processing of regolith derived materials for radiation shielding structures is also of interest. The regolith can be combined with polymer matrix materials to increase the hydrogen content. Phase I deliverables are materials coupons. Phase II deliverables are materials panels or standard materials test specimens, along with relevant materials test data.
- Non-materials solutions are also of interest. Examples are utilizing food, water, supplies, trash, and treated waste already onboard as radiation shielding. This involves developing and utilizing storage containers for food, supplies, and treated waste as multipurpose radiation shielding. This includes developing multipurpose containers for biomaterials to contain treated waste safely without adversely affecting crew

(smell/leakage/handling/transfer). Other options include developing water walls for crew quarters and vehicle walls to be used for storing drinking water, potable water, and treated waste, as well as repurposing the trash and treated waste into protective shielding. Phase I deliverables are detailed conceptual designs. Phase II deliverables are initial prototypes.

- NASA is also interested in out-of-the-box credible solutions for radiation shielding. Phase I deliverables are detailed conceptual designs. Phase II deliverables are initial prototypes.
- Advanced computer codes for rapid computing that can handle complex geometries and large collections of data are needed to model and predict the transport of radiation through space vehicles and structures. These are needed to support optimization studies and analyses for vehicle design and mission planning. Phase I deliverables are alpha tested computer codes. Phase II deliverables are beta tested computer codes.
- Experimental laboratory and spaceflight data are needed to validate the accuracy of radiation transport codes and analysis tools. Phase I deliverables are draft data compilations or databases. Phase II deliverables are formal, publishable, and archival data compilations or databases.

For additional information, please see the following link:

- (http://www.nasa.gov/pdf/500436main_TA06-ID_rev6a_NRC_wTASR.pdf [15])

Sub Topics:

Measurements of Net Ocular Blood Flow Topic H12.01

The goal of this SBIR call is the development of rapid and accurate hardware to characterize the net blood flow to and from the eye. Due to limits on instrumentation, most of the literature on ocular blood flow to date has emphasized measurements that only partially characterize the net flow, such as minimum and maximum velocity in a single retinal arterial vessel or choroidal thickness in the vicinity of the fovea. However, there is significant spatial and interindividual variation in these ocular structures, for example, in choroidal and retinal thickness and in arterial and venous branching structures. Consequently, there are likely to be new insights to be gained from examining the choroid and retina from a bulk perspective. Recent advances in high-quality imaging, such as those based on wide-field Optical Coherence Tomography or high-resolution angiography, have allowed increased depth of penetration at high resolution for unparalleled accuracy in choroidal and retinal measurements that extend well beyond the posterior pole of the eye. The ready availability of computational resources renders it straightforward to capture and analyze the entire time history of ocular hemodynamics.

This SBIR solicits novel hardware that can quantify net ocular blood flow in the retina. Measurements of interest include the temporal history of the following:

- Maps of choroidal and retinal thickness, which include near- and far-field contributions.
- Net volume of the choroid and retina.
- Net volumetric blood flow to and from the choroid and retina.
- Pressures and net luminal areas at the entrance and exit of the choroid and retina.

Measurements must be presented in physical units, such as blood flow in milliliters per minute. The measurement system must also process the raw data, either in a real-time or post-processing mode. Data analysis capabilities should include the calculation of the overall time-averaged mean values, as well as the mean waveform over a cardiac cycle. It would be of significant interest if comparable measurements were made simultaneously of intraocular pressure, reference arterial pressure (systemic, brachial and/or ophthalmic artery), fundus pulsation amplitude, and/or heart rate.

Phase I Deliverables - Concept of hardware capable of producing some or all of the above measurements.

Phase II Deliverables - Prototype hardware and data from a pilot study.

Sub Topics:

Unobtrusive Workload Measurement Topic H12.02

Task design and associated hardware and software impose cognitive and physical demands on an operator and thus, drive the workload associated with a task. This solicitation is looking for technologies and methods to measure, assess, and predict astronaut workload unobtrusively, and to extend these technologies to measuring and predicting astronaut workload during long duration operations. Unobtrusive measures would be ones that do

not require operators to specifically interact with a technology or provide inputs, and would not interrupt an operator's work.

Astronauts on long-duration missions will potentially have long periods of low workload and short bursts of high workload combined with reduced workload capacity that needs to be taken into account for system and mission design. Both high task demand and reduced workload capacity at any phase of a flight may lead to performance errors, which could potentially compromise mission objectives, and consequently the mission.

Astronauts, mission planners, and system designers require the capability to assess and predict when astronauts will be at a reduced capacity resulting from either work underload or from work overload. An unobtrusive workload tool could be used during development to ensure a system produces acceptable workload, or in real-time, to drive schedule modifications or to adapt interfaces based on the current workload the astronaut is experiencing. Unobtrusive objective measures such as video, voice, thermal infrared imaging or eye tracking methods may be more appropriate when measuring long duration workload, so long as the technology's credibility is ensured.

Phase I of this SBIR is to complete a review of the current state of the art in automatically, unobtrusively measuring and tracking workload and informing astronaut of such workload levels in scenarios that are applicable to long duration missions. This Phase I effort will identify suitable unobtrusive measurement technologies and the parameters that need to be included in a candidate workload algorithm and subsequently generate the algorithm. NASA has already supported the development of wrist and arm-worn devices, therefore any unobtrusive wearables proposed should consider alternative concepts and/or new implementations of existing wearable technologies. Phase II of this SBIR is to take the current state of the art and recommendations from the Phase I effort to develop an unobtrusive workload measurement tool prototype, and test and validate the tool.

Sub Topics:

Technology for Monitoring Muscle Protein Synthesis and Breakdown in Spaceflight Topic H12.03

Post flight decrements in skeletal muscle size and function are well documented, however, the true time course of muscle adaptations during long duration spaceflight have thus far been unaddressed. This information is of importance because it can help to identify:

- When the most critical stages of adaption to space are occurring.
- Whether changes are occurring at a constant rate or if they begin to plateau, and if so when.
- Targeted muscle countermeasures to mitigate true muscle loss.

Muscle protein synthesis and breakdown are typically measured via invasive biopsy which will not be feasible during space flight missions. Current terrestrial assays for protein synthesis involve use of stable isotopes to measure incorporation of amino acids into muscle and are determined in muscle biopsy samples. Markers for protein degradation (e.g., MuRF1, Atrogen-1) in muscle biopsy samples are often determined by real time PCR (mRNA expression) or Western blot analysis (protein expression), though these results are primarily qualitative. This subtopic seeks novel, non- or minimally-invasive technologies to measure muscle protein turnover for use in subsequent research studies. The most important measurement would be a synthesis: breakdown ratio indicative of the state of muscle balance (formation, breakdown or stability) as opposed to exact protein synthetic rates. However, absolute protein synthesis and breakdown rates are highly desirable.

This Subtopic addresses the following Human Research Program requirements:

- Risk of Impaired Performance Due to Reduced Muscle Mass, Strength and Endurance
- Gap M24. Characterize the time course of changes in muscle protein turnover, muscle mass and function during long duration space flight.

The technology developed should accurately be able to quantify protein synthesis, breakdown and total turnover.

A successful proposal will include the technologies being considered and detailed test plan for evaluating them during Phase I. A vision for miniaturizing the device and operating the device in microgravity is required.

Phase I Deliverables - Test results and plan for developing a low volume, low mass, easy-to-operate prototype. The

expected TRL resulting from the Phase I effort should be 4.

Phase II Deliverables - Prototype in year 1 with minimal human testing in year 2 to demonstrate efficacy.

Sub Topics:

Advanced NDE Modeling 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 3-D 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. It is assumed that all systems will have high resolution high volume data. Modeling efforts should be physics based and account for variations between material aging characteristics 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 Many Integrated Core (MIC) Architectures. 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, outlining the proposed approach to develop a given product (TRL 2-4), and describing any models and algorithms developed/utilized. Plan for Phase II including proposed verification methods.

Phase II Deliverables - Software of proposed product, report including detailed description of algorithms and models, 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 phenomena 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. 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 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.
- Development of instruments and software for reconstructing 3-D tomographic images that provides a non-intrusive measurement of the spatial phase distribution in gas-liquid flows. Instruments must be capable of a high temporal acquisition (200 Hz or greater) with resolution between phase boundaries within the measured region on the order of 2-3 millimeters or better. The fluids are typically air-water systems. Providing flight qualified hardware with these capabilities will allow for real-time measurements of phase distribution for a number of life support and biology technologies such as reactor beds, separators, and plant habitats.
- Devices that provide rapid or snap freezing of samples are sought due to their capability to provide for the preservation of samples that support a broad range of space research in the plant, microbiology, cell biology and animal biology subject areas.
- Increased use of the Light Microscopy Module (LMM). Several additions to the module continue to be solicited, such as: laser tweezers, dynamic light scattering, stage stabilization (or sample position encoding) for reconstructing better 3-D confocal images.
- 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 handheld portable use. Battery powered wireless operation is desirable. Specific issues to be addressed include: pitting from micrometeoroid impacts, stress fractures, leaking of cooling gases and liquids and detection of abnormal hot spots in power electronics and circuit boards.

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:

International Space Station (ISS) Demonstration of Improved Exploration Technologies Topic H14.02

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. Successful submissions will describe requisite testing on ISS. Proposals that do not require testing at the ISS should respond to other subtopic solicitations in appropriate technical areas. If submitted to this subtopic they will be considered non-responsive.

NASA encourages submissions that increase the Technology Readiness Level of space exploration and pioneering technologies in areas that include but are not limited to the following:

- Ambient temperature catalyst replacement for the ISS Water Processing Assembly.
- High pressure oxygen generation applicable to both ISS and future human space flight vehicles, demonstrated on ISS.

For all proposed technologies, research should at a minimum 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 flight unit or software package for ISS testing.

Phase I Deliverables - Research to identify and evaluate candidate technologies applications to demonstrate the technical feasibility and show a path towards a hardware/software demonstration. 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 prototypes that can be demonstrated on orbit (TRL 8). The contract should deliver 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.

Proposals should be generated to assume costs that are limited to the deliverables and the ISS Program, if chosen for flight, would provide safety, upmass and other integration costs.

Potential NASA Customers include:

- International Space Station Program (http://www.nasa.gov/mission_pages/station/main/index.html [17]).
- Orion Multipurpose Crew Vehicle (<http://www.nasa.gov/exploration/systems/mpcv/index.html> [18]).

Sub Topics:

Recycling/Reclamation of 3-D Printer Plastic Including Transformation of Launch Package Solutions into 3-D Printed Parts Topic H14.03

The National Aeronautics and Space Administration (NASA) has a long-term strategy to fabricate components and equipment on-demand for crew exploration missions. The greater the distance from Earth and the longer the mission duration, the more difficult resupply becomes; thus requiring a significant change from the current space travel supply chain model. The ISS is an ideal platform to begin testing and transitioning from the current model for resupply and repair to one that is more suitable for exploration missions. 3-D Printing, more formally known as Additive Manufacturing, is the method of building parts/objects/tools layer-by-layer. 3-D Printers on-board ISS will use extrusion-based additive manufacturing, which involves building an object out of plastic deposited by a wire-feed via an extruder head. While this process does provide on-demand capability for printing parts, to truly develop a self-sustaining, closed-loop on-orbit manufacturing process that will result in meaningfully less mass to launch and enabling space exploration, a means of recycling/reclaiming readily available materials will ultimately be required.

NASA seeks launch packing solutions that can be composed of materials suitable for recyclable processing into 1.75mm filament and subsequently 3-D printed parts. This capability will significantly decrease current waste and substantially increase sustainability. The solution may be obtained using a variety of approaches, such as:

- Converting commonly used 3-D printing feedstocks into packing solutions, including but not limited foam or bags.
- Transforming traditional packing materials into 3-D Printing feedstock.
- Developing a technology that utilizes a novel approach to identify compatible materials for both packing solutions and 3-D Printing. For example, this could include such materials as netting, fabrics, structures, containers, etc.

Examples of traditional packing materials currently used for ISS, as well as commonly used feedstocks and types of 3-D Printed parts are provided below. These are intended to serve as examples rather than requirements. The proposal does not have to be limited to these materials:

- Foams currently used on ISS:
 - Plastazote (LD24FR & LD45FR).
 - Polyethylene.
 - Polyurethane.
 - PVDF.
 - PTFE film (for bubble wrap).
- Bagging materials currently used on ISS:
 - Pink Poly (not pink and white).
 - Llumaloy (good for ESD compatibility).
 - Tedlar (particularly for containment).
 - Kynar (positive flammability ratings).
- Common Feedstock Materials:
 - ABS.
 - PTFE.
 - PEAK.
 - Ultem.
- Examples of 3-D Printed Parts:
 - Common hand tools.
 - Handles, containers.
 - Clips.
 - Personal items such as grooming tools.
 - 'Seat track' strips.
 - Corresponding studs.

Phase I Deliverable is a Technical Feasibility Study and should provide:

- Demonstration of a close-looped system that provides launch packing solutions that can be recycled into 1.75mm filament for creating 3-D Printed parts without requiring any additional mass other than the shared packing/printing materials and process. The 3-D Printed part(s) must be able to be printed using 1.75mm filament feedstock via a Fused Deposition Melting (FDM) process.
- A materials assessment, which addresses such things as materials composition, flammability, toxicity, off-gassing, etc.
- Technology Readiness Level (TRL) rating from 2-5.
- A Systems Engineering and Proposed Design path for developing an ISS locker-sized hardware demonstration for functional testing at the completion of the Phase II contract.

The ultimate objective is to evolve this technology into a Phase II SBIR ISS Technology Demonstration payload.

Sub Topics:

Optical Components, Sensors, and Systems for ISS Utilization Topic H14.04

The International Space Station (ISS) is an on-orbit research platform that provides a superior environment for human health and exploration, technology testing for enabling future exploration, research in basic life and physical science, and earth and space science as enunciated in the NASA Authorization ACT of 2010. This subtopic would focus on the utilization of ISS as a foremost test bed for test, operation, and validation of the functionality of advanced optical components, sensors and systems for enabling future exploration. The goal of this subtopic research is to satisfy the mission of the International Space Station (ISS) Program by advancing science and technology research and there by significantly contributing to expand human knowledge, inspire and educate the next generation, foster the commercial development of space and demonstrate capabilities to enable future exploration missions beyond low Earth orbit (LEO) as discussed in the International Space Station (ISS) Researcher's Guide is published by the NASA ISS Program Science Office. Under this subtopic, innovative research topics compatible to ISS test environment would address HEOMD core issues related to radiation protection, deep space habitat elements and analog missions.

This subtopic would take advantage of revolutionary and rapid advances that are taking place in optics, materials and processing disciplines. Development of sensors and systems using innovative sources, detectors, materials, components and configurations for accomplishing new and/or improved performance, increased reliability and ruggedness, reduction in size, weight and power consumption (SWaP), and cost would advance HEOMD missions.

Topics of interest include but not limited to optical materials, optical components such high temperature and broadband windows and elements, active and passive sensing architectures, smart sensors and sensor suites including multifunctional aspects, monolithic or hybrid high operating temperature detectors and focal plane arrays, ISS compatible miniature remote sensing systems for characterization of hard targets, terrain mapping, deep space imaging (3-D and hyper spectral) sensors and systems, and precision, navigation, and timing systems.

Sub Topics:
